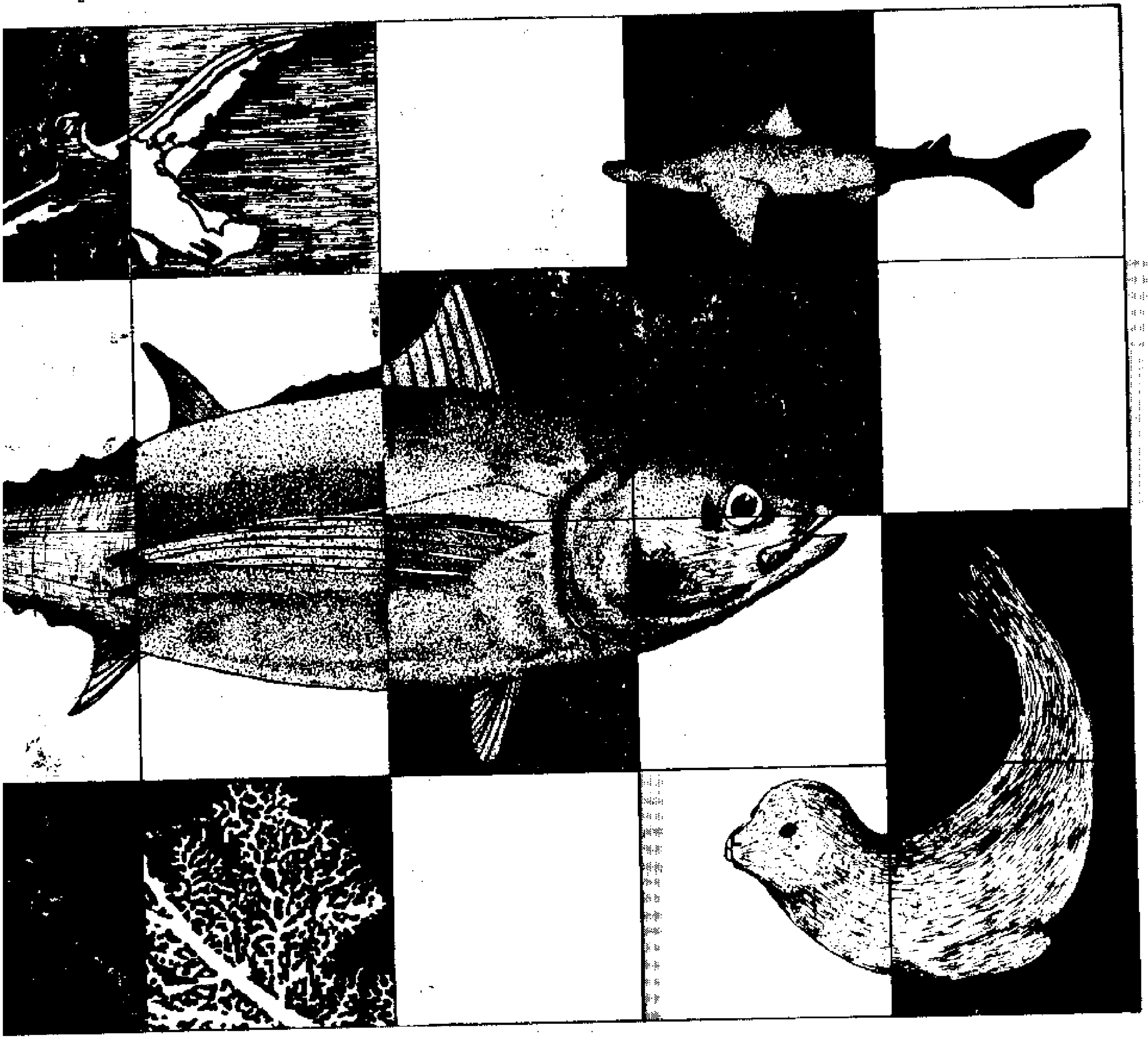
Proceedings of the Symposium on Status of Resource Investigations in the Northwestern Hawaiian Islands

April 24-25, 1980



Proceedings of the Symposium on

STATUS OF RESOURCE INVESTIGATIONS IN THE NORTHWESTERN HAWAIIAN ISLANDS

April 24-25, 1980
Campus Center Ballroom
University of Hawaii
Honolulu, Hawaii

Editors

Richard W. Grigg

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Symposium Sponsors

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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 (U.S. FWS), and the Hawaii Division of Fish and Game (HDFG) was established to conduct a five-year survey and assessment of the marine resources of the Northwestern Hawaiian Islands (Nihoa Island 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 HDFG and seabird resources to U.S. 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 is 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 two years of research. The agency heads who served as members of the steering committee to organize the symposium are Mr. Richard Shomura, Southwest Fisheries Center, Honolulu Laboratory of NMFS; Mr. Kenji Ego, Hawaii Division of Fish and Game; 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 convenor 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.

The proceedings of the symposium contains the manuscripts, the welcoming address of Governor George Ariyoshi; the keynote address by John P. Craven, dean of Marine Programs at the University of Hawaii; an introductory paper by Richard Shomura; a luncheon address by Dr. John Munro, dean of the Faculty of Science of the University of Papua New Guinea; a summary of the Panel Discussion, and Concluding Remarks by John P. Craven.

The editors gratefully acknowledge the professional assistance of Karen Tanoue in final preparation of the manuscripts for publication. Production assistance was also provided by Karynne Chong and Sherry Saito. In terms of organizing and conducting the symposium, Joan Choy and Joan Yamada of the UH Sea Grant College Program provided invaluable assistance. The artwork for the cover of the proceedings as well as several section pages was done by Wendy Nakano, also of the UH Sea Grant College Program.

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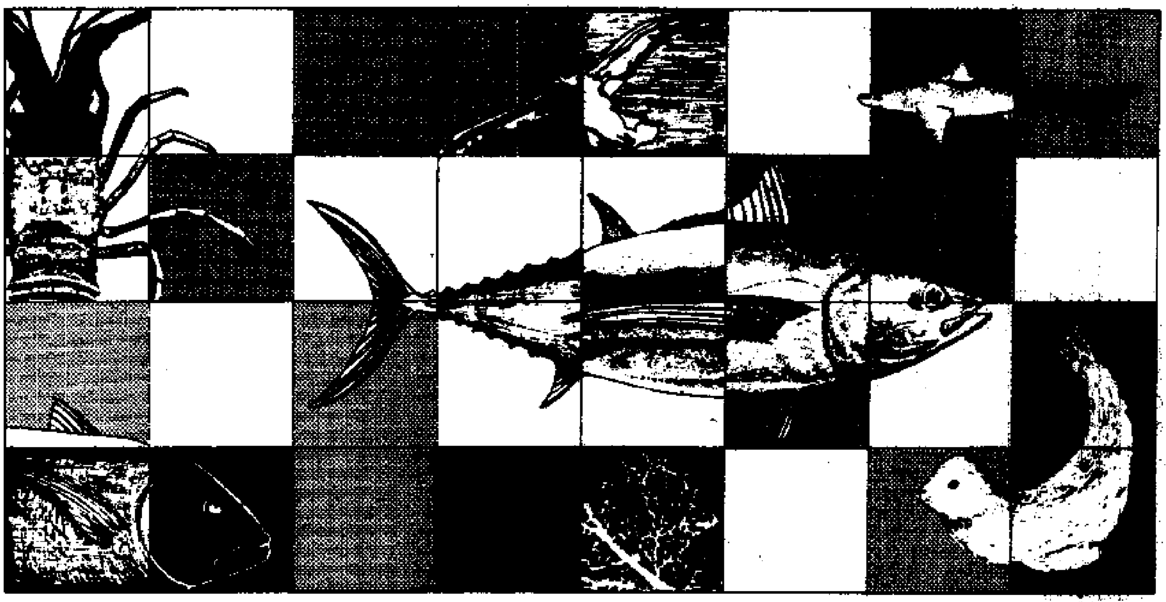
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WELCOMING ADDRESS

Governor George Ariyoshi

State of Hawaii, State Capitol, Honolulu, Hawaii 96813

(Read by Susumu Ono, Director of Hawaii Department of
Land and Natural Resources)

A few weeks ago a visitor said to me, "Governor, you have such a beautiful state--it is a shame that you have no natural resources." I replied, "I am sorry you have not had the opportunity to really know our state, for, as a result of our year-round tropical sunlight we can, if we wish, develop all of the resources that we currently need for a healthy, self-sufficient economy."

I can understand our visitor, for his misperception is as old as American history. The mainland was settled by refugees from oppression and poverty who chose to be independent even in a wilderness. The first expansion of the original colonies was the Louisiana Purchase which was regarded as an excessive addition of wilderness land for the limited purpose of obtaining access to the Gulf of Mexico. Even the famous exploration of Lewis and Clark did not discover the vast deposits of minerals, of copper and iron ore, the rich soil of our farm belt, or the sources of hydroelectric power of the Great Northwest. The acquisition of Alaska was ridiculed as Seward's Folly without realizing that this land of ice and snow was rich with gold and was to be, in the twentieth and twenty-first centuries, a major natural source for oil and coal.

It is thus, only natural for people to believe that these small islands in the middle of a vast ocean lack natural resources. We do not yet know the extent of our resources, but we are beginning to have an idea and it may be that we are richly endowed. I understand that your project has already identified biological resources of the archipelago that were not previously known. The abundance of fish called alfonsin and armorhead in the northern part of the chain was unknown to me and perhaps all but a few scientists. The possibility of a lobster fishery has been identified. Species of coral not previously known from Hawaii have been identified. A new tuna fleet has now operated successfully north of Midway and substantial schools of deep-water shrimp have been located in the Northwestern Hawaiian Islands.

Your work is just beginning, and if you are successful, we shall understand the basic process of growth in the archipelago. This may permit us to engage in the open sea farming of fish by using our fish attractant buoy systems in an intelligent manner or to practice cage culture of a wide variety of fish species, or to manage new and traditional species in more effective ways.

It is not insignificant that, in part, fish farming and aquaculture depend upon energy from the sun. It is solar energy that is perhaps

Hawaii's greatest resource and it appears in many forms--in direct radiation, in agriculture and aquaculture, in wind, in the production of gasohol, in the production of bagasse and mill waste for generating electricity, in ocean thermal energy conversion (OTEC). In addition, we have developed our first geothermal well. All of these forms of energy are now under development and together they can provide an effective self-sufficiency for the state. But the potential is even greater. There exists a potential for energy export. Studies have already shown that OTEC should be able to make ammonia at commercially competitive prices. I understand that ammonia can be used as a fuel to generate electricity at any location. Should this possibility develop, I have been told that Hawaii could export as much energy each year as is now exported from the Middle East.

Even if this were not so, it seems obvious that we have barely scratched the surface in assessing our natural resources. Therefore, your project is vital to the state of Hawaii as the Lewis and Clark Expedition was vital to the Louisiana Territory.

I am particularly pleased with the organization and participation of this Northwestern Hawaiian Islands program. Its tripartite core of the National Marine Fisheries Service, the Fish and Wildlife Service, and the Hawaii Department of Land and Natural Resources guarantees that the full spectrum of environmental and economic concerns will be considered. The additional support from the University of Hawaii Sea Grant College Program and by my Office through the Marine Affairs Coordinator guarantees scientific and executive support and gives validity and prominence to this excellent endeavor.

I await with interest the results of this symposium and I look forward with anticipation to your future discoveries. The knowledge that you will provide is vital to the future of Hawaii and its people.

Mahalo.

I would like to reiterate that the welcoming address is a message from Governor Ariyoshi. As Chairman of the Board of Land and Natural Resources, I would like to add my personal thoughts and comments as far as this symposium is concerned. We are delighted to have been a party to this effort so far and I can assure you that our department will continue to be an active participant in this symposium and the second half of the five-year project. If at any time we can provide assistance to the other parties of the joint effort, please let us know. When I say "we," I mean the Board of Land and Natural Resources, and its members really mean it. Thank you very much.

KEYNOTE ADDRESS

John P. Craven

Dean of Marine Programs, University of Hawaii, Honolulu, Hawaii 96822
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Philosophers frequently talk about the question, if a tree falls in the forest and nobody is there, does it make a sound? Many essays have been written about that, but it is not really a problem to a scientist. If a tree falls in the forest it generates an acoustic wave, also the tree would create an identifiable pattern on the ground and the ground would quake. Also a small amount of dust would be stirred up and by logical processes, deduction, a scientist could go out and make a number of measurements and in fact show that indeed a tree had fallen in the forest.

And so it is with the Hawaiian Archipelago, which has existed for years and years without the presence of man, and as we go out there we will discover to our joy that we can identify the history of the trees that have fallen, the lava flows that have flowed into the sea, and the biological processes that have been going on for millions of years. I even understand that it may be possible to determine past variations in annual water temperature by analyzing the ratio of strontium to calcium in the skeletons of corals collected from various islands in the archipelago. And so it may be possible, if we so desire, to partially reconstruct the physical and biological history of the Northwestern Hawaiian Islands before the time that man arrived. And this is probably a useful thing to do simply to better understand the world and climate in which we live.

But we are concerned with the Hawaiian Archipelago in terms of interactions with man. And man interacts with the archipelago on several levels. The first level of man's interaction is the man purely as an animal, an animal that has little thought for tomorrow, concerned only with subsistence and with wresting an existence from its environment. And as with any animal, there are bound to be impacts on other species which are preyed upon or simply disturbed by new events. In the Hawaiian Archipelago, we have seen this; man as an animal brought with him rabbits and introduced them to Laysan Island. The rabbits multiplied and destroyed the vegetation and greatly disturbed other ecosystems on the island including the marine birds. Eventually the rabbits ate themselves out of house and home and their population declined. Finally man, perhaps as an animal, perhaps as a conservationist, returned to Laysan Island and did in the rest of the rabbits. And now it is my understanding that Laysan Island has nearly recovered to its former state.

And so we see man as an animal moving in to harvest species such as marine sea turtles and possibly bringing with him undesirable pests. And we can expect that such unregulated activity will result in major changes in the balance of natural ecosystems in the Northwestern Hawaiian Islands.

But man is more than an animal! And of course man is distinguished from the rest of the mammals by the characteristic known as one time learning. Man is almost unique as an animal that needs only one negative stimulus in order to learn. It is a favorite saying of politicians that there is no need for the second kick from a mule. And that indeed is a characteristic of human beings, that given one affirmative or negative stimulus we can then repeat the pattern that we wish. Curiously enough, the only other mammal that we know of that is capable of one-time learning is the dolphin, and this perhaps is the reason why many people ascribe superior capabilities to this creature.

Now what does this permit man to do? It allows man to very quickly develop a logic structure, a logic structure which permits him to make an extension into the future that need not be reinforced by continuous or repetitious observations. James Fraser, author of the book THE GOLDEN BOW, pointed out that this is in fact, the start of civilization. But logic works only with respect to the local empirical evidence which is available plus other knowledge available from society at large. One can act on the basis of a complete set of information, a partial set of information, or a purely invented set of information. The latter "fact" which is invented fact is often referred to as dogma.

And so the second intrusion of man into the Hawaiian Archipelago has basically been one of logic and of dogma. And those dogmas have ranged from one side that claims that man can intrude for any purpose of man without causing any impacts of significance. And thus we get airstrips built on Tern Island so that it looks like an aircraft carrier deck instead of part of an atoll. And thus we find some early installations on Midway which illustrate the dogma that one can hardly disturb the natural environment as long as one did something useful for man.

And so we see as we enter the Northwestern Hawaiian Islands to do study that if we enter with preconceived notions, i.e., dogma, that we do two things. And these are the wrong things insofar as inhibiting our own learning of the truth and achieving the desired result, that is management. And this characteristic of logic plus dogma is not just a product of earlier centuries, it exists today and it will exist in the future. And the reason it exists today and will exist in the future is that no matter how much we learn, we will never have sufficient time, money, or resources to acquire all the information to develop all the empirical laws to answer all the questions which may be asked regarding conservation and management. And so inevitably we will fill in the gaps with a subjective understanding which is our own internal way of ascribing dogma. We have seen this with respect to a very serious problem which is that of the Hawaiian monk seal. All of us, of course, have a desire to preserve the Hawaiian monk seal. And yet actions are being taken which many believe are premature and are based upon the dogmatic view that the probable reason for the decline in their populations is intrusion by man as opposed to possible other factors.

And so the first keynote as we approach the Northwestern Hawaiian Islands is that we will be successful if we strip away from our minds as much dogma as possible. It is not given to this project or to this mission to go out and prove a point. This is a joint effort, a quadripartite effort, and it is therefore important that as you go forward in your research efforts, that you steel yourself with the notion that the empirical evidence be the best measure of truth whether or not it is antithetical to your dogma or your preconceived views.

The first aspect then of the Northwestern Hawaiian Islands study that seems to me to be so good is that it has concentrated on obtaining sound scientific empirical data on the basis of a logical structure. But that's not enough, because the empirical information that could be obtained and placed within a logical structure to describe marine ecosystems in the Northwestern Hawaiian Islands is essentially infinite. For example, one could take this room, place thermisters all over it, collect warehouses full of data, and after much labor and analysis determine that on this day, April 24, a large group of people assembled in this room. While this conclusion may be scientifically defensible, from another perspective it might logically be considered as a candidate for Proxmire's golden fleece award.

We therefore must face the fact that we are investigating the Northwestern Hawaiian Islands for subjective reasons, some of which deal directly with the missions of the participating agencies. One organization has the mission requirement to preserve to the extent possible a balanced environment. Experiments must therefore be planned with a logic structure that will provide the critical empirical data necessary to determine what must be left untouched and what can be touched in order to achieve that subjective goal of a balanced environment.

Another participating agency is charged with the mission of developing biological resources for economic benefits to man. So it is equally important to develop a logic structure to gather the required information to satisfy this goal. And there are other organizations which are concerned with science. And we need to develop a logic structure that serves to determine that science needs to be done, such as geophysical processes which govern the formation and evolution of these wonderful islands that make up the Hawaiian Archipelago.

And one should also take into account political factors for these may determine the boundaries of our islands or at least our resources. What kinds of legal questions are going to arise? What are the potential uses of the area and its resources? And what of the impacts of, for example, an archipelagic theory of jurisdiction with jurisdiction being vested to the state or shared between the state and the federal government or further, the international community? A logic structure must be developed in order to guide your future investigations with respect to the problem of jurisdiction and all of the above--preservation, conservation and development of fishery resources and, the development of good science.

So in summary, I would charge you to behave in the highest order for which man strives--to utilize man's unique capability to engage in logic, to measure and store empirical information, and to utilize this information free of dogma in such a way as to achieve the initial goals of your programs. I think you are doing this and I am looking forward to hearing and reading the papers. I wish you well in this symposium.

INTRODUCTION OF TRIPARTITE AND SEA GRANT RESEARCH PROGRAMS IN THE NORTHWESTERN HAWAIIAN ISLANDS

Richard S. Shomura

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Honolulu, Hawaii 96812

Mr. Chairman, distinguished guests, Northwestern Hawaiian Islands (NWHI) symposium participants, ladies and gentlemen. I am indeed honored to be invited to make a few introductory remarks to open this symposium.

I am sure all of you are aware that the NWHI study is still an ongoing and active program and that this symposium is primarily a mechanism to evaluate and assess the results achieved to date. We need this midstream pause to avoid the triple-S disease--Shomura's should've syndrome--a disease which is characterized by a feeling, after the fact, that we should've done this, or should've done that.

Before providing you with some background information on the rationale for the NWHI investigation, I would like to briefly describe the NWHI and state the general objectives of this study.

First, to clear up some nomenclatural problems, the string of islands under investigation is commonly known as the Leeward Islands. Since Leeward is such a nondescript term and could refer to one of several leeward islands located throughout the world, I prefer to follow the State of Hawaii's lead and refer to this part of the Hawaiian Archipelago as the NWHI.

The NWHI are made up of a group of low, rocky islets and coral atolls extending more than 1,000 miles in a northwesterly direction from Nihoa Island to Kure Atoll. Geologically, the NWHI are markedly different from the main Hawaiian Islands. The main islands on which we live are of recent geological vintage, volcanic in origin, and are characterized by high mountains and relatively large land masses. These large land masses--the main islands--even before discovery by man, contained a wide variety of plants and animals. In contrast, the NWHI include a relatively impoverished land fauna, in a limited terrestrial habitat.

Today, many people would describe much of the NWHI area as pristine. Historically, this was not the case. In the late 1800s entrepreneurs began mining operations for guano at Laysan and Lisianski Islands. The non-pristine situation was aptly described in an article which appeared recently in a local newspaper. Besides giving an account of the primitive living conditions on Laysan, there is a description of the havoc caused by the introduction of rabbits on Laysan Island. In addition to mining, others set up harvesting bases to collect feathers of seabirds. In the late 1920s pearl shells were harvested from the lagoons of Pearl and Hermes Reef.

To protect the birds of the NWHI, President Theodore Roosevelt in 1909 designated the area as "The Hawaiian Islands Bird Reservation." In 1940 the area was redesignated "The Hawaiian Islands National Wildlife Refuge" and in 1966 the refuge became a part of "The National Wildlife Refuge System." The State in 1952 also designated the area as a State wildlife refuge.

The NWHI are part of an interesting maze of ownership and jurisdiction. All of the islands from the Big Island to Kure are part of the Hawaiian Archipelago. With the exception of Midway all of the islands are considered part of the State of Hawaii. With the exception of Midway and Kure all of the islands of the NWHI are a part of the Hawaiian Islands National Wildlife Refuge. While the NWHI can be considered legally part of the State of Hawaii, the actual administration of the islands rests with the Fish and Wildlife Service since all except Kure and Midway come under the Wildlife Refuge System. For the management of fish and wildlife on Kure, I believe the State has adopted a policy that is essentially in consonance with Federal regulations.

The NWHI are a classical example of the problems mankind presently faces in allocating access to and availability of resources. Decisions on allocation inevitably must be made in the general framework of "what's best for the nation." Since mankind in this case primarily refers to the citizens of Hawaii and the rest of the nation, we will need to identify the players.

Who are the players with interest in the NWHI? First, there is the naval force on Midway. The Navy command on Midway fluctuates in size depending upon the world military situation, but they generally keep a low profile. The Coast Guard is currently on Kure Island maintaining a loran station. Until last year the Coast Guard also occupied French Frigate Shoals where they maintained a loran station. This station was phased out in 1979. The third group includes the commercial and recreational fishing interests. It should be pointed out that commercial fishing in the NWHI took place before the World War II years. Much of the fishing activity, however, was confined to the lower sectors of the NWHI. Then there is also the interest in the NWHI of the scientific community. The first scientific study of the NWHI was undertaken by the U.S. Fish Commission in 1902 on the research vessel Albatross. Since 1902 research in the NWHI has been sporadic. After nearly three decades of little or no scientific activity in the area, Paul Galtsoff, a fishery biologist in the old U.S. Bureau of Fisheries, undertook an investigation of Pearl and Hermes Reef in 1930. Finally, among the cast of players is a segment of society which has a deep interest in conserving and preserving the fauna and flora of the NWHI.

What are the resources of interest to these special interest groups? First, the military is simply interested in Midway Islands as an operational base, although at one time they were deeply interested in the avifauna. Their interest in the avifauna was primarily in trying to eliminate albatross or at least to discourage the nesting of albatross on the aircraft runway. The fish and invertebrate resources of the NWHI are of interest to the commercial and recreational fishing community. These resources are not completely understood in terms of availability and abundance.

There are many species of seabirds that live and nest in the NWHI. There are also several endemic land birds associated with these islands. These include the Laysan duck, Laysan finch, Nihoa finch, and the Nihoa millerbird. Among the seabirds are the familiar Laysan albatross, black-footed albatross, frigatebird, noddy tern, boobies, shearwaters, and a handful of other species.

For marine mammals, the NWHI is home for the endemic Hawaiian monk seal. The Hawaiian monk seal is presently on the endangered species list, since there is some evidence that the population is declining. Because the number making up the total population of seals is in the order of hundreds and certainly less than several thousands, there is cause for concern. Finally, there is the green sea turtle which nests in the NWHI and is currently on the threatened species list.

All of my ramblings to this point leads up to the general objective of why we are studying the NWHI. Even if society in general was not interested in the area, the isolated nature of the Hawaiian Archipelago and the fact that it is in the outer reaches of the Indo-Pacific fauna would in itself be of tremendous scientific interest and inquiry. The fact that various segments of society have expressed interest in the area, some with conflicting views, makes our investigation even more crucial and necessary. I would like to think that our overall objective is to gain knowledge and understanding of the NWHI marine ecosystem to provide decisionmakers with a sound basis for the utilization or non-utilization of the resources of the area.

I've often wondered what will happen to the NWHI if and when the ice caps melt as has been predicted. If the melting ice caps were to appreciably raise the sea level in the NWHI will the Hawaiian monk seal, if not extinct by then, adapt to a rocky shore habitat? How about the poor green sea turtle that needs to dig her nest in sand; she will find "tough sledding" on rocky shores. Finally, will the albatrosses be able to adapt, possibly ending up nesting on the slopes of Haleakala? Returning to the realities of the present, what we need to know about the resources today is how much is available, and of more importance, the interactions of the various components of the ecosystem. Although we need a quantitative measure of the resources available in the area, it is more important to know what effect the various components of this ecosystem have on each other. What are the pressure points? Is the abundance of the Laysan albatross controlled by availability of food or is it associated with other environmental factors such as temperature?

The process by which we embarked on this study may be of interest to some of you. The Honolulu Laboratory in 1973 went through a major reorganization. In Federal Government circles a major reorganization usually means a cut in budget and a reduction in force. These two things took place in 1973 and the Lab was in a demoralized and chaotic condition. In an early planning session I had with several key staff members we agreed that one way to revitalize the Lab was to embark on a new program, a program that would generate interest, be high on the scale of regional or national needs (this in light of the budget situation) and one which had appeal and could be "sold" through the system. Since we could see the problems that were beginning to surface within the NWHI, it seemed like a study of the NWHI would be important, have high visibility, and would be a program that could generate fiscal support. In the early 1970s preservationists were gathering support to close the NWHI to all human activities; others with commercial inclinations were beginning to be concerned that fishing access to the NWHI would be closed off. The Navy at Midway remained silent and the Coast Guard kept trying to accommodate the many State and Federal regulations and guidelines that control the area.

A quick review of the literature revealed that very little was known of the fauna and flora of the NWHI. It distressed me a bit when I realized that we at the Honolulu Laboratory knew more about the resources of the tropical equatorial Pacific, the pelagic waters of the North Pacific, and even the resources of the Indian Ocean than we did the resources of the NWHI.

In late 1973 we undertook some preliminary field work in the NWHI on the NOAA research vessel David Starr Jordan. Encouraged by our early findings we began a major push through our budgeting cycle to obtain funds to carry out a long-term program. We were successful to a limited extent. We recognized that in the Federal climate of the mid-1970s, obtaining funds and personnel ceilings were difficult. Realizing that the Honolulu Laboratory could not do the entire job properly, I approached the Fish and Wildlife Service, the State Fish and Game, and the University of Hawaii Sea Grant College Program about pooling our collective resources and undertaking a cooperative investigation of the NWHI. I received immediate and positive responses from the Fish and Wildlife Service and Fish and Game. From Sea Grant I received neither a positive nor a negative response. I guess one could say the suggestions of cooperative effort that I made at the Sea Grant advisory meetings fell on deaf ears. In fairness to Sea Grant, the program at that time was embroiled in a tremendous task of reorganizing its aquaculture program. Since that was Sea Grant's largest program at that time it probably took up all of the energy the Sea Grant leadership could then generate.

In any event, I met with Fish and Wildlife Service and Fish and Game officials to scope out a cooperative program. We decided to allocate the research areas pretty much in line with organizational responsibilities; thus, the Fish and Wildlife Service was to undertake research responsibility for the seabirds, Fish and Game for the nearshore fishery resources, and the Honolulu Laboratory for the slope, banks and offshore resources. We found out later that the National Marine Mammal Laboratory of the Northwest and Alaska Fisheries Center, National Marine Fisheries Service in Seattle had research plans for monk seals. In the meantime, we continued to plan cruises to the NWHI from 1975 to 1978. To formalize the cooperative research agreement we developed a document that detailed the plans for the various agencies in a tripartite agreement to conduct research in the NWHI. Although the agreement was signed in 1978, the cooperative research was initiated much earlier. Incidentally, as of mid-1979 the Honolulu Laboratory was given the responsibility for research on Hawaiian monk seals and green sea turtles.

Returning to Sea Grant involvement, or lack of involvement, the best thing that happened to the Sea Grant Program was the return of Dr. Jack Davidson to Hawaii in 1977. An equally fortunate event was the return to the University in late 1977 of Dr. Rick Grigg, who had spent a year in Washington, D.C. Rick was eager to resume his research activities and approached me about some sea time on our research vessel to collect data on precious corals in the NWHI. I took this opportunity to give Rick a long discourse, expressing my disappointment with Sea Grant for its lack of involvement in the tripartite study. As you can probably guess, Rick, with support from Jack Davidson, quickly prepared a NWHI package for Sea Grant support.

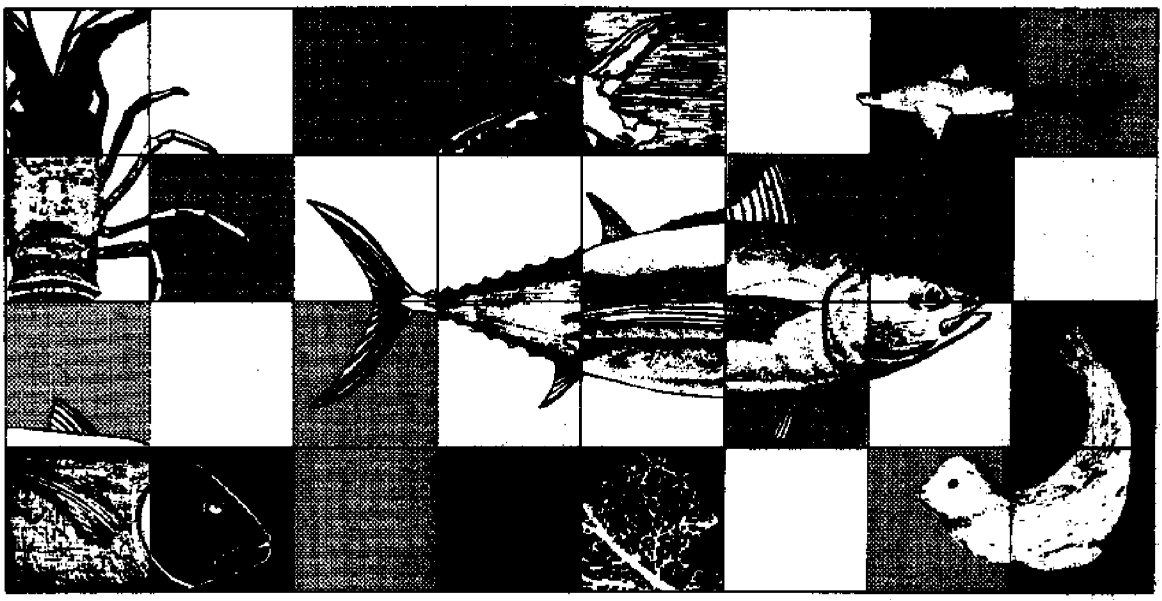
As evidenced by its current deep involvement with this symposium, Rick was successful in influencing Sea Grant to become a full partner in the NWHI studies. The studies currently being supported by Sea Grant are complementary to those being carried out by the other three agencies. In their study of primary productivity and the oceanographic environment in the NWHI, Sea Grant is filling a major research gap.

During the presentations today and tomorrow you will be hearing about some extremely interesting and exciting research. I believe some of the results will turn out to be major contributions toward our understanding of tropical reef ecosystems.

In closing, it is my hope that the final product of this cooperative undertaking will be a monograph bearing a title something like "The NWHI--An Ecosystem Successfully Dissected and Analyzed." Furthermore, I would like to see a paperback version of this monograph entitled "Everything you wanted to know about the NWHI but were afraid to ask."

Thank you.

Onshore Research



THE STATUS OF SEABIRD RESEARCH IN THE NORTHWESTERN HAWAIIAN ISLANDS

Craig S. Harrison and Thomas S. Hida

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Service, NOAA, P.O. Box 3830, Honolulu, Hawaii 96812

ABSTRACT

The five-year objectives of the U.S. Fish and Wildlife Service (FWS) are to enumerate Northwestern Hawaiian Islands seabird populations, inventory food utilized, locate major feeding areas, and determine consumptive rates. To date, preliminary assessment of populations has begun and a comprehensive food habits study is nearing completion. The 3,000 food samples from 18 seabird species analyzed thus far indicate that most birds feed opportunistically on shoaling fish and squid. The fish families Exocoetidae, Mullidae, Carangidae, Synodontidae, Dussumieriidae, Coryphaenidae, Molidae, and Holocentridae and the squid family Ommastrephidae appear to be especially important. Prey length data indicate that most terns and shearwaters feed on prey species in the 2 to 8 cm range and that boobies feed in the 10 to 20 cm range. An encouraging feasibility study using radiotracking with the brown noddy on Oahu resulted in a technique to locate feeding areas. Future objectives include completion of food studies and refinements of population estimation techniques. Information gaps still include location of feeding areas and knowledge of consumptive rates of seabirds. We need a better understanding of life histories, age structure, and annual production of important prey items including Ommastrephidae, Exocoetidae, Mullidae, and Synodontidae.

Northwestern Hawaiian Islands
seabirds
feeding ecology

INTRODUCTION

Seabirds are a relatively poorly studied group of birds. They can be characterized as being relatively long-lived, displaying deferred maturity, reproducing slowly, and possessing salt excretion glands which enable them to drink salt water (Bourne, 1963; Lack, 1967). Most species spend most of their lives at sea, but the fact that they must return to land to breed emphasizes the fact that they are terrestrial expatriates. Hutchinson (1950) contends that seabirds perform an important function for reef communities by concentrating nutrients in a localized area.

Large portions of the worldwide breeding range of the black-footed albatross (Diomedea nigripes), Laysan albatross (D. immutabilis), Bonin petrel (Pterodroma hypoleuca), Christmas shearwater (Puffinus nativitatus), sooty storm-petrel (Oceanodroma tristrami), blue-gray noddy (Procelsterna cerulea), and gray-backed tern (Sterna lunata) are within the Northwestern Hawaiian Islands (NWHI). Additionally 11 breeding species occur in the archipelago with total numbers of seabirds being estimated at 10 million birds. Seabird populations have plummetted when fisheries directly competed with birds for the same prey species in Peru (Idyll, 1973), South Africa and Southwest Africa (Crawford and Shelton, 1978), and possibly California (Ainley and Lewis, 1974). Recent fishery-seabird models indicate that birds may be unable to produce young if forage fish fall to 70% of virgin levels (MacCall, 1980). Tropical seabirds generally feed at the surface, or in the case of some birds of the order Pelicaniformes, within the first few meters. Ashmole and Ashmole (1967) contend that large predatory fish, especially scombrids, are important because they drive prey to the surface and make them available to the birds.

The internationally recognized importance of the NWHI seabird resource and the potential for adverse impacts from improperly managed fisheries in other parts of the world prompted the U.S. Fish and Wildlife Service to agree to enumerate NWHI seabird populations, inventory food utilized, locate major feeding areas, and determine consumptive rates. Crawford and Shelton (1978) point out, "The interrelationships of pelagic fishery and seabird populations signify the overriding importance of sound fishery management for other ecosystem components."

METHODS

The remoteness of the Nihoa to Kure study area has made access a major problem. Cruises on the R/V Townsend Cromwell, military air command flights to Midway, U.S. Coast Guard flights to Kure, and recent FWS involvement on Tern Island have provided sporadic opportunities to study the marine bird resources. In addition, field camps on Laysan Island from March to August in 1979 and 1980 have provided an opportunity to intensively follow reproductive biology, collect monthly food samples, and make detailed population estimates.

The variety of studies carried out to date precludes a detailed description of techniques and methods. Population assessments have been made with several techniques including direct counts and stratified random sampling. All food samples have been collected on the islands by utilizing generally non-lethal techniques. Approximately 100 Bonin petrels and Bulwer's petrels (Bulweria bulwerii) had to be sacrificed due to inabilities to induce regurgitation. In the laboratory, standard analytical techniques including sorting, identification, counting, volumizing, and measuring standard lengths were carried out (Ashmole and Ashmole, 1967). A telemetry project utilizing a 5.4 g transmitter package is described in detail in a forthcoming publication (Harrison and Stoneburner, in preparation). Reproductive biology, phenology, incubation shifts, and chick feeding intervals on Laysan Island were carried out with standard observation techniques, details of which will appear in forthcoming publications.

RESULTS AND DISCUSSION

It cannot be overemphasized that all statements and conclusions are tentative in this continuing study. Population estimates will be refined. Subtleties of feeding habits, including a somewhat different assessment of critical prey items, may well turn up when geographic and seasonal considerations are explored and the entire data base is accessible with automatic data processing techniques.

Populations

Seabird populations, like any real population of wild animals, are dynamic over time. This volatility is confounded by the fact that estimation techniques for some species are inherently imprecise. For example, cliff nesting blue-gray noddies and white terns (*Gygis alba*) on Nihoa and Necker are extremely difficult to census without low level aerial photographic capabilities. Sooty terns (*Sterna fuscata*) can be censused effectively only when incubating eggs. Adults scatter when an investigator enters a colony and once eggs hatch, chicks form crèches and density estimates become very imprecise. Given the propensity of this species to lay in sub-colonies over a 6 to 8-week period, an accurate census is only possible on a particular island by placing investigators at that location for at least a month during spring. Counts of roosting red-footed boobies (*Sula sula*) and black noddies (*Anous tenuirostris*) peak at approximately 0400 and censuses at other times of the day underestimate, often grossly, the true numbers of birds in a colony. On sandy atolls, nests or immobile young, e.g., albatross, are generally the easiest birds to census. This technique ignores large numbers of non-breeding birds which roost at a colony and forage in the vicinity. The attachment of pre-breeders and failed breeders to a colony is insufficiently understood for any species, but is necessary to determine true colony size and concomitant requirements for nearby marine food resources. Burrow nesting birds such as Bonin petrels and wedge-tailed shearwaters (*Puffinus pacificus*) also present special problems. Burrows can be easy to census if not crushed in the process, but may extend far underground and must be excavated in order to determine occupancy. It is a goal for the second half of this study to develop repeatable census methodologies for each species and habitat.

Table 1 presents our best present estimates of NWHI seabird populations and, additionally, mean adult weights for each species. Most bird weights are from Laysan Island and represent a sample size of approximately 50 adult weights per species. NWHI birds are generally heavier than birds from Christmas Island (Pacific Ocean) as reported by Ashmole and Ashmole

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(1967). Most population data are taken from the Atoll Research Bulletin series (Amerson, 1971; Amerson et al., 1974; Clapp, 1972; Clapp and Kridler, 1977; Clapp et al., 1977; Clapp and Wirtz, 1975; Ely and Clapp, 1973; Woodward, 1972). Our data have generally corroborated these estimates, but some changes will undoubtedly be forthcoming at the conclusion of this study. Revisions will reflect both genuine population changes and improved census technology. Estimates for Midway are our own. The largest concentrations of total birds and avian biomass occur on Laysan, Lisianski, and Midway. Midway's populations have been reduced by large scale habitat destruction and the introduction of *Rattus rattus*.

Food habits

Published accounts of feeding habits of tropical Pacific seabirds are limited. Ashmole and Ashmole (1967) provided data for 8 Christmas Island species (N = 800) and Schreiber and Hensley (1976) added 3 additional species for the same study area (N = 175). Table 2 lists samples collected by species and month through November 1979. This study is the most comprehensive tropical seabird work yet attempted. We expect to have

TABLE 2. TOTAL FOOD SAMPLES COLLECTED JANUARY THROUGH NOVEMBER 1979

SPECIES	MONTH												TOTAL
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Black-footed Albatross		41	12	28	42	3							126
Laysan Albatross	1	15	20	30	50	4	1						121
Bonin Petrel			5	36	51								92
Bulwer's Petrel					20	13	10	27					70
Wedge-tailed Shearwater					20	19	13	19	11	7	24		113
Christmas Shearwater			4	3	22	11	28	39	7				114
Sooty Storm-Petrel				7	1								8
Red-tailed Tropicbird		4			31	25	63	51	22	18			214
Masked Booby			11	16	42	10	12	33	2	3	15		144
Red-footed Booby	13	25	15	10	55	11	18	41	14	15	22		239
Brown Booby			4	10	25	8	20	27			21		115
Great Frigatebird		5	5	15	50	11	14	19	7	12	6		144
Sooty Tern			7	21	99	27	28	79	9				270
Gray-backed Tern			7	23	88	10	5	33					166
Blue-gray Noddy					42			1					43
Brown Noddy			14	14	69	4	70	61	3	9	1		245
Black Noddy	17	8	8	31	95	13	79	45	15	37			348
White Tern	4	6	2	4	34	23	18	61	28	11	5		196
TOTAL	35	104	114	248	836	192	379	536	118	112	94	0	2768

adequate sample sizes for all breeding NWHI species except for the sooty storm petrel, but the extremely digested sample condition makes it difficult to provide as much information as we had hoped for the Bulwer's petrel and the Bonin petrel. Data presented here are generally based on sample sizes of 30 to 50 per species and ignore potentially important differences in year, season, and location. We suspect seasonal changes may be very important. Continuing collections are designed to fill information gaps in geography and season.

NWHI seabirds feed on fish, squid, and arthropods. By volume, the blue-gray noddy feeds on the highest percentage of arthropods (25%), especially the insect Halobates sp. Remaining species feed on no more than 8% of this phylum. Procellariiformes (albatross, shearwaters, and petrels) feed on slightly more fish than squid by volume, except for the Laysan albatross (70% squid) and the Bonin petrel (86% fish). The Pelicaniformes (boobies, tropicbirds, and frigatebird) feed almost exclusively on fish (>93% by volume) except for the red-footed booby (Sula sula) (Figure 1). Terns feed predominantly on fish with the

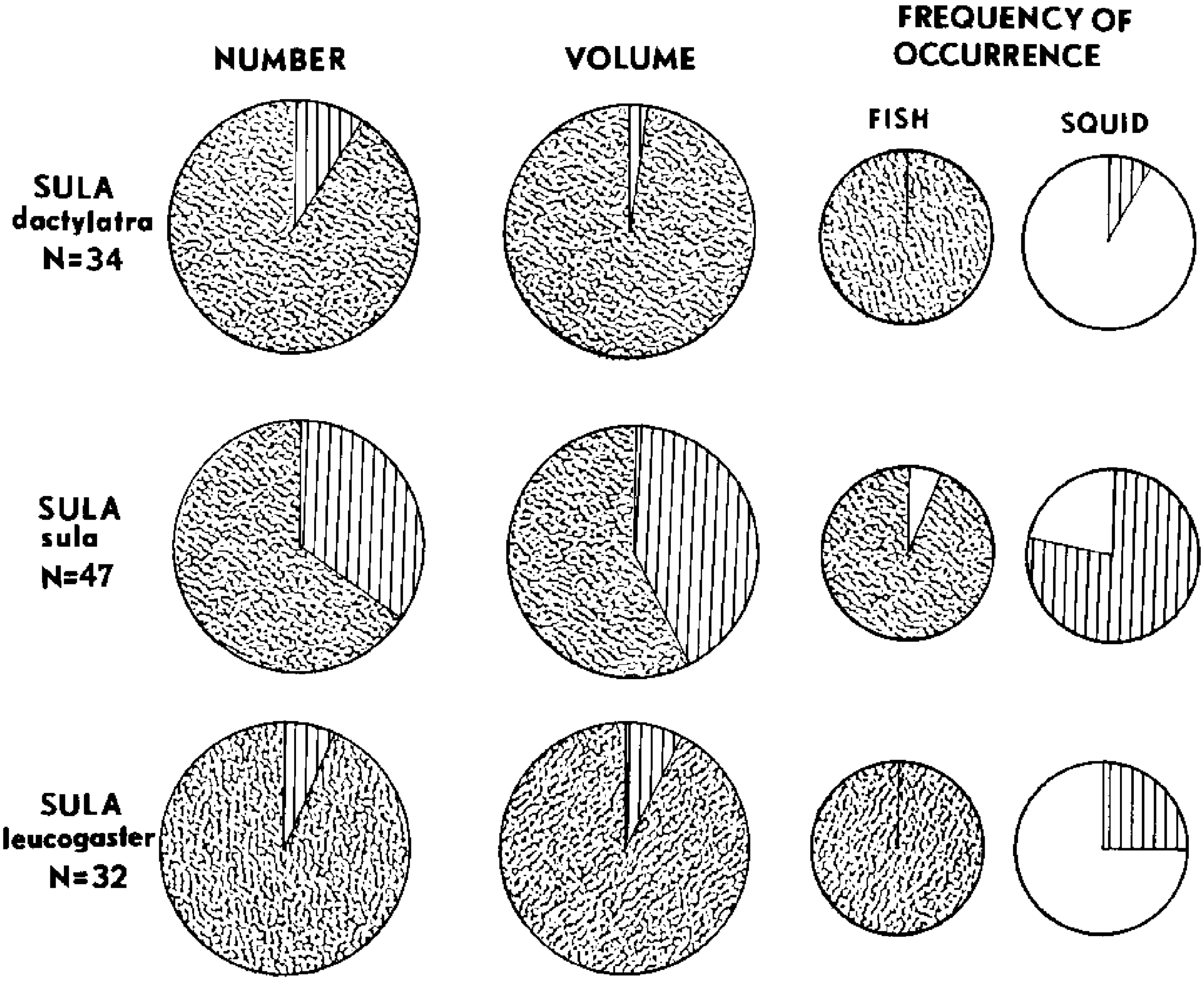


Figure 1. Relative importance of fish (stippled) and squid (lined) in diets of 3 boobies

exception of the sooty tern which feeds on 38% fish and 62% squid. Generally, NWHI seabirds eat a greater percentage of fish than species on Christmas Island.

Table 3 presents a ranking of important fish families in NWHI seabird diets. The rankings are obtained by use of the formula developed by Pinkas et al. (1971) in which

$$IRI = F(N+V)$$

where

IRI = Index of Relative Importance
F = Frequency of Occurrence
N = Numerical Percentage
V = Volumetric Percentage

We agree with their contention that while this equation may not be the last word in assessment of importance of prey items, it is superior to the exclusive use of any one of the commonly calculated statistics which comprise it. Rankings may change with time of year and locality, but at present we recognize the flying fish (Family Exocoetidae, especially *Exocoetus volitans* and *Cypselurus* spp.), the jacks (Family Carangidae, almost entirely *Decapterus* spp.), and the goatfish (Family Mullidae) to be of outstanding importance. Inshore feeding birds are marked with an asterisk in Table 3. Additional important forage families for this group are Dussumieriidae (*Spratelloides delicatulus*), Synodontidae (lizardfish), and Coryphaenidae (both species of mahimahi).

Squid are almost entirely of the family Ommastrephidae, and include the genera *Ommastrephes*, *Symplectoteuthis*, and *Hyaloteuthis*.

Figures 1, 2, and 3 portray feeding comparisons of three congeneric boobies, the masked booby (*Sula dactylatra*), the red-footed booby (*Sula sula*), and the brown booby (*Sula leucogaster*). These figures portray percentages of the major prey groups (number, volume, frequency of occurrence), comparative use of fish families, and comparative lengths of fish consumed. An upcoming monograph will display data for all species and compare localities and seasons where appropriate.

Seabird diets are complex and not easy to generalize in the NWHI. They feed opportunistically on surface shoaling fish and squid and occasionally supplement this diet with crustaceans and insects. They have evolved to utilize an assemblage of prey species, which may help to moderate the vicissitudes of the sub-tropical marine environment. The presence of mid-water fish such as lanternfish (Myctophidae) and hatchetfish (Sternoptychidae) suggest that some species feed nocturnally or crepuscularly, but direct observations are lacking except for sooty terns and wedge-tailed shearwaters (Gould, 1967). Many NWHI populations have apparently evolved breeding chronologies to take advantage of seasonally abundant fish larvae and juveniles of Mullidae, Synodontidae, and Holocentridae.

TABLE 3. RANKED IMPORTANCE OF FISH FAMILIES IN NWHI SEABIRD DIETS

Seabird	Carangidae	Coryphaenidae	Dussumieriidae	Engraulidae	Exocoetidae	Gempylidae	Holocentridae	Molidae	Monacanthidae	Mullidae	Myctophidae	Nomeidae	Ostraciontidae	Scombridae	Synodontidae
Black-footed Albatross					1										
Laysan Albatross					1			2							
Bonin Petrel										1	2				
Wedge-tailed Shearwater	3								2	1					
Christmas Shearwater	2				1					3					
Red-tailed Tropicbird	2	4			3			1							
Masked Booby	2				1									3	
Red-footed Booby	3			2	1										
Brown Booby *	2				1					3					
Great Frigatebird	2				1										
Sooty Tern	5				2	4	3			1					
Gray-backed Tern *	4		1		3					6		2	5		
Blue-gray Noddy *					3					1					2
Brown Noddy	3		6		7	5	4			1					2
Black Noddy *			4		2					1					3
White Tern *		3			2					1					

*Inshore feeding birds

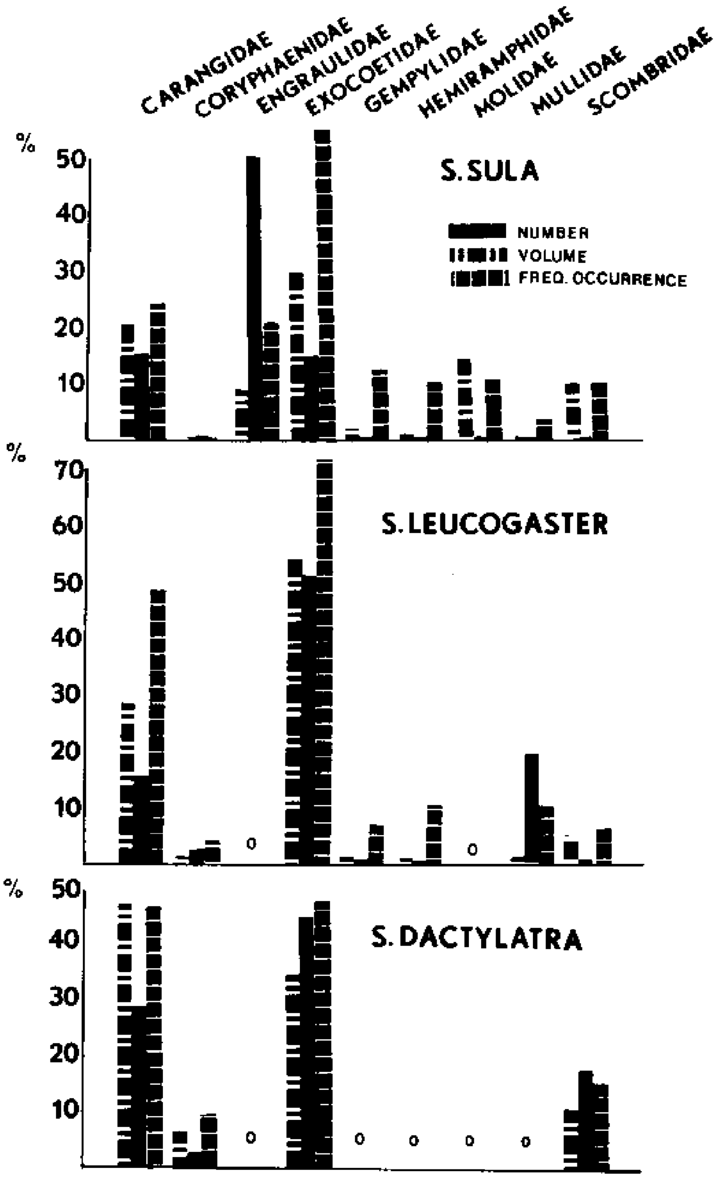


Figure 2. Comparison of fish families preyed on by three booby species

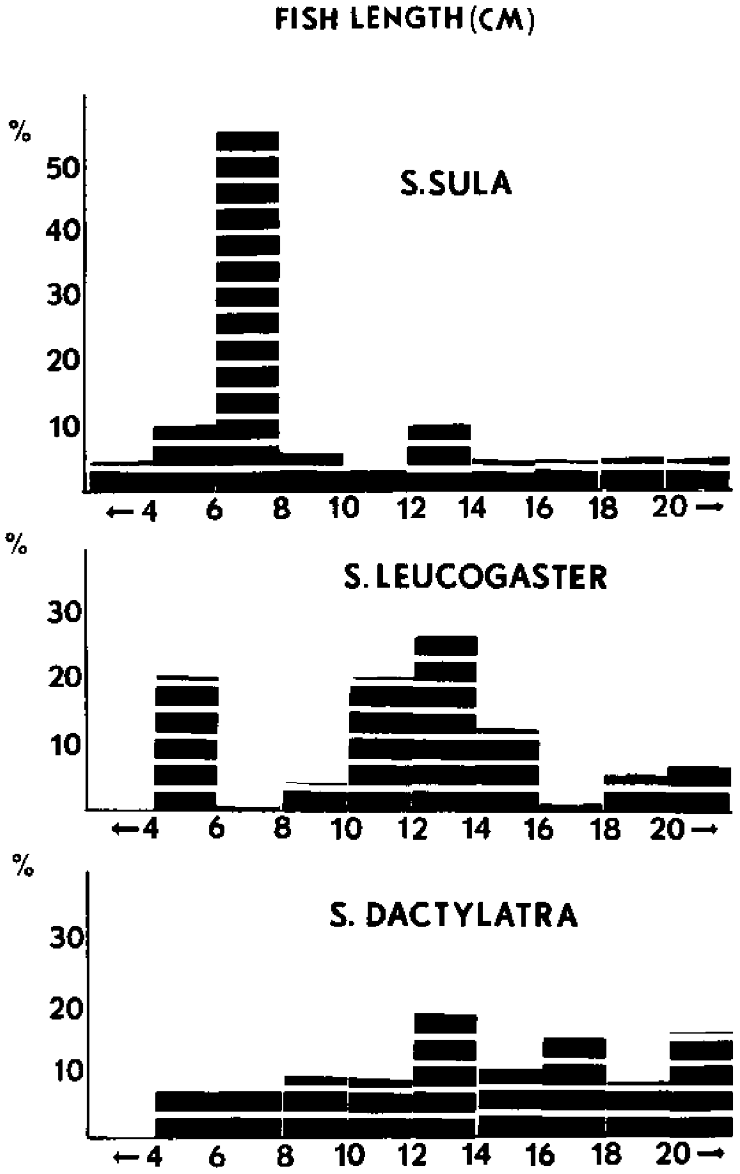


Figure 3. Comparison of fish lengths preyed on by three booby species

Feeding rates

We have no direct information concerning feeding rates. Table 1 lists the first published values for weights of NWHI seabirds. Our Laysan Island studies on growth rates of young, fledging times, and reproductive chronology could be used to determine consumptive rates and the amount of food necessary to raise young if some basic physiological data concerning energy metabolism were available.

Feeding areas

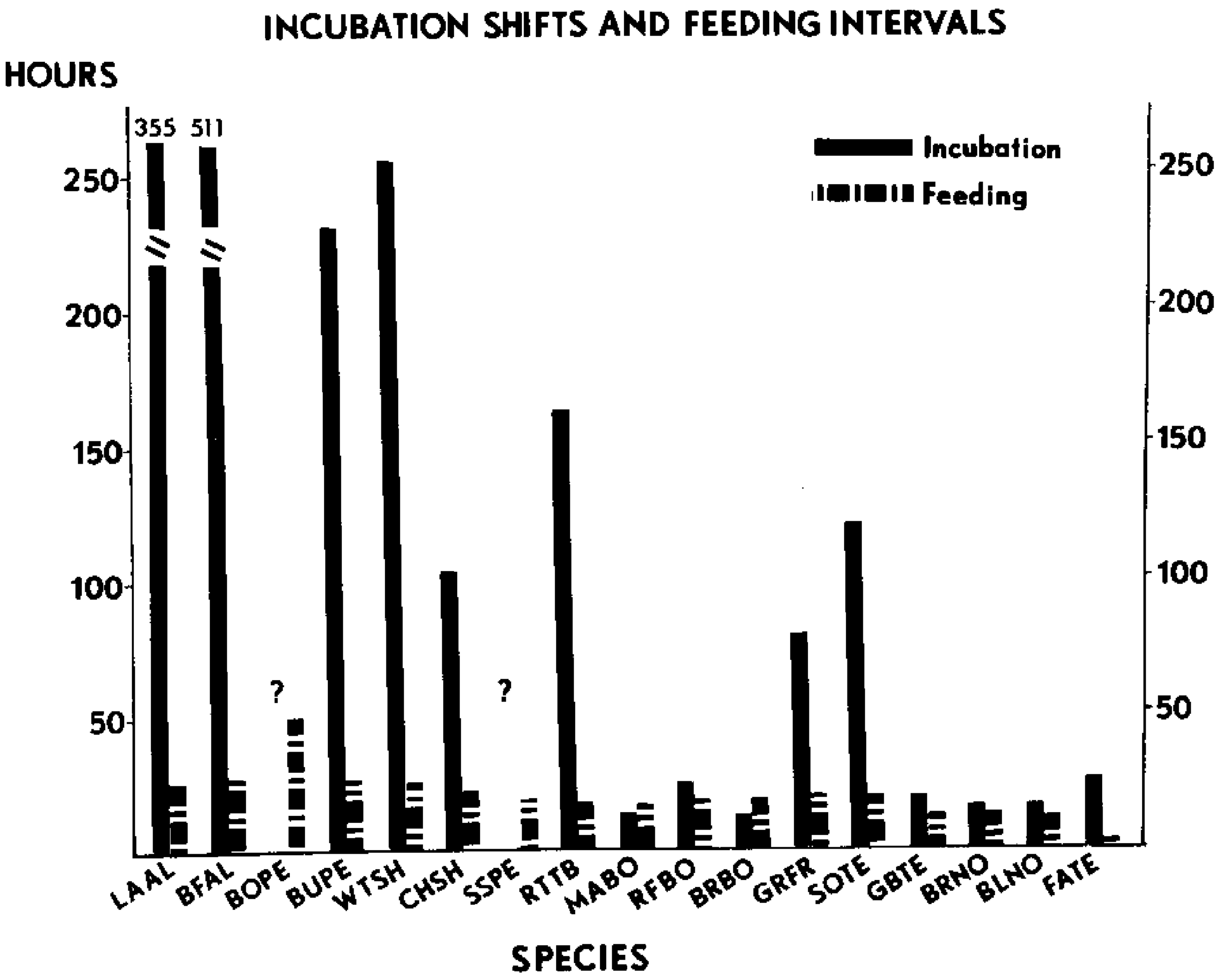
Bourne (1963) stated, "There is clearly a need for more direct observations of where and how birds feed at sea." This situation has not changed in almost two decades. Figure 4 depicts an indirect measure of feeding areas by portraying the lengths of time incubating adults are away at sea during one shift and length of time between feedings for growing chicks. If these times are a true reflection of feeding areas, a sharp contraction of feeding range occurs when the egg hatches. However, we do not necessaily accept the unproven hypothesis that there is a strong correlation between feeding distance and length of time an adult spends away from the colony. For example, two species with vastly different incubation intervals could be feeding in precisely the same area, but one may take longer to locate and obtain its prey.

A feasibility study of radiotracking the brown noddy (*Anous stolidus*) took place on Oahu in September 1979. Although the birds flew beyond our 16-km detection range and consequently we did not learn the precise feeding areas, two important points can be made from Figure 5. The first is that birds of this species do not seek out food in random direction. There is clearly a southerly departing azimuth. The second is that, contrary to views occasionally expressed in the literature, this species does not depart against the prevailing northeast tradewinds and return with them with full stomachs. The fact that Manana Island brown noddies return against the wind indicates southern feeding grounds may be superior to northeastern areas during summer. Aerial location capability in this study would probably have pinpointed feeding areas.

FUTURE RESEARCH NEEDS

The feeding study needs to be completed and data exhaustively analyzed using automatic data processing. Population estimation techniques need to be refined and access to the NWHI during critical times of the year for censusing purposes needs to be assured.

Physiological work exploring energy metabolism of wild and captive birds with concomitant bomb calorimetry of important prey items should make it possible to model marine resource utilization and energy flow for NWHI seabird populations using techniques similar to Wiens and Scott (1976).



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

Figure 4. Comparative lengths of incubation shifts and chick feeding intervals for 17 Northwestern Hawaiian Islands seabird species (Knudtson and Naughton, in preparation)

Effort needs to be directed towards the location of feeding areas. The radiotelemetry work needs to be expanded and aerial survey transects need to be flown using standard techniques (Harrison and Hall, 1978; Harrison, in press) to locate feeding areas for important NWHI colonies.

To assess the importance and seasonality of important prey items in seabird diets, basic life histories and estimates of annual production

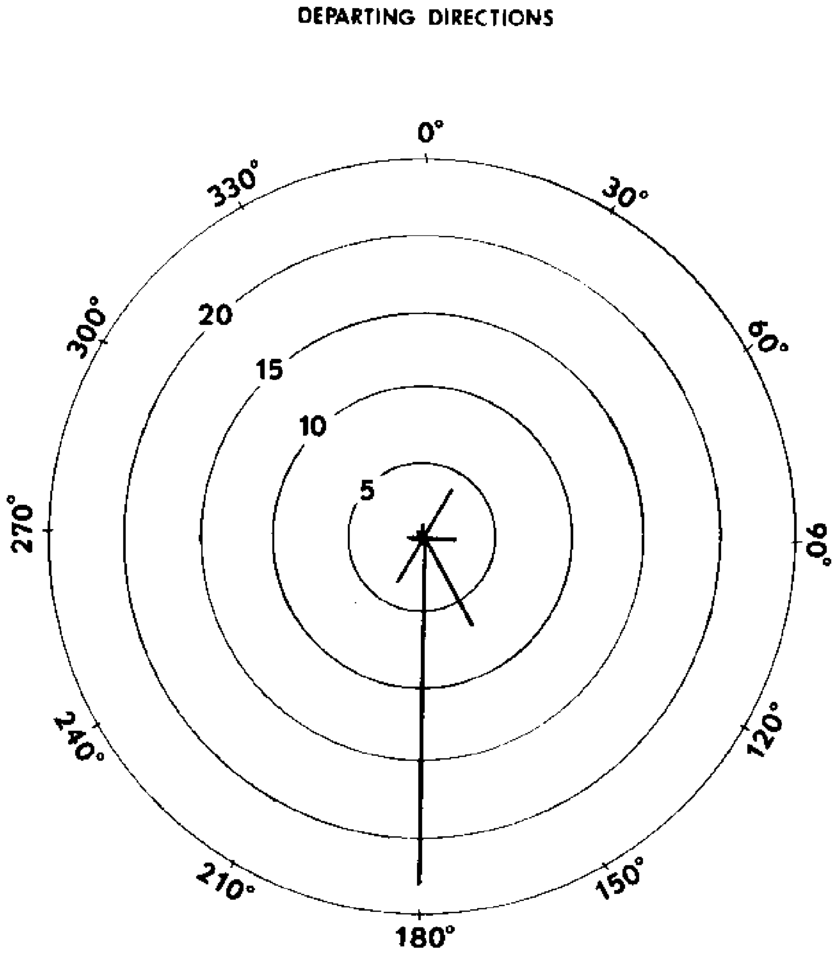

DEPARTING DIRECTIONS

Figure 5. Departing directions of breeding brown noddies from Manana Island. Vector magnitudes signify number of birds detected departing in each 30° sector. (Harrison and Stoneburner, in preparation)

data are needed for Ommastrephidae, Exocoetidae, Mullidae, Synodontidae, and Decapterus sp.

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AN INVESTIGATION INTO UNUSUAL MORTALITY IN THE HAWAIIAN MONK SEAL, MONACHUS SCHAUINSLANDI

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ABSTRACT

Increased mortality was reported in the endangered Hawaiian monk seal population at Laysan Island in the spring of 1978. An investigation of the possible causes of the mortality included sampling of healthy, sick, and dead individuals. Analyses comprised gross and microscopic pathology, hematology, serum chemistry, virology, bacteriology, parasitology, and toxicology. Gastric ulceration in varying degrees due to nematodes was a consistent finding. Evidence of caliciviruses (VESV and SMSV) and *Salmonella* was found in the population. Two of 18 seals tested had elevated total white blood cell counts. A few individuals differed significantly from mean serum chemistry values but no trend was apparent. Liver tissues of two seals tested for ciguatoxin and maitotoxin were positive.

Monachus schauinslandi clinical pathology
mortality ciguatera

INTRODUCTION

The Hawaiian monk seal, *Monachus schauinslandi*, is an endangered species which breeds only in the Northwestern Hawaiian Islands from

Necker Island west to Kure Atoll. Recent censuses indicate the total population has decreased by about 50% since 1958 (Johnson et al., in preparation).

In the spring of 1978, high mortality was observed in monk seals at Laysan Island (B.W. Johnson and P.A. Johnson, Aquatic Mammals Behavioral Research Company, Honolulu, Hawaii 96822, personal communication, 1978). Disease signs apparent in the monk seals were consistent. Animals come ashore emaciated or began to noticeably lose weight as they lay on the beach. The seals abandoned normal hauling out behavior--failing to move into the vegetation behind the beach crest at night. Within 2 to 3 weeks of beginning the weight loss, the animals became completely debilitated and then died in the splash zone or at the high tide line (B.W. Johnson and P.A. Johnson, personal communication, 1978).

This report discusses data collected on specimens taken from 19 dead and 18 live monk seals during April and May 1978 as part of an investigation into the reported mortality.

MATERIALS AND METHODS

Between 4 May and 13 May 1978 we collected specimens and data from a total of 24 Hawaiian monk seals at two locations in the Northwestern Hawaiian Islands to determine if there was any apparent disease process in the seals which might cause the mortality. Ten live yearlings or juvenile seals (MS-01-78 to MS-10-78) and one adult (MS-11-78) were sampled at Laysan Island. In addition, we received tissue sets in formalin[1] from 13 monk seals (collected by Brian W. and Patricia A. Johnson on Laysan Island, 1 March to 1 May 1978) which died at Laysan Island prior to our arrival. Samples were to be collected from a large number of sick as well as apparently healthy animals; however, a storm just prior to our arrival cleared the beaches at Laysan Island of most of the very sick animals with the disease signs mentioned earlier. Seal MS-11-78 was very emaciated and weak and died while being restrained for collection of the samples. At French Frigate Shoals six dead seals were found, only one of which was fresh enough to be necropsied, even through it had been dead at least a day and the tissues were badly autolysed. The other five were too decomposed to yield any information relative to cause of death.

The live animals were physically restrained and blood was collected from the intra-vertebral extradural vein. Packed red cell volumes and white blood cell counts were determined in the field. Serum and plasma for the other clinical bood tests and serological studies were frozen for later analysis. Clinical chemistry tests were performed using standard laboratory procedures (Bio-Science Laboratory, Van Nuys, California). Serum samples from all animals were tested for agglutinating

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

antibodies to *Leptospira* antigen pools nos. 1, 2, and 3.[2] They were also tested for serum neutralizing (SN) antibodies to 19 calicivirus types (vesicular exanthema of swine virus types A_{48}, C_{52}, D_{53}, F_{54}, G_{55}, I_{55}, J_{56}, K_{56}, San Miguel sea lion virus types 1, 2, 4, 5, and marine calicivirus isolates designated 427, 274, fluke, V86, 804T, and 913T) using previously described microtiter techniques (Monta and Bryon, 1974; Smith et al., 1976).

Leptospira isolation attempts were made on samples of liver, kidney, and cerebrospinal fluid taken from MS-11-78. The procedure has been previously described (Smith et al., 1974a; Smith et al., 1974b).

Salmonella incidence in the seals was tested by collection of rectal swabs from all animals and placing them into transport medium in the field. These cultures were tested by one of the authors (Gilmartin) for salmonellae by beginning enrichment and isolation procedures previously described (Gilmartin et al., 1979) within 24 hours of collection of the sample but were also maintained in the holding medium for over 2 weeks, when another attempt was made at isolation of salmonellae (N.A. Vedros, Naval Biosciences Laboratory, Oakland, California 94625, personal communication, 1978).

Swabbings were taken from the nose, throat, and rectum of each animal for virus isolation. These and small slips of lung, liver, kidney, and tonsil from animal no. 11 were placed in ampules of phosphate-buffered glycerine, pH 7.2, and immediately frozen to -55°C. Tissues were thawed and ground up, then they and the swab samples were clarified by centrifugation at 3,000 rpm. Supernatant fluids were placed in a Vero monkey, *Cercopithicus aethiops*, kidney cells and porcine kidney cells (PK-15), incubated at 37° and 30°C, and passaged at least four times as previously described (Smith et al., 1974b).

Stool specimens were collected, as available, from the seals and frozen for later flotation and examination for ova.

Rectal temperatures were determined using an electronic thermistor with a flexible probe inserted at least 30 cm through the rectum.

Tissues for microscopic histopathologic studies were preserved in formalin and examined after hematoxylin and eosin staining.

One canine tooth was extracted from each of the dead seals for aging using a new technique developed for small cetaceans (Pierce and Kajimura, 1978).

Liver specimens from two seals (MS-11-78 and MS-12-78) were assayed for dioxan (2, 3, 7, 8 - tetrachlorodibenzo-p-dioxan) using gas chromatography and high resolution mass spectrometer techniques (M. Gross, University of Nebraska, Lincoln, Nebraska 68588, personal communication, 1978.)

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[2] Difco Laboratories, Detroit, Michigan. These pools contain *Leptospira ballum*, *L. canicola*, *L. icterohemorrhagiae*, *L. bataviae*, *L. grippotyphosa*, *L. pyogenes*, *L. autumnalis*, *L. pomona*, and *L. wolffii*.

Tests for tissue residues of ciguatoxin by radioimmunoassay procedures (Hokama et al., 1977) and ciguatoxin and maitotoxin by bioassay techniques were performed.[3]

Statistical analyses were performed on the clinical chemistry, hematology, and temperature data to test for individuals with values different than the mean. All the live seals sampled with one exception were young (yearlings to juveniles); therefore the adult (MS-11-78) was excluded from these statistical tests and the mean and standard deviation of the data from these animals were taken as a close approximation to parametric values since normals for the population were not known. The farthest-outlying variates within a given sample (i.e., sodium) were then tested to see if they statistically belonged within that sample using a one-tailed t-test of one variate against the assumed population mean (Sokal and Rohlf, 1969). Also, because of the great distance between the islands (approximately 320 nmi), the data for the young monk seals from Laysan Island (MS-01-78 through MS-10-78) were tested with a two-tailed Wilcoxon two-sample test (Sokal and Rohlf, 1969) against those from French Frigate Shoals (MS-13-78 through MS-19-78) for all categories to determine if there were differences between the island populations.

RESULTS AND DISCUSSION

Animals from two age groupings, the young and very old, were represented in the dead animals which were recovered by the Johnsons and the authors. Ten of 14 seals which died and were recovered at Laysan Island were between 1 and 5 years of age; the others were between 18 and 30 years. The net loss in monk seals at Laysan Island during the period from March to July 1978 is estimated to be at least 50 animals (Johnson and Johnson, 1980).

Of the 13 seals which had died prior to our arrival at Laysan Island and from which we received tissue sets, there were seven males and six females. Four of the six dead seals at French Frigate Shoals were females and sex could not be determined for the other two.

Twelve of the live young monk seals sampled were females, five were males and the single adult at Laysan Island (MS-11-78) was a male. Four of the seals sampled at Laysan Island (MS-01, MS-04, MS-07, and MS-10) became emaciated and disappeared by mid-June 1978. The seals sampled at French Frigate Shoals were not similarly monitored.

Statistical tests were performed on the clinical data to identify animals with test results significantly different ($P \leq 0.05$) from the mean of all monk seals sampled. The tests were done to aid in recognizing ill animals in a species for which these clinical parameters had not been determined.

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[3] Radioimmunoassay for ciguatoxin and bioassay for ciguatoxin and maitotoxin were performed by Dr. Y. Hokama and Dr. J. Miyahara, respectively, at the University of Hawaii, John A. Burns School of Medicine, Pathology Department, Honolulu, Hawaii 96822.

When each individual seal's hematology and clinical chemistry test results were compared to the mean of the group, many had at least one test value different from the mean (Table 1). There were only three cases where two animals differed from the mean ($P \leq 0.05$) in the same direction on the same test: MS-05 and MS-07, elevated total white cell count; MS-06 and MS-18, high cholesterol; and MS-08 and MS-15, high alpha-1 globulin.

Monk seals MS-05 and MS-07, with the high white cell counts, are noteworthy because MS-07 is one of four animals which disappeared and presumably died later in the season. MS-07 had the highest white cell count (18,700) of all seals tested and was one of three young seals sampled which appeared underweight and lethargic. Neither of these two with the elevated total white cell counts had any other outstanding clinical data values. Of the other two monk seals which appeared underweight at sampling, one (MS-06) had only a significantly elevated cholesterol and glucose level, which may indicate a fasting animal, and the other (MS-01) had no clinical blood tests different from the mean of the group.

The three other animals which disappeared in an emaciated condition during the summer, MS-01, MS-04, and MS-10, did not exhibit any remarkable findings except for a high lactic dehydrogenase (LDH) in MS-10.

The only other animals with any noteworthy abnormal clinical pathology were MS-09 with a high total protein and beta globulin and MS-16 with a very low packed red cell volume and a high serum glutamic pyruvic transaminase (SGPT). *Salmonella sieburg* was isolated from a rectal swab taken from MS-09 and it is the only seal from which salmonellae were recovered (N.A. Vedros, personal communication, 1978). Although *Salmonella* are common isolates in some pinnipeds (Gilmartin et al., 1979), the high beta globulin and total protein in this animal are probably not related to a chronic infectious bout with this organism as no serum antibody could be detected (N.A. Vedros, personal communication, 1978).

The high SGPT of MS-16 would indicate some liver pathology. The low hematocrit may be due to hemorrhage associated with severe gastric ulceration due to nematode infestation which will be discussed below. Despite the frequency and apparent severity of these parasitic ulcerations observed in dead animals, MS-16 was the only living seal tested which had a low packed cell volume.

The rectal temperature statistics in Table 1 show that all animals tested were within a range of 1.5°C. All of these animals were asleep and dry when initially approached so there had probably been little or no physical activity prior to our restraining them. Thus, these temperatures (with a mean of 36.3°C) reflect resting status, and are very close to that previously reported for young Hawaiian monk seals. Several monk seals were monitored throughout the restraint period, and no change in the temperature reading was noted. Temperatures taken by various means in some other phocids are reported between 36.0°C and 37.0°C.

TABLE 1. SERUM CHEMISTRY, BLOOD COUNTS, AND RECTAL TEMPERATURE STATISTICS FROM 17 YOUNG HAWAIIAN MONK SEALS, 1978

Test	Mean	Standard Deviation	Range	Animals Significantly Different at $P \leq 0.05$	
Sodium (meq/liter)	152.7	8.1	134-167	MS-08 (134)	MS-18 (167)
Potassium (meq/liter)	5.84	0.63	4.6-7.0	MS-03 (7.0)	MS-08 (4.6)
Chloride (meq/liter)	108.7	4.8	96-119	MS-08 (96)	MS-13 (119)
Calcium, total (meq/liter)	5.54	0.37	5.0-6.1		
Inorganic phosphorus (mg/100 ml)	7.49	1.49	5.3-9.6		
Cholesterol (mg/100 ml)	206.7	54.5	121-314	MS-06 (314)	MS-18 (311)
Urea nitrogen (mg/100 ml)	37.1	12.3	21-63	MS-17 (63)	
Uric acid (mg/100 ml)	2.74	0.51	1.7-3.4	MS-02 (1.7)	
Bilirubin, total (mg/100 ml)	0.38	0.28	0.2-1.2		
Alkaline phosphatase (units)	222.0	131.2	74-580		
LDH (units)	758.9	454.7	62-1,640		
SGPT (units)	137.8	57.6	76-290	MS-16 (290)	
SGOT (units)	146.9	45.7	72-220		
Glucose (mg/100 ml)	91.1	24.6	49-141	MS-06 (141)	
Total protein (g/100 ml)	7.32	1.01	4.9-9.5	MS-09 (9.5)	
Albumin (g/100 ml)	2.82	0.36	34		
Alpha-1 globulin (g/100 ml)	0.32	0.33	0.08-1.2	MS-08 (1.2)	MS-15 (0.9)
Alpha-2 globulin (g/100 ml)	1.09	0.53	0.4-1.96		
Beta globulin (g/100 ml)	0.80	0.25	0.4-1.3	MS-09 (1.3)	
Gamma globulin (g/100 ml)	2.30	0.57	1.3-3.4	MS-06 (3.4)	MS-08 (1.3)
Albumin/globulin ratio	0.64	0.09	0.5-0.8		
Packed red cell volume (5)	57.1	4.0	46.0-62.5	MS-16 (46.0)	
White cell count, total (cells/mm^3)	9,745	3,178	5,170-18.700	MS-05 (15,400)	MS-07 (18,700)
Rectal temperature (°C)	36.3	0.54	35.5-37.0		

Rectal swab cultures from more than half of the animals yielded *Edwardsiella tarda* which is of dubious significance as an intestinal tract pathogen.

Neither viruses nor leptospires were isolated from any sample; however, animal MS-05 did carry SN antibodies against VESV I_{55} at the 1:40 dilution and animals MS-13 and MS-19 carried SN titers of 1:10 against SMSV-1. All other tests for virus and *Leptospira* antibodies were negative; however, the finding of calicivirus antibodies (VESV and SMSV) in 3 of 18 animals certainly suggests occasional contact with these agents and may be some indication that virus reservoirs exist along the Northwestern Hawaiian Islands chain. Alternatively, northern elephant seals, *Mirounga augustirostris*, have been reported as far west as Midway Islands (M.J. Rauzon, National Fish and Wildlife Laboratory, Anchorage, Alaska 99503, personal communication, 1978), the western limit of the monk seal range, and caliciviruses have been isolated repeatedly from nursing and weaned elephant seals along the southern California coast (A.W. Smith, Naval Biosciences Laboratory, Oakland, California 94625, personal communication, 1978, 1979). Although there is no evidence to suggest that the recent die-off was in any way related to the presence of caliciviruses, it should be remembered that these agents have been associated with a vesicular disease and reproductive failure in California sea lions, *Zalophus californianus*, northern fur seals, *Callorhinus ursinus*, and domestic swine and cats.

Parasite ova found in the stool of the 10 young live seals at Laysan Island are described in Table 2. The following flatworm ova were recovered from the gastrointestinal tract of the adult (MS-11-78) which died at Laysan Island: *Corynosoma rauschi*, *Contracaecum turgidum*, *Diphyllobothrium cameroni*, *D. elegans*, and *D. hians*. *Contracaecum turgidum*, *Corynosoma rauschi* and *D. hians* were found in the stomach and intestines of MS-12-78 at French Frigate Shoals. These same parasite species were represented in many of the 13 animals which died at Laysan Island between 1 March and 1 May 1978.

All of the animals from which the tissue sets were collected, including the two examined by the authors, were cachetic and severely emaciated. Common findings in these 15 animals included: heart, lack of adipose tissue on the epicardium surface; liver, centralobular congestion, with foci of centralobular necrosis; lungs, congestion and alveolar hemorrhage in about half of the seals; spleen and lymph nodes, little or no evidence of lymphopoietic activity; testes, no evidence of spermatogenesis in males estimated to be subadult to adult; and, gastrointestinal tract, numerous foci of ulceration (many were actively hemorrhaging) with nematodes embedded deep into the stomach wall in all animals and many had additional intestinal lesions from cestodes, similarly embedded in the mucosa.

It is important to note that in December 1978, two additional monk seals were found dead at Laysan Island (B.W. Johnson and P.A. Johnson, personal communication, 1978) in an emaciated condition resembling that seen in April and May; however, these seals, on examination, had very light gastric nematode infestations and only minor ulceration at the phylorus.

TABLE 2. PARASITE OVA IN STOOL OF YOUNG LAYSAN MONK SEALS, 1978

Monk Seal	Cestode Ova*	Capillorid Type Ova*
MS-01	M	--
MS-02	H	L
MS-03	H	--
MS-04	M	L
MS-05	N.D.	N.D.
MS-06	N.D.	N.D.
MS-07	N.D.	N.D.
MS-08	H	--
MS-09	H	--
MS-10	H	--

*Number of ova in 400 power microscope field: L (light) = <25, M (moderate) = 25 to 75, H (heavy) = >75, N.D. = not determined

The extensive pathology caused by parasites, even though common to all of the monk seals which were necropsied during the period of high mortality in the spring, may be the result of seasonal fluctuations in gastric nematode parasite load and not, necessarily, a major factor in the spring 1978 mortality. Gastric nematode infestations, many with associated ulcerations, are relatively common in pinnipeds and since gastrointestinal tracts of only emaciated animals were examined, it is not possible to know the associated parasite pathology in the "normal" population. Table 2, however, indicates many of the apparently normal seals were carrying heavy cestode loads.

No dioxan was detected in the liver samples tested. Ciguatoxin and maitotoxin bioassay analyses of liver tissues from the adult which died at Laysan Island (MS-11-78) and the juvenile at French Frigate Shoals (MS-12-78) were positive. Estimated levels were 30 to 50 times that found in the liver of a control monk seal which had been maintained in captivity for 15 years. Radioimmunoassay for ciguatoxin in the same tissues revealed the liver of MS-11-78 to be about 25% above the control liver, while MS-12-78 was 9% below the control. Subsequent studies, the results of which will be published elsewhere, have shown that eels (known to be a part of the monk seal diet), collected near the islands on which the monk seals haul out, can debilitate and kill northern elephant seals after consumption of as little as 1.7% of the animal's body weight (DeLong and Gilmartin, in preparation).

The parasite associated pathology and the presence of ciguatoxin in the animals were the major findings which might account for this die-off of monk seals. Lack of any pathology in any organ systems (other than gastrointestinal) may discount any infectious disease processes of viral or bacterial origin.

Further study is needed to assess the impact of heavy gastrointestinal parasitism on pinnipeds relative to their general health and ability to feed and otherwise function normally. The signs displayed by the dying monk seals observed at Laysan Island are not inconsistent with what might be expected if the parasites were responsible, but they also could have been caused by the ciguatera syndrome. Ciguatera, which will kill a phocid seal, is known to be present in tropical reef environments and is present in the island chain in at least one of the monk seals' food fish. Continued disease monitoring of the seal population and experimental work in parasitology and ciguatera toxicology will be necessary to resolve the impact of these on the Hawaiian monk seal.

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A REVIEW OF BASIC BIOLOGICAL DATA ON THE GREEN TURTLE IN THE NORTHWESTERN HAWAIIAN ISLANDS

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ABSTRACT

This paper presents an overview of results obtained from a research program of the green turtle (Chelonia mydas) in the Northwestern Hawaiian Islands. Information is provided on reproductive ecology, migratory patterns, predation, food sources, growth rates, and terrestrial basking. Priority research needs include continued monitoring and tagging with Inconel tags at the breeding colony of French Frigate Shoals, radio tracking to determine marine habitat usage, and expansion of tagging efforts in resident foraging pastures throughout the Hawaiian Archipelago.

Hawaiian green turtle
Chelonia mydas
reproductive ecology
migrations
predation
food sources
growth rates
basking

INTRODUCTION

Systematic investigations of the life history and ecology of the green turtle (Chelonia mydas) in the Hawaiian Archipelago were initiated by the author in 1973 with financial assistance from the New York Zoological Society, the U.S. Fish and Wildlife Service, and the Hawaii Institute of Marine Biology. This research has continued to the present time under grants awarded by the State of Hawaii, Office of the Marine Affairs Coordinator (1976-80) and the University of Hawaii Sea Grant College Program (1977-80). In collaboration with Dr. G. Causey Whittow of the University of Hawaii, support has also been obtained from the National Geographic Society to study the unique land basking behavior of Hawaiian Chelonia. Prior to 1973, studies of Hawaiian green turtles were limited to intermittent tagging during visits to the Northwestern Hawaiian Islands by personnel of the Hawaii Division of Fish and Game, the U.S. Fish and Wildlife Service, and the Pacific Ocean Biological Survey Program. In addition, starting in 1967, members of the Koral Kings Diving Club periodically captured and tagged immature green turtles at Midway during the course of recreational diving.

While the author's research program encompasses aggregations of Chelonia occurring throughout the entire 2,450 km length of the Hawaiian Archipelago, greater emphasis has thus far been placed on the northwestern segment of the chain. The rationale for this action is based on the fact that (1) breeding presently only takes place in the Northwestern Hawaiian Islands, (2) land basking, which only occurs in the Northwestern Hawaiian Islands, provides relatively easy access to both males and females, and (3) most of the islands in the northwestern segment of the chain are units of the Hawaiian Islands National Wildlife Refuge designated as Research Natural Areas. Consequently, at least in recent years, green turtles resident to these areas have not been subjected to human exploitation. The major objectives of the author's work have been (1) to identify areas presently used for breeding, basking, feeding and resting purposes, (2) to assess the size, productivity and ecological characteristics of breeding colonies and monitor annual fluctuations, (3) to determine migratory patterns, (4) to identify food sources, (5) to ascertain natural growth rates and ages at sexual maturity, and (6) to determine factors that limit the population.

The green turtle constitutes most of the sea turtles in the Hawaiian Archipelago and is the only species that lives and breeds in the Northwestern Hawaiian Islands. Under provisions of the U.S. Endangered Species Act, the Hawaiian Chelonia population is presently listed as Threatened. Two other species of sea turtles that occur in Hawaiian waters are the hawksbill (Eretmochelys imbricata) and the leatherback (Dermochelys coriacea), both of which are designated as Endangered.

The present paper provides an overview of significant findings thus far derived from the author's research program. An abbreviated list of publications resulting from this work is provided in the "References" section. A more comprehensive treatment of the subject, including a complete bibliography of Hawaiian sea turtles, is presented in Balazs (1979c).

RESEARCH METHODS

The basic methodology used in this program involves the individual identification of turtles with numbered metal tags applied to the trailing edges of the front flippers. Until September of 1976, all tags placed on Hawaiian Chelonia were made of Monel 400, an alloy comprised of copper and nickel. Since 1976, tags specially manufactured from Inconel 625, an alloy of nickel and cadmium, have been used as the primary means of individual recognition. The change to Inconel was made following the author's determination that considerable corrosion had occurred in many of the Monel tags used on Hawaiian Chelonia. No signs of deterioration have thus far been found in Inconel tags.

Tags are applied to unrestrained turtles during the latter phase of the nesting process and, as circumstances permit, during the course of basking behavior. Taggings are also carried out on turtles captured in the water while they are foraging, resting, and in transit. Such captures are accomplished using a long-handled scoop net or by grasping the animals while diving. Since 1973, 1,127 green turtles have been tagged throughout the Hawaiian Archipelago, with 889 of these occurring in the Northwestern Hawaiian Islands. Of this latter total, 501 were adult females, 135 were adult males, and 253 were immature individuals (<81 cm straight carapace length) in which sex could not be distinguished.

Research methods associated with tagging include the recording of body measurements and the noninjurious sampling of food items from the mouth and stomach. Other methods involve nondisturbing and systematic observations of reproduction, basking and foraging, as well as the analysis of turtle remains salvaged from predators and other causes of mortality.

RESULTS

Reproduction

In excess of 90% of all breeding by Hawaiian Chelonia has been found to occur at French Frigate Shoals, a 35-km long crescent-shaped atoll situated in the middle of the archipelago at 23°45'N, 166°10'W (Figure 1). Small groups of turtles and separately nesting individuals using Laysan, Lisianski, and Pearl and Hermes Reef account for the remaining reproductive effort. Only a few nestings have even been recorded at Kure and Midway.

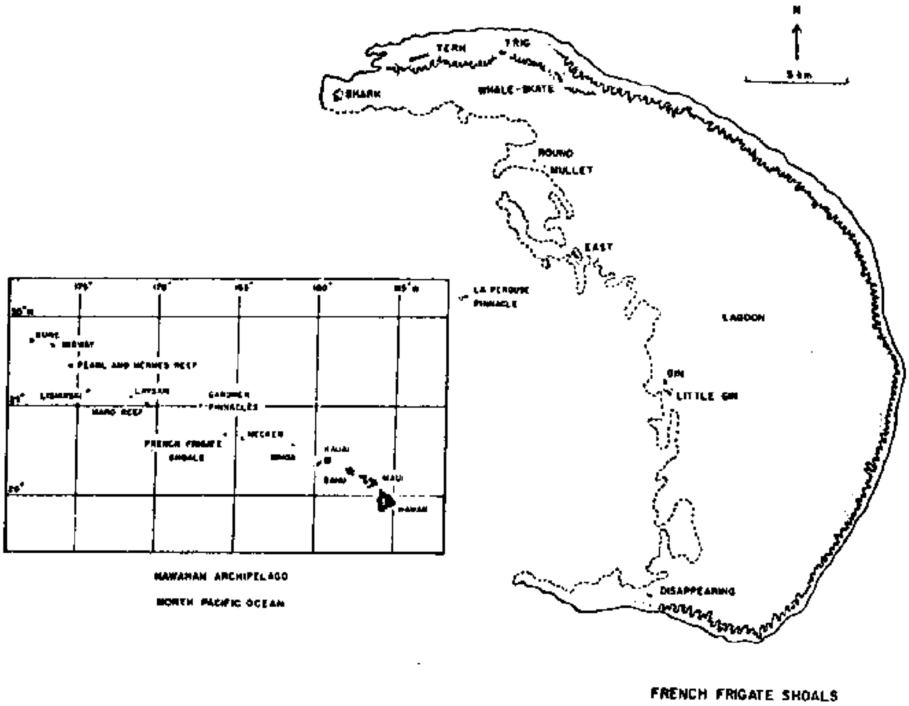

Figure 1. French Frigate Shoals

Courtship and copulation take place in the shallow waters of French Frigate Shoals during the early portion of the breeding season, usually between mid-April and early June. Nesting commences during the middle of May, reaches its peak during late June, and declines to a low level by early August. Some sporadic nesting may occur until mid-September. Nesting takes place over the entire land area of the islets of East, Whale-Skate, Trig, Gin and Little Gin, and along the south shore of Tern. Of the females present for each breeding season, approximately 55% nest on East (4.0 ha) and 35% nest on Whale-Skate (6.8 ha). East Island has therefore been the principal site of research during each breeding season since 1973.

Green turtles nesting at French Frigate Shoals have a mean carapace length of 92 cm with a range of 81 to 106 cm ($N = 379$). Up to six egg clutches may be laid by each female within a season, however the mean is only 1.8 ($N = 208$). Approximately 40% of the turtles lay only once in a season, while 10% make nesting attempts on several consecutive nights but do not lay eggs and often are not seen again. Fewer than 5% of the turtles have been recorded changing islands within a season once nesting has started. The length of time between oviposition in turtles that lay more than once in a season ranges from 11 to 18 days with a mean of 13 days ($N = 89$). During this internesting interval, many of the turtles identified by temporary numbers painted on the carapace are regularly seen basking on the same island where nesting takes place and swimming in the adjacent waters. A maximum diving depth of 12.8 m was recorded with depth gauges attached to two females during internesting intervals in June of 1979.

Usually less than half of the turtles that emerge for nesting on any one night successfully lay eggs. The remaining turtles continue to emerge on subsequent nights until oviposition is achieved or the turtle is no longer present. Many of these nesting attempts involve the nearly complete excavation of an egg chamber before abandonment takes place and another site is selected. In other cases, only rudimentary body pits are dug before a site is abandoned. Four factors contributing to the incomplete excavation of a nest include injuries or amputations of a turtle's hind flippers, insufficient moisture in the substrate, contact with large chunks of coral, and contact with abandoned antenna wire and other debris present on East and Tern.

A sample of 50 egg clutches counted during ovipositon showed a mean of 104 eggs per clutch (range 38 to 145). Multiple regression analysis of these data was conducted to determine if significant relationships exist between the number of eggs in a clutch (y) and the independent variables of time of oviposition within the season (x_1), ratio of the curved and straight carapace widths of the female (x_2), and straight carapace length of the female (x_3). Larger females were found to lay significantly more ($p < .05$) eggs per clutch. Although there was a tendency for fewer eggs per clutch to be laid as the season progresses, this was not significant ($p = .10$). The relationship between the curved-straight width ratio (an index of body thickness) and number of eggs per clutch was also not significant ($p = .30$). The resulting formula for predicting the number of eggs in a clutch is $y = -268.704 + (-0.271)x_1 + 93.768x_2 + 2.819x_3$.

The mean incubation period, or length of time to hatchling emergence, has been found to be 64.5 days (range 54 to 88 days, N = 38). Multiple regression analysis of these data showed no significant relationships between incubation period and time of oviposition within the season, coarseness of the nest substrate, or depth of the egg chamber. The mean egg chamber depth was 60 cm (range 48 to 74 cm). A significant relationship ($p < .05$) was found between depth of the egg chamber and coarseness of substrate, with shallower chambers being excavated in coarser substrate. No significant relationship was found between egg chamber depth and size of the nesting female.

Table 1 presents the results of 40 precounted egg clutches that were excavated and examined following the natural emergence of hatchlings. Multiple regression analyses of these data were conducted to determine if significant relationships exist among (1) % eggs hatched, (2) % hatchling emergence, (3) % dead hatchlings, (4) % partially developed but dead embryos, and (5) % eggs with no apparent development; and the independent variables of (1) time of oviposition within the season, (2) coarseness of the nest substrate, (3) depth of nest, and (4) straight carapace length of the female. The only significant relationship ($p < .05$) found was that the percentage of hatchlings emerging at the surface decreases in egg clutches that are laid as the season progresses.

TABLE 1. RESULTS OF 40 NESTS EXCAVATED AND EXAMINED FOLLOWING THE NATURAL EMERGENCE OF HATCHLINGS

	Mean	Standard Deviation	Range
% Eggs Hatched	76.7	24.2	0-100
% Hatchlings Emerging at the Surface	70.8	24.0	0-97.6
% Dead Hatchlings in the Nest	5.9	9.4	0-52.1
% Eggs Partially Developed but Dead Embryos	10.8	9.9	0-50.0
% Eggs without Development	12.5	22.4	0-100

Reproductive cycles, as measured by remigration intervals, have been documented in 21 nesting females. Fourteen of these turtles (66.7%) displayed a two-year cycle and six (28.6%) a three-year cycle. One turtle (4.7%) was not seen again until six years after being tagged. Thus far, no nesting turtles have been recovered at French Frigate Shoals after only a one-year absence. The present predominance in recordings of two-year nesting cycles is due to the significant increase in tag recoveries made during the 1979 breeding season of turtles tagged two years earlier in the 1977 season. Because 1977 was the first season in which the more durable Inconel tags were used at French Frigate Shoals, continued monitoring and tagging will be necessary to accurately determine the most common nesting cycle. The reproductive cycles of adult males have been documented in 16 cases. Nine (56.2%) of these represented a one-year cycle, five (31.3%) a two-year cycle, and two (12.5%) a three-year cycle. The modulation of reproductive cycles has thus far been recorded in two turtles. This involved a phase change from a three-year to a two-year cycle in a female, and a change from a two-year to a one-year cycle in a male.

The approximate number of females nesting annually at French Frigate Shoals since 1973 has ranged from 94 in 1976 to 248 in 1978 (Figure 2). The mean annual number for this seven-year period is 180. An estimated total of not more than 20 females nest annually at Laysan, Lisianski, and Pearl and Hermes Reef. Earlier estimates of the size of the annual breeding colony at French Frigate Shoals made by Hendrickson (1969) and later quoted by Amerson (1971) ranged from 2,600 to 5,200 turtles. These data have now been shown to be invalid.

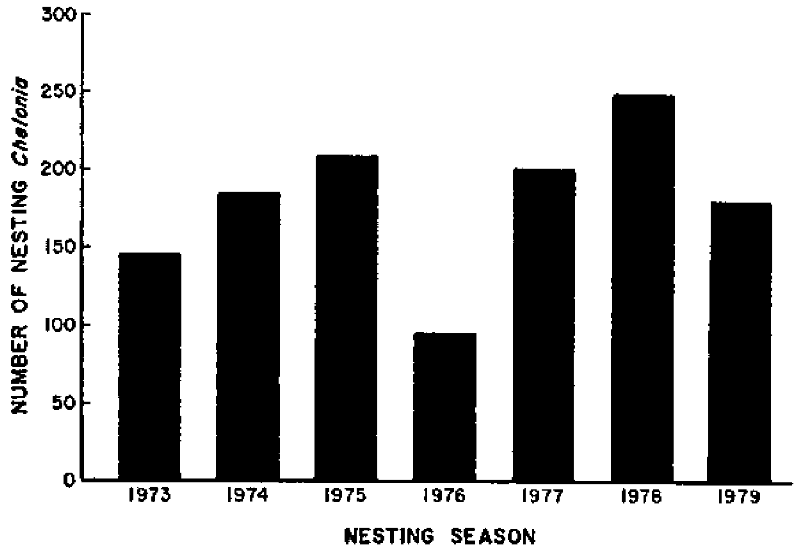

Figure 2. Number of green turtles nesting annually at French Frigate Shoals.

Using the basic reproductive data that have been presented (i.e., 104 eggs per clutch, 1.8 clutches per female, 70.8% emergence of hatchlings per clutch, 180 females per season), an estimated mean annual production at French Frigate Shoals would be 23,857 hatchlings. If the same parameters are assumed for the 20 females nesting at other areas, then 2,651 additional hatchlings would result. The mean annual production of hatchlings for the Hawaiian Archipelago would therefore be 26,508.

Migrations

The breeding assemblage at French Frigate Shoals consists of turtles that periodically migrate from widely separated resident feeding areas throughout the Hawaiian Archipelago. These migrations have been documented for both males and females through 52 long-distance tag recoveries, 31 of which involved French Frigate Shoals and the main Hawaiian Islands, and 21 that involved French Frigate Shoals and the northwestern locations of Laysan, Lisianski, and Pearl and Hermes Reef (Figure 3). The longest voyages thus far recorded are from French Frigate Shoals to Hilo Bay (Hawaii), and from the Ka'u District (Hawaii) to French Frigate Shoals, both of which represent one-way minimum ocean distances of 1,100 km. Fourteen recoveries (4 males, 10 females) have been made between Pearl and Hermes Reef and French Frigate Shoals, a distance of 1,050 km. Mating is therefore taking place between some males and females that live in areas separated by as many as 2,150 km.

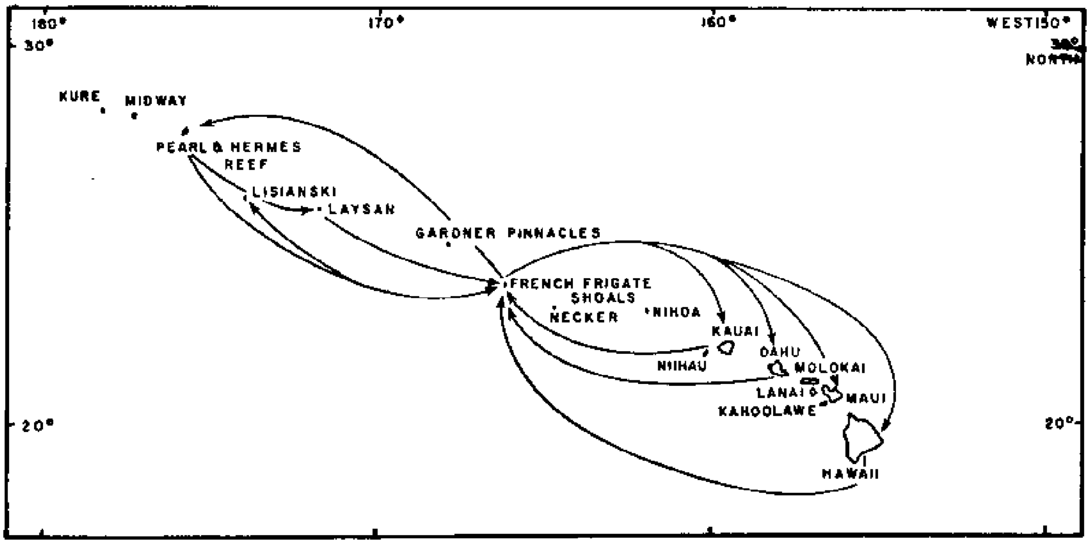

Figure 3. Migrations of adult green turtles in the Hawaiian Archipelago documented by tag recoveries. The actual routes traveled are unknown.

Records of migrations in the Hawaiian Archipelago are unique among sea turtle populations due to the two-way tagging opportunities afforded by the basking behavior, and by the research emphasis placed on turtles in their resident feeding areas. These factors have made it possible to document movements from the feeding areas back to the breeding grounds, a missing segment in all one-way tagging programs where it is only feasible to tag nesting turtles. The ability to record long-distance migrations of males is also a rare research occurrence.

With the exception of two cases, the 146 recaptures of immature turtles (35 to 81 cm) tagged in the Hawaiian Archipelago have all been made in the same resident area where initial tagging occurred. Of the two long-distance recoveries, one involved a 38-cm turtle tagged at Midway and recaptured at Wake Island, 1,900 km to the southwest. However, the weak and apparently pathological condition of this turtle indicates that it may have passively drifted there with prevailing winds and currents. The other long-distance recovery involved a 40-cm turtle tagged at Midway and subsequently reported as having been captured and released alive in Hilo Bay, a distance of 2,300 km. Although two Monel tags were originally placed on this turtle, only one tag was found at the time of recovery. The possibility therefore exists that the tag number was misread due to corrosion or other causes, and that this turtle was not the one tagged at Midway.

Post-hatchling turtles less than 35 cm are rarely found at the inshore feeding areas of the archipelago inhabited by larger turtles. The whereabouts of these smaller turtles is presently unknown, however it is assumed that their developmental habitat is located somewhere in the pelagic environment.

Natural predation

Predation on eggs is not known to occur at French Frigate Shoals. Although two species of ghost crabs (Ocypode ceratophthalmus and Ocypode laevis) are present in relatively small numbers, neither of these crustaceans have been found burrowing into nests.

Predation on hatchlings takes place by both species of ghost crabs, but O. ceratophthalmus is consistently more successful due to its larger size. This predation only occurs in or immediately above the narrow intertidal zone where both crabs periodically dig burrows. The number of hatchlings eliminated by ghost crabs probably does not exceed 5%, or an estimated annual average of 1,200 individuals. Although frigatebirds (Fregata minor) are among the seabirds present at French Frigate Shoals, they are not known to prey on hatchlings on land or in the inshore waters, such as reported in some sea turtle populations (Hirth, 1971). Predation on hatchlings by carnivorous fishes also does not appear to be significant. Numerous ulua (Caranx ignobilis, Caranx melampygus), wrasses (Thalassoma purpureum, Bodianus bilunulatus) and small sharks (Carcharhinus amblyrhynchos) have been captured by the author near East Island during the months when hatchlings enter the water, however no evidence of predation has thus far been found.

Tiger sharks (Galeocerdo cuvier) are virtually the only known natural predators of Hawaiian Chelonia larger than 35 cm. Shark research and control programs periodically conducted around the main Hawaiian Islands found that 18% (Ikehara, 1961), 10.8% (Fujimoto and Sakuda, 1972), and 12.7% (Tester, 1969) of the tiger sharks examined with food in their stomachs had been feeding on turtles. At French Frigate Shoals and Pearl and Hermes Reef, turtle parts were recorded in 31% and 36%, respectively, of the tiger sharks captured that contained food (Taylor and Naftel, 1978). A single shark at Pearl and Hermes Reef accounted for five turtles ranging from 53 to 64 cm. Four of the turtles identified from tiger sharks at French Frigate Shoals were adults ranging from 81 to 94 cm. The digestion rates of turtle parts by tiger sharks are unknown, therefore it is not possible to determine how long this material may have been retained in each stomach.

The only other known natural predator of green turtles in the Hawaiian Archipelago is the large grouper, Epinephelus tauvina. Only a single case of such predation has been recorded in the main islands, and no reports currently exist for the Northwestern Hawaiian Islands.

Food sources

Green turtles in the Hawaiian Archipelago have been documented feeding on 56 species of benthic algae, one marine angiosperm, and nine types of invertebrates. However, the major food sources utilized consist of only nine species of algae (Table 2).

TABLE 2. MAJOR FOOD SOURCES OF GREEN TURTLES IN THE HAWAIIAN ARCHIPELAGO

Location	Benthic Algae
Northwestern Hawaiian Islands (N = 56)	Caulerpa racemosa Spyridia filamentosa Turbinaria ornata Codium edule Codium arabicum Codium phasmaticum Ulva fasciata
Main Islands (N = 85)	Pterocladia capillacea Amansia glomerata Codium edule Codium arabicum Codium phasmaticum Ulva fasciata

The distribution and abundance of benthic algae in the Hawaiian Archipelago are not well known, however standing crop densities of the species preferred by green turtles appear to be far greater in the main islands. For example, certain resident feeding areas around Hawaii, Maui, Oahu, and Kauai have dense growths of the red alga, Pterocladia capillacea, whereas in the Northwestern Hawaiian Islands this is a rare species which is only known to occur in small quantities near Lisianski. Concomitantly, Amansia glomerata is abundant at many main island foraging areas, but scarce in the northwestern segment of the archipelago. Three other algal species, Caulerpa racemosa, Turbinaria ornata, and Spyridia filamentosa, identified as principal food sources in the Northwestern Hawaiian Islands, have never been found as dietary components in the main islands, even though they occur at a number of locations. This would suggest that turtles in the Northwestern Hawaiian Islands feed on these three species out of necessity due to an absence or limited supply of other algae considered more desirable.

The food sources of Hawaiian Chelonia less than 35 cm that are believed to be living in the pelagic environment are completely unknown due to the absence of data. It is, however, reasonable to assume that during this period the turtles are carnivores feeding on invertebrates that occur at or near the surface. In waters surrounding the archipelago, this could include Physalia, Velella, Janthina, the megalops stage of some portunid crabs, and immature individuals of certain oceanic squids that come to the surface at night in large numbers.

Growth rates

Thirty-one immature turtles have been recaptured in which growth could be detected after intervals ranging from 2 to 37 months. Three of these turtles were recaptured on two occasions, thereby providing a total of 34 growth measurements. Thirty-four other immature turtles that were recaptured after intervals of 2 to 20 months showed no measurable growth. This included 1 turtle at Necker, 24 at French Frigate Shoals, 3 at Lisianski, and 6 at Midway. All of these animals were vigorous and appeared to be in good health. The mean rates of growth found at the five study areas in the Northwestern Hawaiian Islands ranged from .07 to .14 cm per month in carapace length (Table 3). If these rates remain constant until maturity, as available data suggest, then turtles measuring 35 cm that are new recruits would require from 27.4 years (at Necker) to 54.8 years (at Kure) to reach 81 cm, the minimum size at which nesting takes place in the population. From 33.9 to 67.9 years would be needed to grow from 35 to 92 cm, the mean size of nesting Hawaiian *Chelonia*. Table 3 presents similar projections for 35-cm turtles that establish residency at the other foraging areas investigated in the Northwestern Hawaiian Islands.

TABLE 3. GROWTH RATES AND PROJECTED YEARS TO MATURITY FOR IMMATURE GREEN TURTLES IN THE NORTHWESTERN HAWAIIAN ISLANDS

Location, Number Tagged, and Size Range	Growth Rate (cm per month)			Interval in Months	Years to Maturity (35 to 81 cm)		Years to Maturity (35 to 92 cm)	
	Mean	Range	N		Mean	Range	Mean	Range
Necker N = 7 39.4-48.3 cm	.14	--	1	20	27.4	--	33.9	--
French Frigate Shoals N = 130 36.4-67.9 cm	.08	.02-.13	19	3-36	47.9	29.5-191.7	59.4	36.5-237.5
Lisianski N = 23 35.9-53.3 cm	.13	--	3	2	29.5	--	36.5	--
Midway N = 252 36.5-59.4 cm	.09	.03-.21	8	6-37	42.6	18.3-127.8	52.8	22.6-158.3
Kure N = 25 29.5-61.6 cm	.07	.04-.12	3	13-25	54.8	31.9-95.8	67.9	39.6-118.8

Relatively faster growth rates have been recorded at foraging areas in the main Hawaiian Islands. Along the Ka'u District, a mean of .44 cm per month has resulted from four recaptures after intervals of 7 to 17 months. In Waimanalo Bay off Oahu, three recaptures showed a mean growth rate of .22 cm per month after intervals of 7 to 22 months. The differences in growth rates found between foraging areas throughout the archipelago are thought to be a function of the sources and abundance of food, rather than seawater temperature. The exceptionally slow growth rates found in the Northwestern Hawaiian Islands undoubtedly have far reaching implications with respect to mortality rates of immature turtles and recruitment to the breeding colony.

Feeding and basking aggregations

Hawaiian Chelonia spend most of their lives residing at inshore areas where they alternate between active foraging and quiescence. In the Northwestern Hawaiian Islands, resident aggregations are known to occur at Necker, French Frigate Shoals, Lisianski, Pearl and Hermes Reef, Midway, Kure, and to a lesser extent at Laysan, Nihoa, and Gardner Pinnacles. Although a few random sightings have been made, it is unknown if turtles reside at, or in some way utilize, the shallow banks with no emergent land located in the northwestern segment of the archipelago.

Basking takes place on calcareous sand beaches at French Frigate Shoals, Laysan, Lisianski, Pearl and Hermes Reef, and Kure. At Laysan and Lisianski, turtles also emerge on calcareous beachrock slabs. At Nihoa, turtles have been recorded basking at the base of the island's northwest cliff. At Necker, basking regularly occurs on a sloping rock ledge and occasionally at a shoreline area comprised of waterworn boulders. Except for La Perouse Pinnacle, basking takes place on all of the islands at French Frigate Shoals, as well as on several unnamed seasonally occurring sandbars. The northern shore of Trig and the eastern shore of Whale-Skate are the most heavily utilized during all months of the year by the resident aggregation. At East Island, basking tends to coincide more with the breeding season. The greatest numbers of basking turtles occur throughout French Frigate Shoals during May and June due to the presence of the migratory breeding assemblage. The incidence of basking then declines as the season progresses. Although basking occurs principally between the hours 1000 and 1800, turtles at Necker have also been found to commonly emerge at night. Similar nocturnal behavior has at times been observed at French Frigate Shoals, Laysan, Pearl and Hermes Reef, and Kure.

The surface temperature of the carapace in turtles basking at French Frigate Shoals can reach up to 42°C. The greatest internal body temperature recorded through the cloaca was 31.3°C at a time when the seawater temperature was 26.3°C. Turtles exhibit very little activity while basking except for occasionally flipping sand on their carapace for thermoregulation. They do not, however, seem to orient their position in relation to the sun. One of the advantages to Hawaiian Chelonia obtained from basking is the reduction in exposure to predation by tiger sharks. Emergence to land at night may be especially advantageous in view of the fact that tiger sharks are mainly nocturnal predators. A further advantage to resting on land would be the conservation of energy by not having to periodically swim to the surface for respiration. Respiration patterns while basking have been found to consist of breath-holds averaging 3.6 minutes, followed by a single shallow breath (Whittow and Balazs, 1979, in press--a, in press--b).

FUTURE RESEARCH NEEDS

Research needs of the Hawaiian green turtle population deemed important for the immediate future include the following activities: (1) continued monitoring and tagging with Inconel tags during additional breeding seasons at French Frigate Shoals; (2) expansion of tagging efforts directed at immature turtles in resident foraging areas, particularly around the main Hawaiian Islands; (3) radio tracking of adult females and males at

French Frigate Shoals to identify marine habitat usage during the breeding season; (4) determination of digestion rates of green turtles in tiger sharks; (5) continued investigations of the ecology and thermal physiology of the rare land basking habit; and (6) survey and tagging of turtles in foraging areas at Wake Island and Johnston Atoll to determine if Hawaiian Chelonia utilize these isolated oceanic locations.

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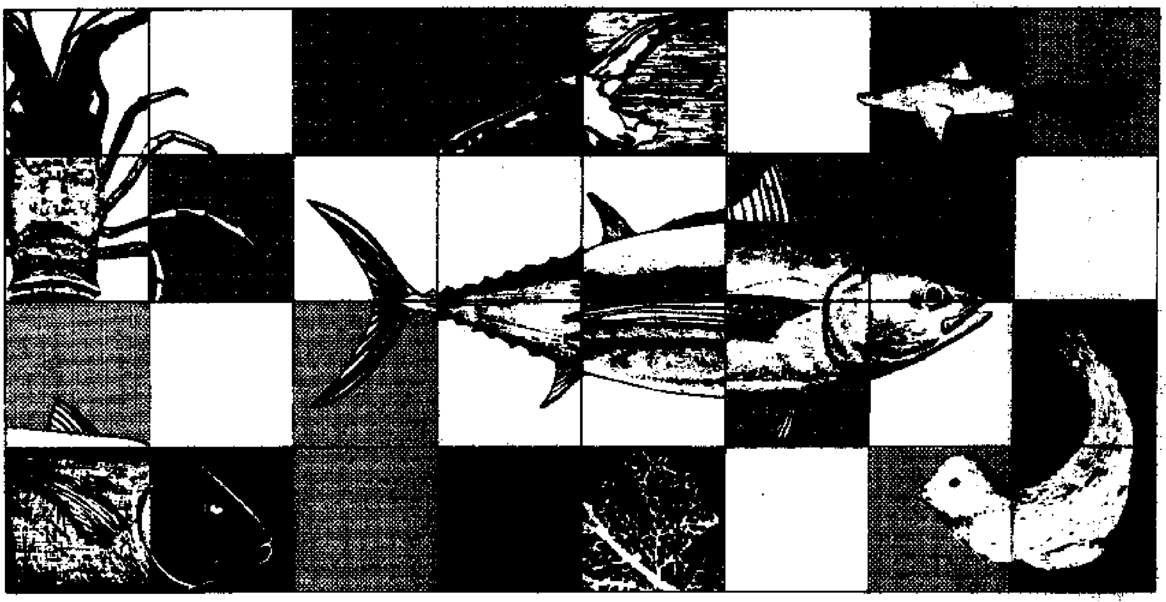
Nearshore Research



THE STRUCTURE OF REEF FISH COMMUNITIES IN THE HAWAIIAN ARCHIPELAGO: INTERIM STATUS REPORT

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ABSTRACT

The structure of reef fish communities in the Hawaiian Archipelago is being studied as part of a broad investigation of marine resources in the Northwestern Hawaiian Islands. To date, communities have been sampled at eight islands or island groups: Kure, Midway, French Frigate Shoals, Necker, Nihoa, Niihau, Oahu, and Hawaii. Other locations will be sampled soon. The following generalizations are evident in the data collected so far, but remain tentative until sampling has been completed. (1) Forces that determine the distribution patterns involve either environmental factors (including biological interactions) or fishing pressures. (2) Northwestern communities show close ties with communities in both the warm temperate and the tropical western Pacific, but southeastern communities show close ties only with communities in the tropical western Pacific. (3) The predominant members of the northwestern communities, as a group, are better attuned 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. (4) Many species prominent in shallow-water communities in the northwest occur only in deeper water southeastward. (5) The southeastward distributions of species in the northwestern communities are limited by both environmental factors 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

Our knowledge of reef fishes in Hawaii is based almost entirely on what is known of the inhabitants of reefs surrounding the high islands. We know little of the fishes that live on reefs around those low bits of land and expansive shallows that stretch more than 1,500 km northwestward from the high island of Kauai. These are the Northwestern Hawaiian Islands, a vast region that constitutes less than 1% of the land area in the archipelago, but about 65% of the marine environment between shore and 100 fathoms (Bryan, 1954). Clearly the reef resources here, still virtually untouched by humans, greatly exceed those of the long exploited high islands.

Not only do the reefs of the Northwestern Hawaiian Islands encompass greater area, they also include more varied habitats. Although each of the high islands offers many distinct reefs, it is a mix that tends to be repeated from island to island. Probably this is because each high island presents a similar underwater setting. Being in essence one or more large volcanic peaks that block the prevailing wind and seas, they support distinctive windward and leeward reefs. And the area available for shallow reefs around these islands tends to be limited to relatively narrow shelves, beyond which the seafloor drops sharply to great depths.

In comparison, shallow reefs exist in highly dissimilar circumstances 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 covered by the high islands. Probably more important, however, 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, an anomalous 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.

This great diversity of reef habitats strongly influences how fishes are distributed over the archipelago. Because a species is defined by a combination of characteristics adapted to specific environmental conditions, it should be most successful where those conditions are best approximated. Thus, its distribution should reflect its environmental requirements. The importance of this concept to those that would manage Hawaiian fishes is obvious. If we know both the requirements of a species and the characteristics of a habitat, we should be able to predict that species occurrence in that habitat. And where the occurrence fails to meet the prediction, it should be possible to identify the root of the discrepancy.

So, I believe that study of how Hawaiian reef fishes are distributed over the archipelago will identify many of the forces that shape their communities.

Several other investigations, past and present, contribute to this effort. The project is based on my earlier study of reef fishes at Kona, Hawaii (Hobson, 1972, 1974) and is closely tied to current studies of the reef benthos (see paper by Grigg and Dollar) on the same reefs. And because I believe that trophic relationships are the major forces shaping the structure of reef fish communities, I expect valuable interaction with the current studies of trophic relationships among fishes in the Northwestern Hawaiian Islands (see paper by Parrish et al.).

This is a preliminary report on the project's current status. Anticipated contributions to the scientific literature include the distribution patterns of certain key species done in collaboration with Leighton Taylor, and an analysis of ecological relations in distribution patterns done in collaboration with Richard Grigg.

METHODS

This study is based on direct observations, using SCUBA, of reef communities between shore and depths of 20 to 35 m. Work at each island begins with a general reconnaissance where representative habitats are identified and all species seen are listed. Having acquired a general familiarity with the area and its fauna, 25 x 4 m transect lines are established in the representative habitats. My experience with transect counts to assess fish communities under varied conditions has shown this to be an effective sample area. A longer line too often cannot be contained within a single type of habitat. Cryptic forms escape notice when more than about 2 m from the line. Also, the standard 72 cu. in. diving tank provides just a bit more air than it takes to complete a count at the deeper stations.

The counts are made as follows. The preliminary reconnaissance and previous experience have established species likely to be present, their relative numbers, and their general behavior. As I lay out the line (a fiberglass metric measuring tape), moving rapidly, I count those species that tend to avoid humans. Then I return along the line, counting those species that are attracted to humans, but moving fast enough to avoid repeated counts of those individuals that follow. Finally, I move slowly back along the line, carefully inspecting crevices for cryptic, sedentary forms that readily go unnoticed. I spend 40 min. on each count so that each habitat receives equal attention, and during this time note any fish within the sampled area that I have reason to believe was not counted earlier. The tally generally includes more individuals than are in the area at one time. With the limited number of counts I am able to make, this methodology has proven the most effective way to determine which species frequent the sampled habitat. It does not, however, provide data for projections of biomass.

To make the counts more accurately reflect community structure, it is necessary to make an adjustment for certain species, generally grazing acanthurids or scarids, that roam over the reef in exceptionally large aggregations. Typically these aggregations include several hundred individuals, and experience has shown that their chance entry--or non-entry--into the sample area will produce a distorted picture of community structure. The problem is exaggerated in this study because there is opportunity for just a relatively few transect counts in any one place. I have concluded that it is best to record these schools (estimates of the number of individuals) as footnotes, whether or not they enter the same area, and not use them in calculating the index used to characterize community structure. This procedure seems to be working out. Generally when such schools are present there are enough conspecifics present apart from these large schools to rank the species among the major components of the community.

The counts are not without inherent bias. Generally, highly cryptic forms like muraenid eels are grossly underrepresented. In some habitats the same is true of certain nocturnal species, like holocentrids, that spend the daytime under cover. And although the water was clear enough at all stations to include the entire water column in the counts, certain very small species like atherinids and engraulids that school just under the surface were not included because their numbers, and sometimes their identities, could not be determined consistently in observations made from the seafloor. These problems, however, applied equally to all counts, so do not weaken the comparisons.

Finally, I did not count small juveniles because their numbers vary greatly with the season and from year to year for reasons unrelated to conditions on the reef. Their inclusion would, in fact, obscure, rather than clarify, the adaptiveness of the established adult to the habitat under study.

Following the transect count, I inspect the surrounding area for other species, noting their relative abundance, and any indications that the transect counts might have produced a misleading assessment of the community. These supplemental observations contribute to the interpretations drawn from the transect data and are especially important as added support when a species is noted to be absent.

Eight islands, or groups of islands, have been sampled to date (Table 1).

RESULTS

Temporal variations in community structure

The communities at different locations in the archipelago are being sampled at different times--often one or more years apart. There would be serious problems with the comparisons if the communities change much from year to year. But their major components, at least, remain essentially unchanged over the period of time involved here, as determined by transect counts made at Kona over three years and at Midway over two years. Because space is limited here, I present data from just one site at each location (Tables 2 and 3), but two other sites at Kona and

TABLE 1. STATIONS WHERE THE FISH COMMUNITIES HAVE BEEN SAMPLED WITH TRANSECT COUNTS AND OTHER OBSERVATIONS, JULY 1977 TO SEPTEMBER 1979

Island	Dates	No. Transect Sites	No. Transects	Depth (m)	Depths of General Obs. (m)
Hawaii	7/77; 10/78; 9/79	3	36	2-12	shore to 35
Oahu	7/77; 11/77; 10/78; 5/79; 9/79	2	8	7-10	shore to 35
Niihau	11/78	2	4	7-10	shore to 20
Nihoa	11/78	2	4	8-10	shore to 35
Necker	11/78	1	2	15	shore to 20
Fr. Frig. Sh.	11/78	5	8	9-12	shore to 20
Midway	8/77; 9/79	8	16	2-12	shore to 35
Kure	8/77; 9/79	8	14	2-12	shore to 35

TABLE 2. MAJOR SPECIES ON ONE CORAL REEF AT KONA, HAWAII

1977 Rank	Species	Relative Abundance Index[1]		
		1977	1978	1979
1	*Chromis agilis*	19.1	18.0 (1)[2]	18.5 (1)
2	*Ctenochaetus strigosus*	12.7	15.8 (3)	15.4 (2)
3	*Zebrasoma flavescens*	12.1	16.6 (2)	13.8 (3)
4	*Chaetodon multicinctus*	8.4	10.1 (4)	8.3 (4)
5	*Chromis vanderbilti*	6.3	0.9	4.7 (5)
6	*Thalassoma duperreyi*	6.1	4.4 (5)	3.4 (7)
7	*Acanthurus nigrofuscus*	4.4	1.7 (9)	1.0
8	*Plectroglyphidodon johnstonianus*	3.3	3.0 (7)	1.8 (8)
9	*Centropyge potteri*	3.1	3.3 (6)	3.8 (6)
10	*Chromis hanui*	2.4	2.8 (8)	1.8 (8)
		4 transects $\bar{x}$ no. sp. 34 $\bar{x}$ no. ind. 185	4 transects $\bar{x}$ no. sp. 33 $\bar{x}$ no. ind. 159	4 transects $\bar{x}$ no. sp. 35 $\bar{x}$ no. ind. 191

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

[2] Numbers in parentheses indicate rank that year if in top 10.

TABLE 3. MAJOR SPECIES OUTSIDE WINDWARD REEF AT MIDWAY ATOLL (ONE LOCATION)

1977 Rank	Species	Relative Abundance Index[1] 1977	Relative Abundance Index[1] 1979
1	*Acanthurus triostegus*	16.3	11.7 (3)[2]
2	*Chromis ovalis*	14.2	13.9 (1)
3	*Acanthurus leucopareius*	12.3	12.8 (2)
4	*Myripristis amaenus*	7.0	6.1 (7)
5	*Stegastes fasciolatus*	6.3	8.5 (5)
6	*Kyphosus cinerascens*	5.4	4.9 (8)
7	*Thalassoma duperreyi*	4.9	8.5 (4)
8	*Acanthurus nigroris*	4.7	0.4
9	*Abudefduf abdominalis*	2.7	7.6 (6)
10	*Thalassoma ballieui*	1.9	2.9 (9)
		2 transects $\bar{x}$ no. sp. 33 $\bar{x}$ no. ind. 316	2 transects $\bar{x}$ no. sp. 35 $\bar{x}$ no. ind. 223

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

[2] Numbers in parentheses indicate rank that year if in top 10

another at Midway produced similar results. Not only do the same species predominate from year to year, but they do so in approximately the same relative numbers. It is important that this condition exists at both ends of the archipelago, because fish community structure can be more changeable at higher latitudes (unpublished data).

Spatial variations in community structure

I have yet to sample certain important locations in the archipelago, e.g., Gardner Pinnacles, Maro Reef, Laysan, and Pearl and Hermes, so many relationships remain unexamined. Nevertheless, data now in hand illustrate certain patterns that probably are significant.

Because the reef habitats change progressively from one end of the archipelago to the other, it is meaningful to compare conditions on the island of Hawaii with those at Midway-Kure. It is striking that the major species at Kona tend to lose dominance northwestward until they are rare or absent at Midway-Kure (Table 4), whereas the major species at Midway-Kure, while they tend to decline somewhat in relative numbers southeastward, nevertheless are generally more evenly distributed over the archipelago (Table 5).

TABLE 4. NORTHWESTWARD OCCURRENCES OF MAJOR SPECIES[1] ON TRANSECT LINES AT KONA, ISLAND OF HAWAII

Species	Hawaii	Oahu	Nihoa	French Frigate S.	Midway-Kure
Chaetodon multicinctus	****	**	**	**	●
Plectroglyphidodon imparipennis	****	●	**	*	0
Chromis agilis	****	●	0	*	0
C. vanderbilti	****	****	****	****	●
Acanthurus nigrofuscus	****	****	****	****	0
Zebrasoma flavescens	****	***	●	*	●
Ctenochaetus strigosus	****	****	**	****	**

[1] Listed are the species that represented >10% of all individuals counted on any one of the 36 Kona transect lines. Asterisks represent the largest percent of all individuals counted that were of that species on any one transect line at each location.

**** = >10%　　*** = 5-9%　　** = 1-4%　　* = <1%
● = seen (but not on transect)　　0 = not seen

TABLE 5. SOUTHEASTWARD OCCURRENCES OF MAJOR SPECIES[1] ON TRANSECT LINES AT KURE AND MIDWAY ATOLLS

Species	Kure-Midway	French Frigate S.	Nihoa	Oahu	Hawaii
Myripristis kuntee	****	●	●	*	**
Flammeo sammara	****	●	●	●	*
Kyphosus cinerascens	****	**	****	●	**
Mulloidichthys flavolineatus	****	●	●	●	**
Chromis ovalis	****	****	****	●	●
Dascyllus albisella	****	***	●	●	●
Stegastes fasciolatus	****	**	**	***	***
Thalassoma duperreyi	****	***	***	***	***
T. ballieui	****	**	**	**	*
Scarus dubius	****	**	●	0	*
S. sordidus	****	**	●	●	*
Acanthurus leucopareius	****	**	**	●	***
A. nigroris	****	**	**	**	***
A. triostegus	****	**	**	**	***

[1] Listed are the species that represented >10% of all individuals counted on any one of the 30 Midway to Kure transect lines. See footnote 1 of Table 4 for explanation of symbols.

I believe that the combination of exploratory reconnaissances, general observations, and transect counts produced reasonable species lists for most locations. If so, the patterns of occurrence of even the relatively minor species in these lists can be meaningful. The data show that 21 of the species seen more than once on transect lines at Kona were not seen on transects or during other observations at Kure or Midway, and 12 of the species that recurred on the transect lines at Kure and Midway were not seen on transects or during other observations at Kona (Table 6).

Generally the comparisons drawn in this report are limited to observations made during this study. This is to reduce the bias that would otherwise stem from my many observations in the high islands, especially Hawaii and Oahu, during previous years. It is significant, however, that during all of my intensive work at Kona, I saw only one of the species listed in part II of Table 6--an occasional *Caranx ignobilis*. Similarly, two other species--the histiopterid *Histiopterus typus* and the pomacanthid *Genicanthus personatus*--seen repeatedly on reefs as shallow as 20 m at Midway and Kure (though not on transect lines) have not been seen in the high islands.

The shift in community structures from one end of the archipelago to the other is not a smooth progression. The various islands, and certain groups of islands, have distinct features that influence their fish communities. This was most evident at French Frigate Shoals. Two relatively common species, *Chaetodon trifascialis* and *Chaetodon citrinellus*, were not seen elsewhere in the archipelago during this study. *Chaetodon trifascialis* invariably occurred with coral of the genus *Acropora*, which dominated some reefs there, but is rare or absent elsewhere in the archipelago (see paper by Grigg and Dollar). An additional feature of fish communities in the Northwestern Hawaiian Islands is the relatively high incidence in shallow water of the large terminal male phase of many labrid species. Most prominent are: *Bodianus bilunulatus*, *Coris flavovittata*, *Anampses cuvier*, *Thalassoma purpureum*, and *Thalassoma ballieui*. These are especially numerous at Midway and Kure.

DISCUSSION

It is premature to draw broad generalizations about the structure of reef fish communities throughout the archipelago because too many critical locations remain unsampled. Nevertheless, the data in hand suggest certain patterns likely to be strengthened by future sampling.

Because conditions differ so from one end of the archipelago to the other, it is not surprising that dominant species vary from place to place. Forces likely to limit distribution of the various species fall broadly in one of two categories: environmental factors (including biological interactions) and fishing pressures.

Undoubtedly, a great variety of environmental pressures exist in the wide range of reef habitats between the island of Hawaii and Kure Atoll. These would be expected to influence both the northwestward distribution of species more prominent in the southeast (such as those at Kona, Tables 4 and 6, part I), and the southeastward distribution of species more

TABLE 6. SPECIES THAT RECURRED ON TRANSECT LINES AT ONE END OF THE ARCHIPELAGO, BUT WERE NOT SEEN AT ANY TIME AT THE OTHER END

	I. Species that recurred at Kona[1]	Most northwestward sighting
1.	*Cephalopholis argus*	Niihau
2.	*Aphareus furcatus*	French Frigate Shoals
3.	*Monotaxis grandoculis*	" " "
4.	*Parupeneus bifasciatus*	Niihau
5.	*Chaetodon ephippium*	Nihoa
6.	*C. reticulatus*	Kona
7.	*C. lineolatus*	"
8.	*Plectroglyphidodon sindonis*	French Frigate Shoals
9.	*Coris gaimard*	" " "
10.	*Thalassoma fuscus*	" " "
11.	*T. quinquevittata*	" " "
12.	*Scarus rubroviolaceus*	" " "
13.	*Ctenochaetus hawaiiensis*	" " "[2]
14.	*Naso lituratus*	" " "
15.	*N. brevirostris*	" " "
16.	*Plagiotremus goslinei*	Necker
17.	*Rhinecanthus rectangulus*	"
18.	*Cantherines sandwichiensis*	French Frigate Shoals
19.	*Pervagor melanocephalus*	Kona
20.	*Ostracion solorensis*	"
21.	*Canthigaster amboinensis*	French Frigate Shoals

	II. Species that recurred at Midway-Kure	Most southeastward sighting
1.	*Carcharhinus amblyrhynchos*	Nihoa
2.	*Ostichthys pilwaxii*	Midway
3.	*Epinephelus quernus*	"
4.	*Oplegnathus fasciatus*	"
5.	*O. punctatus*	"
6.	*Goniistius vittatus*	French Frigate Shoals
7.	*Caranx ignobilis*	Necker
8.	*C. cheilio*	Midway
9.	*Carangoides ferdau*	"
10.	*Epibulus insidiator*	French Frigate Shoals
11.	*Cheilinus bimaculatus*	Oahu
12.	*Cheilio inermis*	"

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[1] Other than species listed in Table 4.

[2] William Walsh, University of Hawaii, personal communication, November 1978.

prominent in the northwest (such as those at Kure-Midway, Tables 5 and 6, part II). Fishing pressure, too, would be expected to have an impact. But because, historically, fishing by humans has been concentrated in the southeastern part of the archipelago, a measurably impact would be expected only in the southeastward distributions of certain species more prominent in the northwest.

Environmental factors that limit distribution northwestward

All of the species more prominent at Kona (Tables 4 and 6, part I) demonstrate a close relationship with fishes in more southerly waters of the tropical western Pacific. Even the one Hawaiian endemic among the major forms--Chaetodon multicinctus--has a close Indo-West-Pacific analog, C. punctatofasciatus (Gosline, 1956). From this evidence alone one might expect these species to be limited northward by lower water temperatures, and undoubtedly many are. But at least over the southeastern half of the archipelago--from the island of Hawaii to French Frigate Shoals--it seems that other environmental factors are more powerful than water temperature in determining the distribution patterns of at least some species.

Consider, for example, Acanthurus nigrofuscus, which Randall (1960, p. 248) reported to be "...probably second in abundance among surgeonfishes in Hawaii only to the manini" (A. triostegus). Based on its occurrences in a variety of habitats during this study, A. nigrofuscus is dominant only where much of the seafloor is exposed basalt--a widespread feature of high-island reefs. Its dependence on some factor related to exposed basalt seems evident through the Northwestern Hawaiian Islands as far as French Frigate Shoals, where its prominence is confined to La Perouse Pinnacle, the only location there with exposed basalt. A. nigrofuscus was not seen at Midway or Kure, where exposed basalt is absent.[1] A similar dependence on some factor associated with exposed basalt, but with an added feature associated with surge-swept shallows, is suggested in the distribution patterns of the pomacentrids Plectroglyphidodon imparipennis and P. sindonis.

It would also appear that forces other than those associated with water temperatures limit the distribution of Zebrasoma flavescens into the Northwestern Hawaiian Islands. In this case, the limiting factor seems related to the absence there of well-developed lee shores. On the high islands--at least Oahu and Hawaii--this species is prominent only in certain leeward habitats (Brock, 1954).

Despite the low water temperature during the winter at French Frigate Shoals, the reef habitats are more favorable to at least some Indo-West-Pacific forms than are reef habitats in the high islands, such as corals of the genus Acropora and the co-occurring butterflyfish Chaetodon trifascialis. These species, common throughout most of the tropical Indo-Pacific

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[1] The apparent relation of Acanthurus nigrofuscus to exposed basalt in Hawaii is questioned by the widespread prominence of A. elongatus--considered synonymous with A. nigrofuscus by Randall (1956)--on basaltless coral reefs of the Marshall Islands (Schultz and Woods, 1953).

region, are rare or absent from most of the Hawaiian Archipelago, in the south as well as in the north.

The butterflyfish *Chaetodon citrinellus* is another species widespread in the Indo-Pacific region and common at French Frigate Shoals, but was unseen elsewhere during this study. Gosline and Brock (1960) considered it to be rare in Hawaii.

The element favorable to certain Indo-West-Pacific species in reef habitats at French Frigate Shoals, but not around the high islands, is unknown. Perhaps barrier reefs that enclose expansive shallows--a prominent setting here and in the western Pacific, but limited around the high islands--establish some required element. Barrier reefs are widespread northwestward from French Frigate Shoals to Midway and Kure. I am anxious to sample the intervening islands--Gardner Pinnacles, Maro Reef, Laysan, Lisianski, and Pearl and Hermes--to determine where the various Indo-West-Pacific forms prominent at French Frigate Shoals, but absent at Midway-Kure, drop out. Because Midway and Kure are coral atolls, they must satisfy many of the environmental requirements of these species. But water temperatures on shallow reefs there drop below 18°C (Mauck, 1975), which probably are intolerably for many. However, low water temperatures have not limited *Epibulus insidiator*. This Indo-West-Pacific labrid apparently finds some needed environmental feature on reefs from French Frigate Shoals to Kure Atoll that is lacking on the volcanic islands to the southeast.

Environmental factors that limit distribution southeastward

The major species at Midway-Kure (Table 5), like the major species at Kona, discussed above, are closely related to fishes on the tropical western Pacific. But considered together, they probably are more representative of the Hawaiian fauna than is the Kona group. More evenly distributed over the archipelago, the Midway-Kure group includes four Hawaiian endemics (*Chromis ovalis*, *Dascyllus albisella*, *Thalassoma duperreyi*, and *T. ballieui*), compared to only one (*Chaetodon multicinctus*) in the other groups. Hence, the Midway-Kure group would seem generally more attuned to the Hawaiian environment.

A new element enters the discussion, however, when we consider those species less numerous than the above which nevertheless occurred in Midway-Kure transect counts, but absent at Kona (Table 6, part II). Among these are species that demonstrate close ties with more temperate regions of the western Pacific. Both *Oplegnathus fasciatus* and *O. punctatus* are prominent in coastal waters of Japan, where they are popular game fishes (Masuda et al., 1975). Despite their common occurrences at Kure and Midway they are rare southeastward in the Hawaiian chain. *Oplegnathus punctatus* has not been recorded in Hawaii until now and *O. fasciatus* has been recognized from just one specimen taken almost a century ago. Gosline and Brock (1960) considered it a dubious record.

Similar ties to warm temperate western Pacific habitats are suggested by the frequent occurrences on shallow (10 to 20 m) reefs of *Ostichthys pilwaxii* and *Goniistius vittatus*, as well as *Histiopterus typus* (which were not counted on transect lines but were seen repeatedly elsewhere). Both *O. pilwaxii* and *H. typus* occur in Japanese waters, as do close relatives of *G. vittatus* (Masuda et al., 1975), but here still another dimension enters the discussion: variations in depth of occurrence with latitude. Although *H. typus* appears to be genuinely rare to the southeast [Gosline and Brock (1960) were aware of just two specimens], the populations of *O. pilwaxii* and *G. vittatus* seem limited to deeper water. Based on experience centered in the high islands, Gosline and Brock (1960) made no mention of *O. pilwaxii* (as *O. japonicus*) being uncommon, but noted (p. 143) that it "...is probably the deepest water species of all the holocentrids." And they reported (p. 203) that *G. vittatus* (as *Cheilodactylus vittata*) is "...not uncommon in water about 100 feet deep."

It is a well recognized principle of zoogeography that fishes widely distributed over latitude occur in deeper water toward the equator (e.g., Hubbs, 1948). Furthermore, studies along the North American west coast, where the pattern is reversed with local upwelling, have shown that the phenomenon is based on water temperatures (Hubbs, 1948). So we should expect a straightforward relation between depth and water temperature to account for the distributions of at least some of the species that inhabit shallow reefs in the northwest, but only deeper reefs further south. This may account for the distribution of the angelfish *Genicanthus personatus*, for example, which is relatively common on reefs 20 to 30 m deep at Midway and Kure, but which has been reported only from deep water around the high islands (Randall, 1975). And it may explain why the large terminal male phase of the labrid *Bodianus bilunulatus* lives on reefs as shallow as 1 to 2 m at Midway and Kure, but at Kona rarely occurs in shallower depths than 20 m. It may even account for the similar distribution of the grouper *Epinephelus quernus*, which I found to be numerous in water as shallow as 5 m at Kure and Midway, but which frequents fairly deep water southeastward (Gosline and Brock, 1960). In this last case, however, the situation is clouded by yet another consideration--fishing pressures.

The impact of fishing pressures on distribution

The absence of fishes like *Epinephelus quernus* in shallow water to the southeast might reflect increased fishing pressures. Certainly *E. quernus* is an easy mark for spear fishermen, who without doubt have taken a heavy toll of shallow-water reef fishes around the high islands. Similar uncertainty surrounds the southeastward occurrences of *Caranx cheilio*. This species was represented on transect lines at Midway that were in depths of 5 m (Table 6, part II), but it was not seen at French Frigate Shoals or southward. Does this reflect fishing pressures or restriction to deeper water in the south?

The marked decrease in numbers of some species southeastward cannot be attributed to population shifts into deeper water, however, because they inhabit shallow reefs throughout the archipelago. Certainly the distribution patterns of some, like the shark *Carcharhinus amblyrhynchos*, may find some environmental feature of high-island reefs unfavorable, as they seem generally sparse there. Others, however, are known to thrive on reefs of the high islands, and their current low numbers in the study areas likely reflect fishing pressures. Considering just those listed in

Tables 5 and 6, part II, we can point to Myripristis kuntee and Caranx ignobilis. Myripristis kuntee is well known to be a prime target of spear fishermen, and C. ignobilis is coveted by spear fishermen and shore fishermen alike. A similar appraisal of the species more prominent in the south (Tables 4 and 6, part I) fails to suggest species likely to be subjected to strong fishing pressures. Of the species listed, only the grouper Cephalopholis argus and the snapper Aphareus furcatus would seem likely possibilities. Cephalopholis argus, however, has in fact been expanding its range northward since it was introduced into the high islands from Tahiti several decades ago, and A. furcatus, a relatively small, generally solitary species, is not particularly sought after.

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PROGRESS REPORT ON THE NEARSHORE FISHERY RESOURCE ASSESSMENT OF THE NORTHWESTERN HAWAIIAN ISLANDS: 1977 to 1979

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ABSTRACT

The State Department of Land and Natural Resources, Division of Fish and Game is currently engaged in a study to assess the nearshore fisheries resources of the Northwestern Hawaiian Islands (NWHI) pursuant to a Tripartite Cooperative Agreement with the National Marine Fisheries Service and the U.S. Fish and Wildlife Service. Preliminary results obtained by various data collecting methods suggest that the fishery resources in the nearshore area of the NWHI are basically similar to that of the main Hawaiian Islands. Shallow shoreline areas along certain islets were found to be densely populated with fishes. Fish species rare or unknown to the main islands were noted in the Northwestern Hawaiian Islands. Other species common to the main islands appeared to diminish northwestwardly along the NWHI chain. Large fish were common in the nearshore area. Stomach content examinations indicated that the diets of selected species of commercially valuable fishes varied widely.

INTRODUCTION

The nearshore waters of the Northwestern Hawaiian Islands (NWHI) are reputed to have excellent fishing potential that could enormously benefit the fishermen of Hawaii. In recent years, increased attention given 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 Department of Land and Natural Resources (DLNR) of the State of Hawaii formally entered into a five-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 Northwestern Hawaiian Islands. The DLNR's 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 66 feet in depth. Totally, the nearshore area comprises nearly 300,000 acres. With the terrestrial and offshore resource assessment studies being conducted by the FWS and NMFS, respectively, 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, this is our fourth year of field research under this agreement. The nearshore surveys accomplished to date have been made possible through funding support 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.)

Primary objectives of the nearshore fishery resource assessment study are 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 fish species were investigated. Moreover, identification of macro-algae and macro-invertebrates, density estimates of certain shellfish, and behavioral characteristics of certain wildlife were noted.

METHODS

The National Oceanic and Atmospheric Administration's research vessel, Townsend Cromwell, was utilized as the primary platform from which smaller crafts were launched to carry field research parties to the nearshore areas for the NWHI study. The U.S. Coast Guard also provided logistical support to survey Kure Atoll in December 1979.

Data on fish species composition, density, and size distribution are primarily obtained through underwater dive fish transecting techniques that are modified as necessary to allow quantitative and qualitative inventory of the biota and habitat. Generally, this involves the laying down of a pre-measured transect line extending up to 250 yards along which fish species on both sides of the line are counted and their sizes estimated. Tabulation of fish species and their sizes are also accomplished within a 100-foot diameter circular underwater area to diminish the risks of encounters with sharks and to enable the surface support craft to anchor in close proximity to the divers. Our diving activities were conducted in depths ranging from 5 to 20 feet because of restrictions imposed on the use of SCUBA equipment until diving standards are formally established.

Other methods to determine fish species composition and sizes include the collection of samples with hook-and-line, thrownet, and spear. These collections provided the specimens for determining identification, size, stomach content, sex, and gonad development. Fish samples were collected for other researchers to study age through otolith examination and ciguatoxicity through tissue analysis. Additionally, samples of macro-invertebrates and macro-algae were hand-collected and brought back for identification and other scientific research purposes.

Specimens of ulua were obtained by handline fishing for tagging. 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 being taken.

RESULTS AND DISCUSSION

To date we have surveyed about 50% of the nearshore area in the Northwestern Hawaiian Islands. The data collected thus far tend to indicate that the fishery resources in the NWHI are by and large similar in composition to that of the main Hawaiian Islands with a few different fish species.

Splash zone

Surveys were conducted at the splash zone on all of the island areas in the NWHI except for Maro Reef where no emerged land was observed. Substrate types were predominantly lava rocks, limestone, and sand. Lava rock substrate dominated the splash zone at Nihoa and Necker Islands, La Perouse Pinnacle in French Frigate Shoals, and Gardner Pinnacles whereas limestone foundations were common to Laysan, Lisianski, and Midway Islands, Kure Atoll, and Pearl and Hermes Reef. Permanent sand beaches occurred at all islands except Necker Island and Gardner Pinnacles.

The 'ohiki or ghost crab (*Ocypode* spp.) were the only organisms observed on the permanent sand beach habitat. In contrast, a variety of macro-invertebrates and macro-algae species were recorded on lava rock and limestone habitats. Invertebrates that were common to the lava rock habitat were the 'opihi (family Patellidae), ha'uke'uke (*Colobocentrotus atratus*), pipipi (family Neritidae), periwinkle (family Littorinidae) and a'ama crab (*Grapsus grapsus*). Macro-invertebrates on limestone substrates included periwinkles and a'ama crabs, but there were noticeably less on lava substrates. Exceptions were noted at Laysan Island and Kure Atoll where large quantities of periwinkles and a'ama crabs, respectively, were observed. Macro-algae species common to rocky limestone and lava substrates in the splash zone were the green algae, *Caulerpa racemosa*, and the red algae, *Gelidiella* sp.

Inner nearshore zone

Surveys in the inner nearshore zone revealed large concentrations of aholehole (*Kuhlia sandvicensis*), moi (*Polydactylus sexfilis*), 'ama'ama (*Mugil cephalus*) and iao (*Pranesus insularum*) throughout most of the island areas in the Northwestern Hawaiian Islands.

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

Outer nearshore zone

A total of 184 underwater fish counts have been conducted at all island areas in the NWHI during the past three years and the numbers for each island area are summarized in Table 1. Of the 184 fish counts, 33 are repetitive counts from 25 fish transect stations which, although varying in fish densities and composition to some degree, do not indicate significant annual variation in the fish population. Further, some preliminary data on winter surveys conducted at Kure Atoll suggest that piha (Spratelloides delicatulus) and kawakawa (Euthynnus affinis) are not nearly as abundant during the winter as compared to the summer months. Also, the gray reef shark (Carcharhinus amblyrhynchos) appeared to be more abundant in the nearshore waters during the early rather than the latter part of the summer season.

TABLE 1. NUMBER OF FISH COUNTS CONDUCTED BY LOCATION IN THE NORTHWESTERN HAWAIIAN ISLANDS DURING 1977-79

Location	Number of Fish Counts		
	Initial Survey	Resurvey	Total
Nihoa	5	3	8
Necker Island	2	2	4
French Frigate Shoals	28	11	39
Gardner Pinnacles	1	0	1
Maro Reef	13	3	16
Laysan Island	15	3	18
Lisianski Island	16	2	18
Pearl and Hermes Reef	39	7	46
Midway Islands	6	0	6
Kure Atoll	26	2	28
Total	151	33	184

While 176 fish species have been recorded through the fish transecting, general observation and specimen collecting activities have accounted for nine additional species, bringing the total number of fish species observed to 185. The tiger shark (*Galeocerdo cuvier*), for example, was recorded through observation surveys conducted from skiffs and appeared to be abundant at certain locations such as off Maro and Pearl and Hermes Reefs and Laysan and Lisianski Islands. At Lisianski Island, six 12 to 14-foot tiger sharks were recorded from an area of about one-half square mile during a single morning's observation.

Of the 185 fish species noted, 17 were common to all islands and 13 species have been enumerated from 9 of the 10 island areas in the NWHI. Fish species recorded from all islands were the gray reef shark, piha, cornetfish (*Fistularia commersoni*), white ulua (*Caranx ignobilis*), moana (*Parupeneus multifasciatus*), nenue (*Kyphosus cinerascens*), the butterflyfishes (*Chaetodon fremblii* and *Chaetodon miliaris*), a'awa (*Bodianus bilunulatus*), saddleback wrasse (*Thalassoma duperreyi*), ho'u (*Thalassoma purpureum*), hinalea lauhine (*Thalassoma ballieui*), manini (*Acanthurus triostegus*), maiko'iko (*Acanthurus leucoparius*), maiko (*Acanthurus nigroris*), kala (*Naso unicornis*), and kihikihi (*Zanclus cornutus*). Table 2 below reflects the number of fish species recorded by the individual island areas of the NWHI group.

TABLE 2. NUMBER OF FISH SPECIES RECORDED BY LOCATION FROM THE NORTHWESTERN HAWAIIAN ISLANDS DURING 1977-79

Location	Number of Fish Species Recorded		
	Underwater Fish Counts	Other Survey Methods	Total
Nihoa	80	8	88
Necker Island	60	8	68
French Frigate Shoals	115	18	133
Gardner Pinnacles	30	10	40
Maro Reef	72	8	80
Laysan Island	97	7	104
Lisianski Island	81	9	90
Pearl and Hermes Reef	112	14	126
Midway Islands	71	9	80
Kure Atoll	84	16	100

Generally, the number of acanthurid species appears to diminish in a northwesterly direction along the NWHI chain. For example, species common to nearshore areas throughout the main Hawaiian Islands, such as the nae' nae (*Acanthurus olivaceus*), were not observed beyond Maro Reef, and the lavender tang (*Acanthurus nigrofuscus*) and palani (*Acanthurus dussumieri*) were not seen beyond Laysan Island. Further, the achilles tang (*Acanthurus achilles*) dropped out of our fish counts after Lisianski Island.

The number of triggerfish species also exhibited a diminishing trend in a northwesterly direction. Although commonly observed in the nearshore areas of the main Hawaiian Islands, the two humuhumunukunukuapuaa species, *Rhinecanthus rectangulus* and *Rhinecanthus aculeatus*, were not observed beyond Necker Island. The triggerfishes *Sufflamen bursa* and *Sufflamen frenatus* were only observed at Nihoa on the southeastern end of the NWHI chain.

On the other hand, the butaguchi ulua (*Caranx cheilio*), which is relatively rare in the main Hawaiian Islands and found only in deeper waters of over 30 fathoms, was observed in very shallow waters (5 feet) and in occasional large groups of 200 to 300 individuals at Kure Atoll.

With regard to species missing from or rare to the main Hawaiian Islands nearshore habitat, the butterflyfish *Chaetodon trifascialis*, previously known only from a juvenile caught in Kaneohe Bay, Oahu, was observed off La Perouse Pinnacle in French Frigate Shoals. This butterflyfish is believed to be almost exclusively dependent upon polyps of the *Acropora* coral for food, which is present in the NWHI but very rare in the main Hawaiian Islands. Another species relatively common in the NWHI group but rarely seen off the main Hawaiian Islands is the sling-jaw wrasse (*Epibulus insidiator*).

The family Oplegnathidae was represented by two species in the NWHI nearshore area, namely, the ishigakidai (*Oplegnathus fasciatus*) and the ishidai (*Oplegnathus punctatus*). Although common to several island areas in the Northwestern Hawaiian Islands, these fishes were not abundant in the nearshore area.

In addition a striped-ulua species (*Carangoides* sp.), known to occur, but not documented, in waters off the main Hawaiian Islands, was recorded in the fish counts at the NWHI.

Depending on the selection of locations for the underwater fish counts, considerable variation in fish densities were noted. Generally, fish densities were low in flat-bottom areas and ranged from zero to a few pounds of fish per acre. Conversely, higher standing fish crops were recorded where the bottom profile was irregular. The highest standing crop of 10,867 pounds of fish per acre represented by 36 fish species was recorded at such a habitat off Kure Atoll, with the weke (*Mulloidichthys vanicolensis*), nenue, and the butaguchi contributing significantly to this density.

The nenue appears to contribute most to the biomass of the fisheries in the outer nearshore zone of the Northwestern Hawaiian Islands.

In terms of numbers, the baitfish piha far outnumbered other species of fishes in the outer nearshore zone, but their small size (1 to 2 inches) did not contribute much in terms of weight.

Many species of fish in the nearshore area of the NWHI appeared to be larger than those in the main Hawaiian Islands. For example, large wrasses such as the hilu (Coris flavovittata) and ho'u (Thalassoma purpureum) ranging from 14 to 18 inches in length were commonly observed in the NWHI, but such large sizes are rarely seen in the main Hawaiian Islands. The white ulua appeared to be an exception. Although 60 to 80-pound size white ulua were abundant in the NWHI, the larger sizes of over 100 pounds, which are occasionally caught off the main Hawaiian Islands, were rarely observed.

White ulua at Pearl and Hermes Reef and Lisianski Island exhibited extremely aggressive behavior by nipping at the diving personnel during the fish counts. The spinning propellers of outboard motors operating at slow idling speed were also frequently attacked by the larger size ulua.

White ulua tagging

In 1978 and 1979, some 343 white ulua ranging in size from 2 to 100 pounds were caught and tagged from French Frigate Shoals, Maro Reef, Laysan and Lisianski Islands, Pearl and Hermes Reef, and Kure Atoll to determine growth and movement of the species. Most of the fishes tagged ranged in the 5 to 10-pound classes. In terms of catchability and the rate at which it was possible to tag the white ulua, we found that for a school of fish containing about 200 individuals, up to 40 fish weighing between 2 and 10 pounds could be caught with two handlines and tagged within the first half-hour of fishing at Maro Reef and Lisianski Island. The catch rate then gradually declined beyond the first half-hour of fishing effort. Of 155 fish tagged in 1978, one white ulua was recovered at Lisianski Island in 1979 which is the only recovery we have to date. Unfortunately, without the identifying plastic disc tag, it was not possible to extract meaningful data from the fish. There is a need to consider alternative tagging methods, however.

Information derived from fish samples

A total of 921 fish specimens representing 66 species were collected by various methods. In addition to providing length and weight data, the specimens were used to evaluate dietary items, sex, gonad conditions, ciguatoxin levels, and age analysis of select fish species by appropriate research investigators.

Some 833 samples representing 64 fish species were examined for stomach contents. The 15 fish species contributing significantly to the fish biomass in the nearshore area and their primary diet items are as follows (the numbers enclosed by parentheses reflect the number of individual fishes examined):

1. Nenue (18). Brown algae comprised the major diet of this species although red and green algae were also consumed. In addition, fish and crustacean remains were present. Based on the condition of food found in the stomach, the nenue apparently feeds during both day and night hours.

2. Manini (56) and Maiko (5). Selected types of green and red algae were favored over brown algae for these diurnal feeders.

3. Ama'ama (39). Diatoms are the primary food of this species which appeared to ingest a considerable amount of fine sand particles during its day feeding activities.

4. Uhu (5). Gut contents of the diurnal feeder *Scarus perspicillatus* were similar to those of the mullet with finely crushed sand coral particles, and what appeared to be green algae.

5. A'awa (62), Hinalea lauhine (8), and Hou (17). Sea urchins, brittle stars, gastropods, crabs, lobster appendages, fishes, algae, and corals appear to be the primary diet items of these day-feeding species.

6. Aholehole (65). Diet items were primarily juvenile crustaceans that included crabs, shrimps, spiny (*Panulirus* spp.) and slipper (family Scyllaridae) lobsters, and stomatopods. Other items, including polychaete worms and small fishes such as piha, were also a part of the diet of this nocturnal feeder.

7. Weke-a'a (*Mulloidichthys flavolineatus*) (37). This species is primarily a nocturnal feeder; its stomach contents showed crabs, shrimps, and polychaete worms which occur in sandy substrates to be the major food items.

8. Moi (68). Food items recovered from stomachs examined indicated shrimps including the penaeids, crabs, stomatopods, juvenile lobsters, octopus, and small fishes such as piha and the filefish (*Pervagor spilosoma*) to be the primary food items of this nocturnal feeder.

9. White Ulua (104) and Omilu (27). Stomach contents of the white ulua, which appeared to be primarily a night feeder, included spiny and slipper lobsters, shrimps, portunid crabs, octopuses (*Octopus cyanea* and *Octopus ornatus*), eels, cornetfish, squirrelfishes (family Holocentridae), and surgeonfishes. The omilu, on the other hand, was primarily a diurnal fish feeder with piha comprising the bulk of its diet.

10. Gray Reef Shark (12) and Tiger Shark (4). Fish species including eels, surgeonfishes and piha, and octopus comprised the primary diet of the gray reef sharks examined. The tiger sharks caught and examined in the lee of the seabird nesting

island areas such as off Laysan Island and Pearl and Hermes Reef primarily contained albatrosses and boobies in their stomachs. On the other hand, a 10-foot tiger shark caught at Maro Reef showed that in the absence of seabirds, spiny lobsters (*Panulirus marginatus*) which were abundant in the area comprised a major part of its diet.

Gonad condition was determined from the fish samples used in the stomach content study. As with the main Hawaiian Island areas, the data preliminarily suggest that the moi, white ulua, and u'u (*Myripristis murdjan* and *Myripristis amaenus*) spawn during the summer months while the 'ama'ama, a'awa, and kumu (*Parupeneus porphyreus*) spawn during winter. Further, two pregnant gray reef sharks were noted from Maro Reef, one in July 1977 and the other in July 1979.

A total of 624 individual fish samples from the nearshore area representing 59 species were tested for ciguatoxin levels. Results of the test are included in the ciguatera study by NMFS. Also, 42 fish head samples represented by six species have been forwarded to NMFS for their age determination study through examination of otoliths.

Other information collected

A total of 101 macro-algae species were collected from the nearshore area of the NWHI. Five species common to all island areas were the green algae *Caulerpa racemosa* and *Dictyosphaeria versluysii* and the red algae *Jania* sp., *Porolithon gardneri*, and *Porolithon onkodes*.

There were 22 stony and two soft coral species recorded from the nearshore area of the NWHI which included two species of *Acropora* corals, rare or absent in the main Hawaiian Islands. Macro-invertebrate species noted from the nearshore area included various species of mollusks, echinoderms, and crustaceans totalling 63 species.

Nearshore lobster trapping was conducted on a limited scale to provide information complementary to the NMFS offshore lobster study. Observations also were made during the underwater fish counts. Six traps set at Laysan in 1977 resulted with no catch. The 33 traps set at Maro Reef during the past three years resulted in an average catch of nearly six lobsters per trap per night. At Lisianski Island, six traps set overnight in 1977 caught only two lobsters. Finally, 14 traps set overnight at Pearl and Hermes Reef in 1977 averaged slightly more than one lobster per trap. The catch rate of lobsters in the nearshore area appears to correlate with data obtained by NMFS in the offshore areas at these locations.

Green sea turtle sightings were recorded in all nearshore waters of the NWHI chain. Concentrations of over 10 turtles in an estimated one-half square mile surface area were observed at Lisianski and Midway Islands.

Spinner porpoises were observed within the lagoons of Pearl and Hermes Reef and Kure Atoll.

Whereas adult monk seals appear to be cautious and kept their distance from snorkel divers conducting the fish transects, juveniles throughout most of the island areas in the NWHI reacted curiously by following divers at a distance of about 10 feet.

FUTURE RESEARCH NEEDS

As indicated earlier, we have completed three years of a five-year investigation on the living resources that occur in the NWHI. As such, the data and discussions presented in this report of the nearshore areas should be regarded as preliminary, at least until the study can be completed after 1981. Further, mention was made on our inability to use SCUBA to conduct fish count and observation dives beyond 20 feet in depth. During the remaining two-year study period, research efforts in the nearshore area of the NWHI will especially concentrate on obtaining fish count data from the 20 to 66-foot depth range using SCUBA, for which equipment use has been cleared though appropriate governmental authorities.

To date, our survey efforts have covered representative nearshore areas from about 50% of the Northwestern Hawaiian Islands chain. In order to insure completion of the study by 1981, a request for $50,000 has been submitted for supplemental budget consideration by the State legislature to charter a vessel in place of the Townsend Cromwell, whose services may not be available for the nearshore surveys during FY 1980-81. Additionally, we intend to coordinate efforts with the U.S. Navy and Coast Guard to secure logistical support for land-based research opportunities at Kure Atoll and Midway Islands.

Beyond the nearshore area studies, our department, subject to funding approval, will be implementing various research projects which will complement the ongoing research efforts of the tripartite agreement. Among these are projects which will assess the commercial feasibility of the bottomfishes, shrimp, and Kona crab in the deeper waters of the NWHI areas, the availability of baitfish and aku resources in the NWHI, and the longline tuna resources in the 200-mile Fishery Conservation Zone of the Hawaiian Islands which includes the Northwestern Hawaiian Islands.

RESULTS OF CIGUATERA ANALYSIS OF FISHES IN THE NORTHWESTERN HAWAIIAN ISLANDS

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ABSTRACT

Ciguatera is a form of fish poisoning caused by ingestion of certain species of fish. This study deals with the distribution of ciguatoxic fishes in waters of the Northwestern Hawaiian Islands (NWHI) and with a market sampling program to detect and remove ciguatoxic amberjack or kahala, Seriola dumerili, prior to its sale to the public. The results showed that ciguatoxic fish occurred throughout the entire NWHI from Nihoa to Kure Island. There were no detectable trends in rejection rate of the NWHI fishes with respect to area of capture; however, the analysis of data collected on kahala indicated a higher incidence of toxic fishes in the Nihoa-Raita Bank region. Of the 47 NWHI species tested between 1977 and 1979, the rate of rejection, based on a recently developed radioimmunoassay, was higher among fishes in the snapper-grouper complex. These included Caranx ignobilis, C. cheilio, Seriola dumerili, Epinephelus quernus, Etelis carbunculus, Lutjanus kasmira, and Pristipomoides filamentosus. Among inshore species sampled by the National Marine Fisheries Service and the Hawaii Division of Fish and Game, particularly high in rejection was Kuhlia sandvicensis and Cheilinus rhodochrous, followed by Myripristis amaenus, M. murdjan, Mugil cephalus, Caranx melampygus, Polydactylus sexfilis, and C. ignobilis. Of 926 kahala sampled between April and December 1979, 116 fish or 13% were rejected. The rate of rejection, high in April-May, declined steadily to December. The results also showed a low positive but significant correlation between fish size and toxicity.

Northwestern Hawaiian Islands
ciguatera
amberjack
snapper-grouper complex

INTRODUCTION

Ciguatera, a disease with certain characteristic neurotoxic and gastroenteritic symptoms produced by ingestion of a wide variety of fish belonging to groups such as the snappers, groupers, jacks, barracudas, surgeonfishes, and wrasses from toxic areas, appears to be widespread throughout the oceanic islands of the Pacific between the 30° parallels of latitude (Helfrich et al., 1968). The occurrence of ciguatera in some valuable food species found in the central Pacific affects not only the population by causing illness but also, as is often the case, deprives them of a major source of much needed protein. In areas that are seriously affected, it has restricted full development of fisheries and utilization of the available fish stocks.

At the outset of the Northwestern Hawaiian Islands (NWHI) survey and assessment investigation, provisions were made to conduct sampling for ciguatoxic fishes based on documented outbreaks of ciguatera occurring not only among the civilian population in the major Hawaiian Islands but also among U.S. naval and civilian personnel stationed at Midway Islands. It occurred to us that ciguatoxic fishes may also be found elsewhere in the archipelago and that the successful marketing of fishes caught in the NWHI would depend to a large extent on the wholesomeness of fishes from this area.

Together with the Hawaii Division of Fish and Game (HDFG), the Honolulu Laboratory of the Southwest Fisheries Center, National Marine Fisheries Service (NMFS), initiated an extensive sampling program to study the occurrence and distribution of ciguatoxic fishes in the nearshore and offshore waters of the NWHI.

In the spring of 1979, following a sudden outbreak of ciguatera among the local populace, the Honolulu laboratory, together with other state agencies and the fishing industry, also began a project of routinely sampling and pretesting amberjack or kahala, Seriola dumerili, which had been implicated in most of the outbreaks. By mid-April 1979, information supplied by various governmental agencies and fish retailers indicated that about 30 to 35 recent outbreaks could be documented and that perhaps another 50 to 100 individuals were affected but had not reported it to the health authorities.

Prior to 1977, ciguatera research throughout the Pacific relied on relatively crude bioassays to detect the presence of toxin in fish tissues (Banner et al., 1960, 1961). It was not until 1977, when two significant breakthroughs were announced, did researchers see any way to solve some of the pressing problems dealing with ciguatera. One was the discovery of a dinoflagellate, originally misidentified as Diplopsalis sp., but subsequently identified as a new species, Gambierdiscus toxicus, as the likely causative agent in ciguatera outbreaks (Yasumoto et al., 1977) and the other was the development of the radioimmunoassay (RIA) method of detecting ciguatoxin by scientists at the University of Hawaii John A. Burns School of Medicine, Department of Pathology (Hokama et al., 1977).

METHODS

Initially, our sampling effort was concentrated on commercially important species; however, if time and circumstances permitted, we also sampled other less valuable species. From each fish, we obtained tissue samples from the dorsal musculature (A), ventral abdominal musculature (B), gonads (C), and liver (D). Subsequently, liver collection was discontinued and additional muscle tissue were collected from the anal region (E).

At sea as well as at the United Fishing Agency auction market where only kahala are sampled, each tissue collected is placed in a plastic vial, labeled, and either frozen (while at sea) or kept in the fresh state until processed. Data collected on the fish include date, catch location, water depth, sex, length, weight, and vessel name. When it was not possible to obtain exact catch locality, particularly for many of the kahala sampled at the fish auction market, broad geographical areas were substituted. Obtaining data on catch locality for the kahala is very difficult or impossible in some cases because fishermen who land their catches to be auctioned may have fished several islands and banks during the course of a trip and cannot provide exact information on where a particular fish was caught.

The samples are processed by the University of Hawaii Department of Pathology to determine toxicity levels of the fish tissues from radioactive counts per minute per gram of tissue (c/m/g). Based on studies of fish involved in clinically evaluated cases of ciguatera, and on mouse and mongoose toxicity tests, levels of toxicity were established as follows (Y. Hokama, University of Hawaii, John A. Burns School of Medicine, Pathology Department, Honolulu, personal communication):

c/m/g tissue	Toxicity levels
<350,000	Negative
350,000 to 399,999	Borderline
>399,999	Positive

RESULTS

About 16% of all the fish sampled by NMFS and HDFG showed either a positive or borderline rejection level when tested by the RIA method. Of the 1,494 fish sampled, 1,250 were negative, 148 were borderline, and 96 were positive.

Table 1 shows the results of the RIA for fishes sampled by the HDFG in the nearshore areas of the NWHI. Because the list of species sampled is lengthy (624 fish; 60 species) and many of the species had few samples, the table includes only those species for which 10 or more samples were available for the 3 years--1977 through 1979--combined. Among the species tested, *Cheilinus rhodochrous* had a rejection rate of 71% which is exceptionally high. This was followed by *Myripristis amaenus* with 45%, *M. murdjan* and *Mugil cephalus*, both with 18%, *Caranx melampygus* with 14%, and *Polydactylus sexfilis* and *C. ignobilis*, both with 13%. All of these are commercially valuable on the Hawaiian fresh fish market.

TABLE 1. THE NUMBER OF NEGATIVE (n), BORDERLINE (b), AND POSITIVE (p) REACTIONS (n-b-p) OBTAINED WITH THE RADIOIMMUNOASSAY CONDUCTED ON FISHES CAUGHT DURING NEARSHORE SURVEYS CONDUCTED BY HAWAII DIVISION OF FISH AND GAME. ONLY SPECIES WHERE 10 OR MORE SAMPLES WERE COLLECTED IN 1977-79 ARE INCLUDED.[1]

Species	1977	1978	1979	Rejection (%)
Carcharhinus menisorrah	--	8-0-0	3-0-0	0
Myripristis murdjan	--	5-2-0	4-0-0	18
M. amaenus	--	4-3-1	2-1-0	45
Polydactylus sexfilis	--	7-0-1	27-3-1	13
Kuhlia sandvicensis	--	2-1-2	47-2-0	9
Caranx ignobilis	24-5-2	16-3-1	47-2-0	13
C. melampygus	--	3-0-2	9-0-0	14
Mulloidichthys flavolineatus	--	1-0-1	31-1-1	9
Kyphosus cinerescens	--	2-1-0	11-0-0	7
Mugil cephalus	--	4-3-1	19-1-0	18
Bodianus bilunulatus	--	3-0-5	53-1-0	10
Cheilinus rhodochrous	2-2-10	2-0-0	1-0-0	71
Thalassoma duperreyi	--	0-1-1	53-1-0	5
Acanthurus triostegus	--	0-2-0	52-0-0	4

[1] Data from Henry Okamoto, Aquatic Biologist, Hawaii Division of Fish and Game.

Whereas the HDFG concentrated their sampling effort on nearshore fishes, the NMFS sampling included many of the offshore species, although some inshore species were included as a result of recreational fishing conducted during the *Cromwell*'s refueling and rest stops at Midway (870 fish; 47 species). From Table 2, it can be seen that among the members of the carangids where 10 or more samples were collected, *Caranx ignobilis* had the highest rate of rejection, reaching 32% from 19 fish sampled. This was followed by *C. cheilio* with 11% rejection and *Seriola dumerili* with 10%. The only species of serranid, *Epinephelus quernus*, sampled during our survey had a relatively high rejection rate of 18%. Among the snappers, 3 of the 10 *Etelis carbunculus* or 33% showed hazardous levels of ciguatoxin followed by a 23% rejection rate among *Lutjanus kasmira*. *Pristipomoides filamentosus* also showed a relatively high rate of rejection, reaching 15% in our samples. Table 2 shows that most of the rejected fish were sampled at Necker and French Frigate Shoals.

Among the inshore fishes caught and sampled, only *Kuhlia sandvicensis* showed alarmingly high levels of ciguatoxin. Of the 47 fish sampled, 27, or 57%, were positive or borderline according to the RIA. This rate of rejection is considerably higher than that obtained from the HDFG nearshore samples collected from 1977 through 1979.

Most of the other fishes sampled were few in total numbers; therefore, it is difficult to draw definite conclusions about whether ciguatoxin occurs in any significant amounts in their tissues. None showed

TABLE 2. THE NUMBER OF NEGATIVE (n), BORDERLINE (b), AND POSITIVE (p) REACTIONS (n-b-p) OBTAINED WITH THE RADIOIMMUNOASSAY CONDUCTED ON FISHES CAUGHT DURING THE NATIONAL MARINE FISHERIES SERVICE SURVEY CRUISES TO THE NORTHWESTERN HAWAIIAN ISLANDS IN 1977-79

	Nihoa	Necker	French Frigate Shoals	Brooks Banks	Gardner Pinnacles	Raita Bank	Maro Reef	Laysan	Northampton Seamount	Pioneer Bank	Neva Shoals	Lisianski	Unidentified Bank #8[1]	Pearl and Hermes	Midway	Kure	Unidentified Bank #10[2]	Total All Banks	Rejection (%)
Carangidae																			
Carangoides ferdau	--	--	--	--	1-1-0	--	--	--	--	--	--	--	--	1-0-0	--	--	--	2-1-0	33
Caranx cheilio	9-1-0	10-0-0	9-2-0	--	5-0-0	3-0-0	12-1-1	20-1-1	--	--	--	2-0-0	--	9-1-0	4-1-0	8-1-1	--	91-8-3	11
C. ignobilis	--	--	5-1-1	--	2-0-0	--	--	2-0-0	--	3-3-1	--	--	1-0-0	--	--	--	--	13-4-2	32
C. lugubris	--	--	--	--	1-1-3	--	--	--	--	--	--	--	--	--	--	--	--	1-1-3	80
C. melampygus	--	1-0-0	--	--	2-1-0	--	--	--	--	--	--	--	--	--	--	--	--	3-1-0	25
C. speciosus	--	--	--	--	--	--	--	--	--	--	--	--	--	--	11-0-0	--	--	11-0-0	0
Elagatis bipinnulatus	--	2-0-0	--	--	1-0-0	--	--	--	0-1-0	--	--	--	--	--	--	--	--	3-1-0	25
Seriola dumerili	2-0-1	15-0-3	5-1-0	2-0-0	2-0-0	2-0-0	8-0-1	12-1-1	--	--	2-0-0	6-0-0	5-0-0	19-0-0	2-0-1	1-0-0	--	83-2-7	10
Serranidae																			
Epinephelus quernus	2-1-0	6-0-0	11-1-0	0-0-3	4-3-1	3-0-0	16-2-5	4-0-0	4-0-0	3-0-2	6-0-0	7-0-0	7-1-1	18-0-0	--	7-2-0	2-0-0	100-10-12	18
Lutjanidae																			
Aprion virescens	1-1-0	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	1-1-0	50
Etelis carbunculus	--	--	--	--	--	--	--	2-0-0	--	--	--	--	--	2-0-1	--	3-2-0	--	7-2-1	30
E. marshi	--	--	2-0-0	--	4-0-0	--	15-0-0	8-1-0	4-0-0	--	7-0-0	--	8-1-0	17-3-0	--	--	--	65-5-0	7
Lutjanus kasmira	11-1-3	1-0-0	11-2-2	4-0-0	--	--	--	--	--	--	--	--	--	--	--	--	--	27-3-5	23
Pristipomoides filamentosus	4-0-0	51-6-3	27-10-1	--	7-0-0	--	17-1-0	17-1-0	6-0-0	1-0-0	2-0-0	1-0-0	--	0-1-0	--	--	--	133-19-4	15
P. sieboldii	--	4-0-0	2-0-0	1-0-0	--	1-0-0	1-0-0	--	1-0-0	--	--	--	--	3-1-0	--	--	--	13-1-0	7
P. zonatus	--	--	5-0-0	1-0-0	--	--	6-0-0	0-0-1	2-0-0	--	1-0-0	--	7-0-0	1-0-0	--	--	--	23-0-1	4
Kuhliidae																			
Kuhlia sandvicensis	--	--	--	--	--	--	--	--	--	--	--	--	--	--	20-12-15	--	--	20-12-15	57

[1] Unidentified bank #8 is located at lat. 26°17'N, long. 174°34'W.
[2] Unidentified bank #10 is located at lat. 28°58'N, long. 178°42'W.

exceptionally high rejection rates, although mention should be made of some members of the families Muraenidae and Acanthuridae that showed presence of ciguatoxin in varying degrees. These would include _Gymnothorax flavimarginatus_, _G. hepaticus_, _Acanthurus triostegus_, and _A. nigroris_.

In the kahala testing program, which began in April 1979, the number of fish tested until the end of December 1979 reached 926. Of these, 78 were borderline and 38 were positive in the RIA for a total rejection of 116 fish, or 13%. The rejection rate was relatively high in April 1979 when 63% of the kahala sampled were rejected but decreased in May to 24%, in June to 16%, then fluctuated between 3 and 6% until December when the rejection rate rose slightly to 10% (Table 3).

TABLE 3. THE NUMBER OF KAHALA SAMPLED WITH RIA, BY MONTH, THE NUMBER AND PERCENTAGE OF NEGATIVE, BORDERLINE, AND POSITIVE REACTIONS OBTAINED WITH THE RIA, AND THE TOTAL NUMBER AND PERCENTAGE OF FISH REJECTED PRIOR TO SALE

1979	Total Sampled	Negative	%	Borderline	%	Positive	%	Total Toxic	%
Apr.	52	19	37	10	19	23	44	33	63
May	122	93	76	21	17	8	7	29	24
June	174	147	84	24	14	3	2	27	16
July	153	149	97	4	3	0	0	4	3
Aug.	92	88	96	4	4	0	0	4	4
Sept.	73	71	97	2	3	0	0	2	3
Oct.	90	87	97	3	3	0	0	3	3
Nov.	65	61	94	1	1	3	5	4	6
Dec.	105	95	90	9	9	1	1	10	10
Total	926	810		78		38		116	

According to information provided by the fishing vessels, the area of capture of these kahala varied from as far south as the island of Hawaii northwestward to Raita Bank, a distance that spans 1,723 km. By geographical area, then, it appears that rejection was higher among kahala caught in the NWHI, principally from the area between Necker and Raita Bank, with the rejection level reaching 32% (Table 4). This was followed by a rejection rate of 29% among fish caught off the south coast of Oahu, and a rate of 24% among fish caught off Maui. Fishes caught at Penguin Bank also were rejected at a fairly high rate of 17%

Of particular interest is the relationship between fish size and toxicity. Prior to the start of the kahala sampling program, sale of fish weighing 9 kg (20 lb) or more was usually discouraged, because ciguatera outbreaks in the past allegedly implicated fish that were 9 kg or more in weight. Examination of our data showed that the size of kahala sampled between April and December 1979 varied from 0.57 to 45.4 kg (1.25 to 100.25 lb). Fish that were rejected fell in a range

TABLE 4. THE NUMBER OF KAHALA SAMPLED BY AREA AND THE NUMBER AND PERCENTAGE REJECTED BASED ON RESULTS OF RADIOIMMUNOASSAY

Area of Capture	Number Sampled	Number Rejected	% Rejected
Gardner Pinnacles	153	10	6
Necker-Raita Bank	132	42	32
Nihoa	1	0	0
Kauai	1	0	0
Oahu			
Southeast Coast	34	3	8
South Coast	77	22	29
North Coast	32	4	12
Molokai	5	0	0
Penguin Bank	151	26	17
Maui	17	4	24
Hawaii			
East Coast	192	12	6
South Coast	12	0	0
Unknown	119	9	7

from 0.79 to 26.88 kg (1.75 to 59.25 lb). Preliminary analysis showed that there is a low positive but significant correlation between toxicity level (tissue E) and fish size ($r = 0.101$; $df = 1,202$; $p < 0.01$).

DISCUSSION AND CONCLUSIONS

The preliminary results obtained from our NWHI samples show some agreement with those given by Sylvester et al. (1977). In the snapper-grouper complex of fishes in the Virgin Islands (includes snappers, groupers, grunts, jacks, porgies, triggerfishes, filefishes, and wrasses), the family Carangidae contains the most species prone to be ciguatoxic, followed by snappers and groupers. All are carnivores that attain relatively large sizes.

It is interesting to note that Pristipomoides filamentosus, considered to be a top-quality food fish and highly prized on the local fresh fish market, had a rejection rate of 15%. Yet, this species has never been implicated in any outbreaks among local citizens (Kubota, 1972).

According to Hokama et al. (1977), the RIA may produce "false positives." The binding of the anti-ciguatoxin-human serum albumin to non-toxic fish could be due to sensitivity of the test, to cross-reacting antigenic determinants, or to non-specific binding. There is also the possibility that most, if not all, marine fishes already contain low undetectable levels of ciguatera-like compounds. It should be emphasized, however, that although some "false positives" may occur as a result of the binding of anti-ciguatoxin-human serum albumin to non-toxic fish tissues, this should not detract from the value of the test. As demonstrated by Hokama et al. (1977), clinically documented toxic fishes

(fishes that have been actually implicated in ciguatera outbreaks) have given significantly higher c/m/g tissue than non-toxic fishes.

FUTURE RESEARCH NEEDS

Although NMFS field sampling included 47 species, most of which came from our offshore stations, it appears now that effort will need to be redirected to gather more data and samples from members of the families belonging to the snapper-grouper complex, all of which are commercially valuable in the Hawaiian Islands. With few exceptions, members of this complex showed varying rates of rejection with the RIA.

Processing of biological samples will continue so that the data base may be strengthened with respect to diet and sexual maturity and relationships of these variables to toxicity may be examined. Additional areal and seasonal coverage is also needed so that the distribution and seasonal occurrence of ciguatoxic fishes can be more clearly understood. Also planned are in-depth statistical analysis of the data collected from the NWHI fishes and of the data collected in the kahala testing program.

SUMMARY

From 1977 through 1979, NMFS and HDFG sampled 1,494 fish in the nearshore and offshore waters of the NWHI for ciguatera analysis. Of these, 244, or 16%, were rejected because the detected levels of ciguatoxin with RIA were considered hazardous to humans. Ciguatoxic fishes occurred throughout the NWHI and no apparent trend could be seen in their distribution. In the kahala sampling program, the data indicated a higher rate of rejection among fish caught between Nihoa and Raita Bank than among those caught in waters around the major islands. Of 926 kahala sampled between April and December 1979, 116 fish or 13% were rejected. Preliminary analysis suggests that there exists a low but statistically significant positive correlation between kahala size and toxicity.

Among the offshore species sampled by NMFS, those that belong to the snapper-grouper complex showed a relatively high degree of rejection. Nearshore species that showed high rejection rates included *Kuhlia sandvicensis* and *Cheilinus rhodochrous*.

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PRELIMINARY NOTES ON GROWTH AND TOXICITY OF THE DINOFLAGELLATE GAMBIERDISCUS TOXICUS FROM HAWAIIAN WATERS

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ABSTRACT

An investigation of the physical and chemical parameters which affect growth rates and toxin production in laboratory cultures of the Kaneohe Bay isolate of the toxigenic dinoflagellate *Gambierdiscus toxicus* Adachi and Fukuyo revealed that the organism is photoautotrophic. An optimum growth rate (1.2 divisions/day) occurred in f medium with 100% seawater. Media supplemented with aqueous extracts of a mixture of macroalgae (common substrates for *G. toxicus*) enhanced yields (cells/ml) 20-fold that of control cultures at peak population density. *Acanthophora spicifera* (Vahl) Boergesen and *Sargassum polyphyllum* J. Agardh gave greatest enhancement of the ten species tested.

Mouse intraperitoneal injections of *G. toxicus* extracts revealed three toxins, tentatively identified as ciguatoxin, maitotoxin, and unidentified "acetone-soluble" toxin, based on molecular polarity and characteristic symptomology. The levels of these toxins varied greatly in the seven cultures tested.

ciguatera
toxin dinoflagellate
nutrition

INTRODUCTION

Recently the dinoflagellate *Gambierdiscus toxicus* Adachi and Fukuyo has been implicated as the source of ciguatoxin in the coral reef ecosystems (Yasumoto et al., 1977a, 1979a). This microscopic unicellular alga (to 83 μ in diameter) grows primarily as an epiphyte on certain brown and red seaweeds on the reef flats, with population densities varying greatly within short distances (Yasumoto et al., 1979b). In 1975, detritus samples collected from a ciguatera-endemic area of the Gambier Islands had toxicities proportional to the number of *G. toxicus* cells. Compounds identical to ciguatoxin and maitotoxin (found in tropical surgeonfishes) in their known chemical and pharmacological characteristics were extracted from semipurified samples of the alga (Yasumoto et al., 1977a, 1979a, 1979b). However, when this species was cultured in the laboratory, maitotoxin was produced in quantity but "meager amounts of ciguatoxin, if any" were found (Yasumoto et al., 1979a).

The same species (G. toxicus) was found in 1978 in the water tables of the Hawaii Institute of Marine Biology (HIMB), Kaneohe Bay, and subsequently in scattered locations on a few reefs around Oahu. A small bloom occurred at Pokai Bay in August 1978, coincident with an outbreak of ciguatera in fish from that area. Gambierdiscus toxicus has also been identified in the Caribbean (Taylor, 1979).

The factors controlling toxin production, growth rate, and yields of laboratory cultures of G. toxicus, HIMB isolate, were investigated in order to determine factors triggering massive toxic blooms of the dinoflagellate in the wild.

METHODS

Growth studies were performed on clones of G. toxicus from a Kaneohe Bay population originally isolated in August 1978 and which were routinely cultured at 25° to 27°C in polystyrene petri dishes (Falcon 1007) with 8 ml media under Vita-lite fluorescent irradiance of 1,500 $\mu W/cm^2$ for 16 hrs/day. Since mucilage exudation and clumping precluded electronic particle counting, growth rates and cell yields were determined by direct counting of all cells in each dish in replicates of eight or more per variable. Additionally, for investigating conditions which would provide the greatest yields of toxin, cultures were grown in 3.5 and 12-gallon Pyrex carboys containing 10 to 40 ℓ of media, at irradiance levels of 1,700 $\mu W/cm^2$ from 40 W Vita-lite fluorescent lights 16 hrs/day at 25° to 28°C and with air bubbling at a rate not greater than 1 ℓ/min.

Culture media included f (Guillard and Ryther, 1962) and ESM (Provasoli, 1964). Media were sterilized by autoclaving and/or by filtration with 0.22 μMillipore and 0.2 μNuclepore filters. A range of 70, 80, 90, and 100% seawater was prepared by addition of distilled water to Kaneohe Bay seawater with the salinity of about 35 °/₀₀. NaH_2PO_4 and sodium beta glycerophosphate were compared as phosphate sources, and NH_3 and $NaNO_3$ as nitrogen sources.

Seaweed extract supplements

Fresh macroalgae were macerated in a blender, autoclaved for 15 minutes, and filtered through 0.22 μMillipore GS filters. Extracts were added to experimental cultures in f media at 0.1% by volume. First, a mixture of phaeophyte and rhodophyte extracts, predominantly Acanthophora spicifera (Vahl) Boergesen and Sargassum polyphyllum J. Agardh, was added to cultures of different clones of the Kaneohe Bay population of G. toxicus. Next, the experiment was repeated using clone 17, the fastest growing control clone (Figure 1). In a third experiment, separate extracts

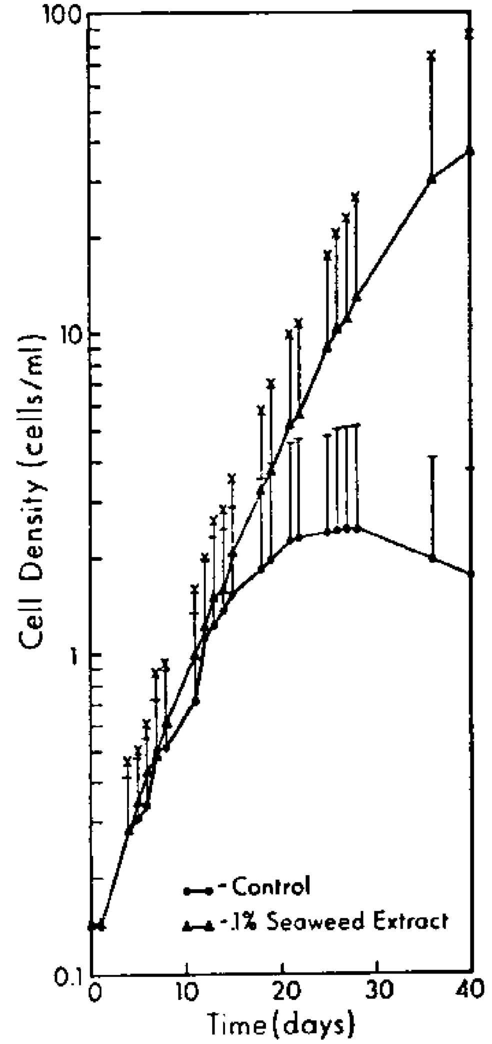

Figure 1. Growth of G. toxicus in f medium unsupplemented and with seaweed extract ("S")

of 10 species of macroalgae (Table 1) were added to cultures of the same clone. In subsequent experiments, media were routinely supplemented with a mixture of the most stimulating extracts (those from the two algae, Acanthopora spicifera and Sargassum polyphyllum). This media supplement (0.1% by volume) was designated "S." Soil extract (Pringsheim, 1946) was compared with "S" (seaweed extract) for enhancement of peak cell density. Heterotrophic growth was tested for using 5% seaweed extract and sodium beta glycerophosphate in f medium in the dark for 3 months.

TABLE 1. THE EFFECTS OF EXTRACTS OF VARIOUS MACROALGAE ON YIELDS OF *G. TOXICUS* CULTURES

	Alga extracted and used as media supplement (f medium)	Peak Population Density Ratio of Extract : Control
1.	*Acanthophora spicifera* (Vahl) Boergesen	1.96
2.	*Sargassum polyphyllum* J. Agardh	1.96
3.	*Turbinaria ornata* (Turner) J. Agardh	1.48
4.	*Gracilaria* sp.	1.30
5.	*Sphacelaria furcigera* Kutzing	1.22
6.	*Laurencia succisa* Cribb	1.09
7.	*Lyngbya* sp.	1.04
8.	*Pseudobryopsis* sp.	0.91
9.	*Polysiphonia* sp.	0.87
10.	*Wrangelia penicillata* C. Agardh	0.39
11.	Control (no seaweed supplement)	1.00

Bacterial populations in unialgal cultures were depressed by addition of a mixture of sodium benzylpenicillin (1.095 μM) and streptomycin sulfate (0.137 μM) to f medium. In 10 ℓ cultures, the medium and antibiotics were exchanged at regular intervals (7 to 10 days).

Toxicity

Toxin was tested for in either heat-dried (102°C for 24 hours) or lyophilized cells of *G. toxicus* cultures. Cells were extracted by sonication in acetone, followed by refluxing of the residue in methanol for 1 hour, twice. The methanol and acetone extracts were combined, and solvent was evaporated. The residue was partitioned in ether/water (4.1, v/v), and the ether and water fractions treated separately. The ether fraction was evaporated to dryness and the residue re-dissolved in hexane/80% aqueous methanol (1/1, v/v). The methanol fraction was evaporated, weighed, and prepared for mouse-toxicity tests. This was designated the "ciguatoxin fraction."[1] The aqueous fraction from the ether/water partitioning was extracted three times with water-saturated butanol, and the aqueous phase discarded. The butanol fraction was evaporated, and the residue dissolved in acetone ("acetone-soluble toxin") and methanol (acetone-insoluble toxin, or maitotoxin). Solvents from the extracts were evaporated under nitrogen, the samples weighed, and a portion dissolved in 30 μℓ methanol and 0.3 ml 1% aqueous Tween solution. The three extracts were injected into mice (28 g or lighter) intraperitoneally, and the toxicity of each sample was monitored by symptoms and time of death.

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[1] The "ciguatoxin fraction" behaved like ciguatoxin in the extractive procedure and elicited the symptomatology characteristic of ciguatoxin when injected into mice; however, as the small amounts of this fraction obtained precluded the use of the definitive test on the Na+ ion flux in excitable membranes (Rayner, 1972), its identification with ciguatoxin must be regarded as tentative.

RESULTS

Nutrition

In the mostly inorganic (except for vitamins and EDTA) f medium, G. toxicus is still growing after one year and clone 17 divided at an average rate of 0.12 divisions/day for 27 days, indicating that the organism is photoautotrophic. Full-strength seawater (in f medium) gave the best yields (cell/ml) vs. culture media with lower salinity levels. Gambierdiscus toxicus was able to use either sodium beta glycerophosphate or NaH_2PO_4 as a phosphate source, although bacterial growth was promoted in the organic phosphate supplemented cultures. Cultures grew best with $NaNO_3$ (1,760 µM) as a nitrogen source. There was no growth in media supplemented with greater than 200 µM NH_4CL and less than three divisions at levels below that which may be the result of utilization of intracellular reserves of nitrogen. No heterotrophic growth was detected in the dark cultures.

Treatment of large cultures with the synergistic mixture of penicillin and streptomycin (Plotz and Davis, 1962) resulted in apparently bacteria-free unialgal cultures of G. toxicus, but in 10 ℓ cultures fungal contamination occurred.

Seaweed extract

Cultures with 0.1% mixed seaweed extract, designated "S," averaged 28 times the yield of control cultures at peak population density (cells/ml). Upon repeat with the fastest growing control clone, a yield of 20 times control values was obtained, whereas soil extract-supplemented cultures reached populations only 0.2 as dense as control populations. In addition, 10 macroalgal species were extracted and tested individually for effect on growth of G. toxicus cultures (Table 1). The addition of Acanthophora spicifera and Sargassum polyphyllus extracts each enhanced the yield of experimental cultures 1.96 times over that of control cultures; the Turbinaria ornata extract enhanced the yield of experimental cultures 1.48 times that of the control (Table 1). Current investigations are focused on the chemical basis for the stimulatory effect.

The fastest growth rates recorded to date were at 25° to 27°C under Vita-lites, in f medium, clone 16 at 1.2 divisions per day for 2 days, and in f medium + "S," clone 29 at 0.55 division per day for 8 days.

Larger cultures (1 to 30 ℓ) of G. toxicus gave yields ranging from 0.02 to 0.09 g dry weight/liter (Table 2). The best yields were from cultures grown in Fernbach flasks (1 ℓ) using f medium + "S" (Figure 1).

Toxicity

Table 2 shows that three types of toxins based on polarity and mice symptomatology were detected in the seven large cultures of G. toxicus tested to date. The levels of the three toxins--ciguatoxin, maitotoxin, and an unidentified acetone-soluble toxin--varied widely among the cultures, from undetectable to lethal at a low dose. Upon injection with

TABLE 2. TOXICITY OF G. TOXICUS CULTURES

Volume	Dry Weight cells (g)	Yield Cells (g/L)	Media	Contaminants	Toxicity* (Dose [µg/g]; Death time [hrs])		
					Ciguatoxin	Acetone-soluble Toxin	Maitotoxin
3L	0.29	.09	ESM	bacteria, flagellates	55.6; L; 2.4	42.2; NL	102; L; 0.1
15L	1.4	.09	f	bacteria, 5µ green coccoid alga	407; L; 3.5-6	75.8; L; 7-20	259; NL-MS
15L	1.03	.07	f	bacteria, chrysophyte(50%)	141.8; NL-MS	103; L; 0.6	520; NL
30L	0.698	.02	ESM	bacteria	431.4; NL	332.8; NL	1248; NL
10L	0.313	.03	ESM+S	bacteria	440.6; NL	259.6; NL, MS	510.3; NL, MS
10L	0.722	.07	ESM+S + antibiotics	fungi	4803.9; NL	147.3; NL	2390.4; NL, PS
34L	1.348	.04	f + S	bacteria	4091; NL	191.6; NL	2504.4; L; 14-18

*L = lethal
NL = not lethal

MS = mild symptoms
PS = pronounced symptoms

extracts purified from cultures 1 and 2, the test mice displayed sluggishness, diarrhea, hypersalivation, dyspnea (hard breathing and hyperventilation), then severe spasmic and violent convulsions followed by death at doses of 55.6 to 407 μg/g. These symptoms were indistinguishable from those reported for ciguatoxin from surgeonfish and turban shells (Yasumoto et al., 1976; Yasumoto and Kanno, 1976; Scheuer et al., 1967). Mild symptoms due to ciguatoxin, noted in culture 3 extracts, at 141.8 μg/g included sluggishness, a mucous covering over the eyes, and mild paralysis in the hind limbs. For maitotoxin (from cultures 1 and 7), from doses of 102 and 2,504.4 μg/g, death in the mice was preceded by rapid paralysis which lasted for a long period, then less violent convulsions than those caused by ciguatoxin. These symptoms were similar to those reported for maitotoxin purified from surgeonfish, Ctenochaetus striatus (Yasumoto et al., 1976). Pronounced matitotoxin symptoms (in culture 6, at 2,390.4 μg/g) were paralysis of hind limbs, spasms, a rapid heart beat, and loss of balance (wobbly walking). Mild symptoms of maitotoxin (in cultures 2 and 5, at 259 and 510.3 μg/g) included swollen eyes and sluggishness. The "acetone-soluble" toxin from aqueous extracts of cultures 2 and 3, at 75.8 and 103 μg/g gave symptoms of mild convulsions with very rapid paralysis and death. Mild symptoms of this toxin, noted in culture 5, included sluggishness and loss of aggressive behavior.

DISCUSSION

In these preliminary studies, we are identifying parameters affecting growth rate and total biomass in cultures of G. toxicus, which will be helpful in producing dense mass cultures for chemical and pharmacological studies on ciguatoxin and other associated toxins involved in ciguatera poisoning. Further, the factors underlying the sporadic distribution of G. toxicus populations on macroalgae and coral rubble in coral reef systems may now be pursued more rapidly with the culture information available from this study.

Relevant to such considerations are the effects of salinity, nutrient concentrations, and seaweed extract-supplements on growth rates and yields of G. toxicus in laboratory culture. Nordli (1957) also found stimulation of marine dinoflagellate cultures when algal extracts were added to the growth medium. In the present study the spectacular stimulation (as high as 28-fold) of yield of G. toxicus by supplementation of media with aqueous extracts of macrophytes such as Acanthophora, Sargassum, and Turbinaria (Figure 1 and Table 1) is of particular interest since these algae are selected as substrates by the dinoflagellate. It has been reported that G. toxicus cells are chemotactically attracted to several of these macrophytes (Yasumoto, 1979). The chemical factors involved in this growth stimulation by aqueous seaweed extracts are not known. One component, humic acids, which act as effective chelating agents for trace metals such as iron, has been shown to increase growth rate and yield of marine dinoflagellates (Prakash and Rashid, 1968). Experiments to determine which fractions of the seaweed extract are nutritionally beneficial are now in progress.

The culture studies in f medium indicate that G. toxicus is photoautotrophic. This result emphasizes the importance of measuring the influence of environmental parameters on the photosynthetic capacities of this dinoflagellate.

Production of axenic culture is important for verification of G. toxicus as the source of ciguatoxin. The present study has demonstrated that the alga can tolerate levels of antibiotics which will depress bacterial populations, but the contamination by fungi must now be eliminated either chemically, using anti-fungal agents, or by washing the clones.

Toxin levels and yields of mass cultures of G. toxicus indicate that, while reasonable amounts of cells can be cultured, toxin levels vary greatly apparently dependent upon culture conditions not yet defined, so amounts and type of toxin produced in a given volume are still unpredictable. The presence of a new toxin in addition to ciguatoxin and maitotoxin in G. toxicus (Table 2) adds further complexity to the problem. The "acetone-soluble" toxin found in G. toxicus cultures resembles an "acetone-soluble" toxin which co-occurred with maitotoxin and ciguatoxin in the gut contents of a parrotfish, Scarus gibbus (Yasumoto et al., 1977b), and in coral rubble detritus (Yasumoto et al., 1979b). Both the toxin from the parrotfish gut and that from the dinoflagellate produced strong paralytic actions and rapid death in the test mice. Yasumoto et al. (1977b) assumed this "newly found toxin" to be a basic compound of small molecular size, differing from scaritoxin which was not found in the parrotfish gut but is dominant in the flesh of that organism. These findings offer further support for the speculation that ciguatera poisoning from fishes may be due to several toxins which are possibly related biosynthetically (Banner, 1976; Scheuer et al., 1967). The factors controlling the biosynthesis of toxins in G. toxicus cultures are currently the focus of research.

FUTURE RESEARCH NEEDS

Since this is a new project, our research has just begun. We plan to characterize more completely the optimum conditions for G. toxicus, in Aquil+ medium, including factors such as pH, salinity, temperature, vitamin and trace metal requirements, and the growth-stimulating effect of aqueous seaweed extracts. The possibility that G. toxicus may be facultatively heterotrophic (either saprophytic and phagocytic) will be investigated. Attempts to follow gamete fusion by nitrate depletion or reduced salinity as in other dinoflagellates will be made. The parameters affecting photosynthetic rates and pigments in G. toxicus will be studied. Factors controlling ciguatoxin, maitotoxin, and acetone-soluble toxin production will be investigated. For verification that this dinoflagellate is the organism responsible for biosynthesis of these toxins, a clone of G. toxicus (currently in culture) will be mass-cultured under axenic conditions and tested for presence of all three toxins. Field studies will be conducted on G. toxicus populations in the Northwestern Hawaiian Islands in conjunction with monitoring of ciguateric outbreaks.

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THE STATUS OF REEF STUDIES IN THE HAWAIIAN ARCHIPELAGO

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ABSTRACT

Reef benthic ecology is of importance in the overall investigation of resources in the Hawaiian Archipelago because of habitat and trophic interdependencies. A major goal of this study is to discover interrelationships between reef communities and species of ecological or commercial importance. Preliminary findings support the following conclusions.

1. Corals and coral reefs exhibit declining trends in growth and development northwestward within the Hawaiian Archipelago.

2. Within the Hawaiian Archipelago, a threshold for atoll formation, herein termed a "Darwin Point," exists near 29°N latitude. Geophysical evidence suggests the Darwin Point has existed within 2° of this latitude for 20 million years.

3. In general, species do not gradually drop out as the Darwin Point is approached. The formation of Hawaiian reef ecosystems appears to be an all or none phenomenon.

4. Differences in reef coral community structure between islands throughout the Archipelago are most likely due to variability in physical conditions and successional age. These differences may account for dissimilarities in species abundance patterns at higher trophic levels and therefore may be useful indices for resource management.

benthic ecology
Hawaii
Darwin Point
coral growth
community structure
succession

INTRODUCTION

The importance of coral reefs to the geology and biology of the Hawaiian Archipelago is hard to overestimate. Were it not for the ability of coral reefs to grow upward and keep pace with rising sea level over millenia, many atolls, reefs, and shallow banks at the northwestern end of the chain would have drowned long ago due to gradual subsidence of their foundations, erosional effects, and eustatic changes in sea level (Sterns, 1966; Schlanger and Gillett, 1976). Indeed, were it not for coral growth, the Hawaiian Archipelago would presently be approximately 1,200 km shorter in legnth and consist of 5 less islands and about 23 fewer shallow banks and shoals.

Hermatypic corals are usually the most prominent and conspicuous members of the reef; however, several studies have shown that limestone production by coralline algae, mollusks, echinoderms and foraminifera are of the same order of magnitude as corals (Chave et al., 1972; Smith and Kinsey, 1976). However, for reef development, only the limestone which is permanently retained by the reef (net production) is important. In this context, corals provide the basic framework and control the accumulation of sediments in, on, and around coral reefs (Wells, 1957; Hoffmeister and Multer, 1964). The growth of corals is therefore fundamental to understanding reef development.

Corals and coral reefs are also important because they provide the physical habitat, shelter, and food for most species that make up reef ecosystems. In the Northwestern Hawaiian Islands some of the more important species which occur within or are partially dependent upon reef ecosystems include spiny lobsters, reef fishes, monk seals, green turtles, and seabirds.

Hence, corals are of importance to reef resources on two scales; a macro-scale in which corals play a structural role in the development and maintenance of reefs and atolls; and a micro-scale in which corals provide the shelter and food requirements of species which inhabit the reef. Accordingly, the major emphasis of this research has been placed on reef development and coral community structure throughout the archipelago. This research design is consistent with the major goal of the tripartite program, namely, to assess the marine resources of the NWHI and develop rational management plans which encompass the utilization of some species without jeopardizing the preservation of others. The outline of this paper is: (1) to review original objectives; (2) to describe progress to date; and (3) to present future research needs.

OBJECTIVES

The major objective of this research is to "characterize" coral reef benthic ecosystems throughout the Hawaiian Archipelago. More specifically, our objectives are:

1. To analyze the species composition and community structure of reef ecosystems at representative stations off all major islands in the Hawaiian Archipelago

2. To distinguish qualitatively various physiographic regions (habitats) that comprise Hawaiian reefs and to estimate their areal coverage at each major island, reef, or shoal in the archipelago

3. To measure the maximum potential growth of corals and reef development in terms of linear accretion and calcium carbonate production off all major islands

4. To determine qualitative relationships between benthic reef communities and species of commercial and ecological importance throughout the archipelago

5. To quantify interrelationships between the benthos and species of commercial and ecological importance at French Frigate Shoals by increasing sampling effort and incorporating data sets of other research projects into an ecosystem model (see paper by Polovina and Tagami)

CORAL GROWTH AND REEF DEVELOPMENT

Methods

In the past, a variety of measures have been used to measure calcium carbonate production by corals and other reef organisms. Chave et al. (1972) have distinguished between potential, gross, and net production. Potential production refers to the calcification rate of an individual organism or colony, gross production to the calcification rate of the community (the product of potential production and the proportion of reef covered by calcifying organisms), and net production to the carbonate retention rate of the reef.

Three basic approaches have been used to measure coral and reef growth: chemical, stratigraphic, and biological (Chave et al., 1972). The chemical approach measures the depletion of alkalinity in the water overlying a reef in order to determine the net $CaCO_3$ precipitation (Smith, 1973). The alkalinity depletion method produces a measure of the amount of calcium carbonate extracted from the water column. It produces a value for carbonate production somewhere between gross and net production depending on the amount of precipitate actually retained by the reef. The stratigraphic approach involves measuring the vertical accumulation of limestone in cores of reef terraces together with obtaining estimates of their ages to determine rates of net reef growth (Emery et al., 1954). The stratigraphic method gives a true measure of net production, i.e., the amount of calcium carbonate permanently retained by the reef. The biological approach utilizes actual measurements of growth rates of individual calcifying organisms. These growth rates can be obtained in situ by repeated measurements of colony size over known time intervals. Live corals may also be exposed to alizarin red stain which is incorporated into the skeletal matrix and serves as a mark from which to measure linear growth after the coral is sacrificed and sectioned (Lamberts, 1974). A third biological method of determining reef growth involves measuring bands of varying bulk density deposited in the coral skeleton. Knutson et al. (1972) have shown that band pairs of high and low density normal to the axis of growth are deposited annually. Hence, band pairs provide a long-term growth history for coral colonies retrospectively.

The biological methods described above are measures of rates of potential production and when corrected for the areal proportion of calcifying reef cover provide rates of gross production. The determination of gross production used in this study is modified so that the growth of a single species, Porites lobata, is assumed to be representative of all corals present. This assumption appears to be valid since Maragos (1972) found that the growth in mean solid radius of corals of substantially different growth form is very close to the radial growth of hemispherical or massive colonies like P. lobata. Furthermore, the growth rate of P. lobata is intermediate compared to other massive corals (Buddemeier et al., 1974).

At each of 14 major islands or reefs spanning the length of the archipelago, ten colonies of P. lobata were collected from 10 m depth from an equivalent physiographic locality (southwest exposure). In the belt of northeast trades in the tropical north Pacific, the most well developed offshore reefs occur off southwestern island exposures (Grigg and Maragos, 1974; Dana, 1979). Growth studies were conducted in the most optimal seaward areas off each island in order to obtain measures of maximum potential reef accretion. Values thus obtained should represent maximum potential rates with respect to upward growth necessary to keep pace with changes in sea level.

In the laboratory, colonies were cross-sectioned along axes of maximum growth. The next step was to x-ray the cross sections (4 mm thick) of coral. Estimates of mean annual linear growth were obtained for each colony from the x-radiographs by measuring the widths of all density band pairs that could be discerned (Buddemeier, 1974) (See Figure 1-A).

Colony mass accretion was calculated as the product of mean linear growth rate and mean colony density (Figure 1, part C). Reef accretion was estimated by multiplying the mean colony mass accretion at each island by the proportion of total coral cover at that island determined from transect data (Figure 2, part B). Since linear measurements were made along the axes of maximum growth and measures of coral cover were taken from optimal areas (southwest exposures), our estimates of reef accretion rates should be considered estimates of maximum potential gross production.

Results

The results illustrate several striking effects. First, a clear and well-defined pattern of declining growth as a function of latitude exists within the archipelago (Figure 1, parts A, B, and C; and Figure 2, parts A and B). At the southern end of the chain, the rate for individual

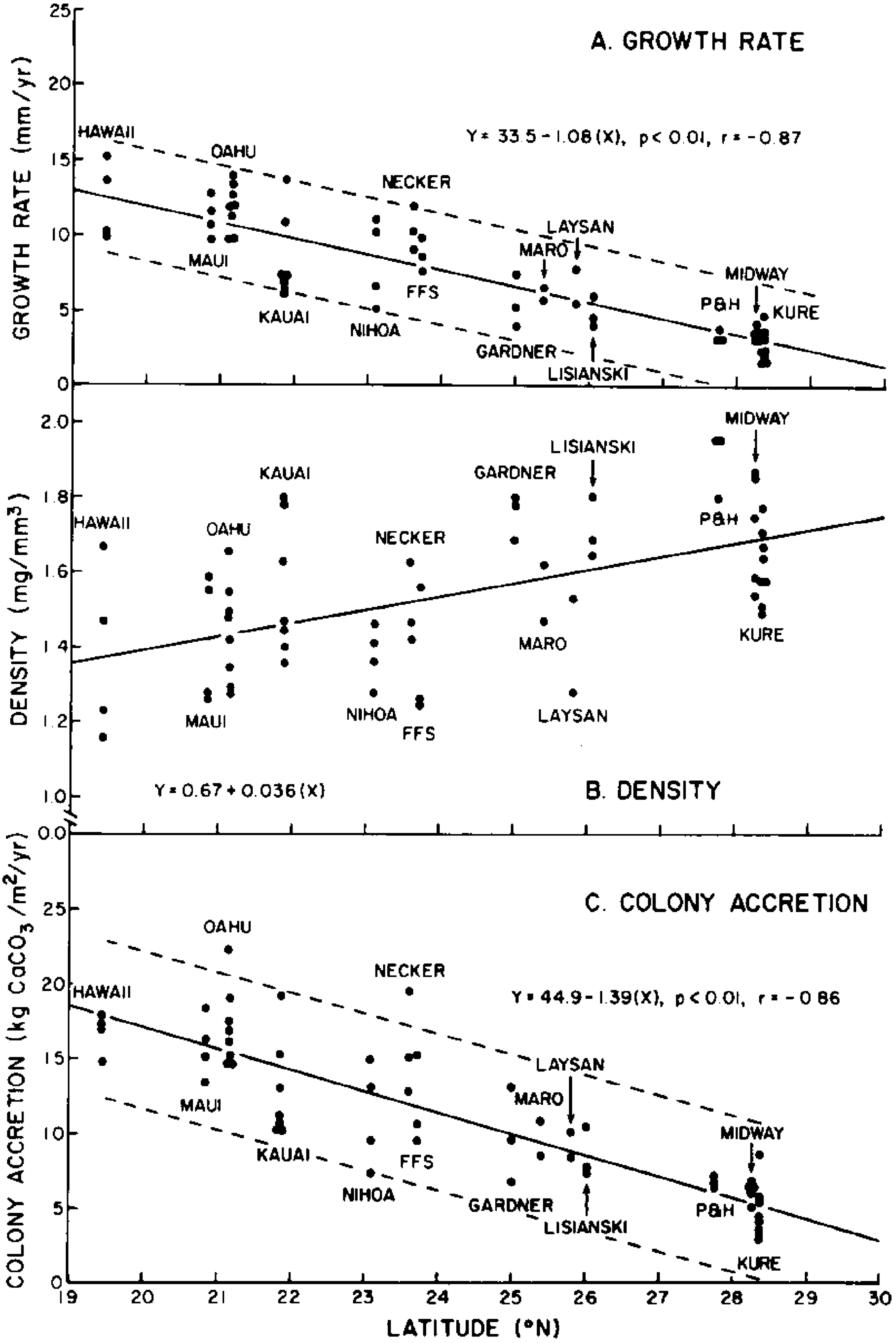

Figure 1. Growth rate (A), density (B), and colony accretion (C) of *P. lobata* in the Hawaiian Archipelago

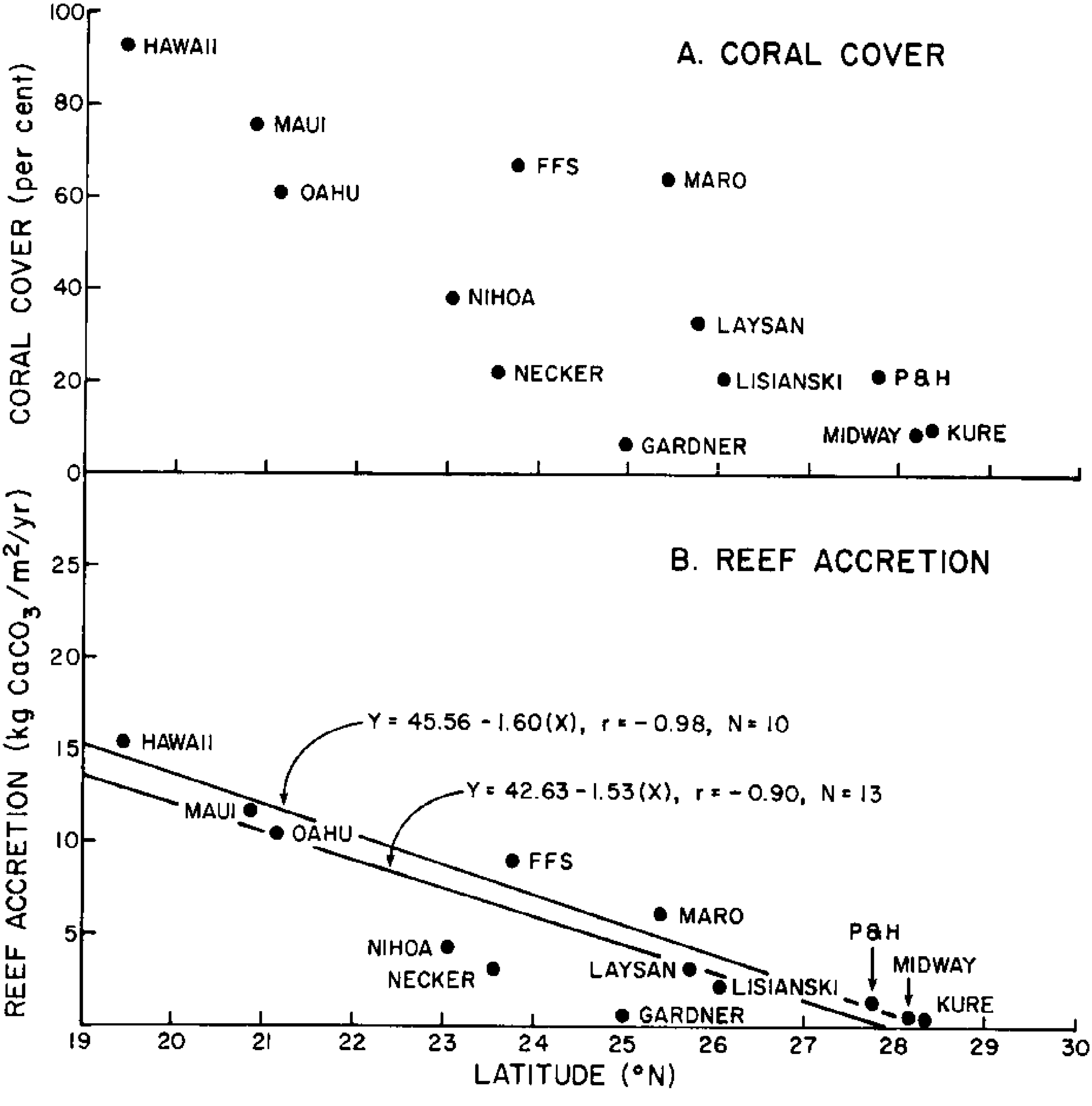

Figure 2. Mean coral cover (A) and reef accretion (B) of seaward reef stations at 10 meters depth off all major Hawaiian islands. In part B, the upper regression line was calculated without the data for Nihoa, Necker, and Gardner Pinnacles.

colonies of P. lobata is about 12 mm per year compared to 3 mm per year at Kure Atoll, the northwestern-most extreme. In terms of colony accretion of calcium carbonate, equivalent rates are about 18 and 5 kg $CaCO_3/m^2/yr$. For reef accretion (maximum potential gross production) which takes into account coral cover, these rates convert to 14 and 0.5 kg $CaCO_3/m^2/yr$ (Figure 2, part B). The average value for reef accretion in the archipelago is 5.23 kg $CaCO_3/m^2/yr$ and would occur at a latitude of 25.5°N (Figure 2, part B) between Gardner Pinnacles and Laysan Island. The values for reef accretion at the southeastern end of the Hawaiian Archipelago (15 $kg/m^2/yr$ or about 11 mm/yr) compare favorably with data for Panamanian reefs (7.5 to 10.4 mm/yr) collected by Glynn and Macintyre (1977) who measured growth in situ (biological method).

Smith and Kinsey (1976) using the alkalinity method to measure $CaCO_3$ production, present data from a variety of environments which suggest that a consistent value closer to 4 kg $CaCO_3/m^2/yr$ is representative for most coral reefs in the world. Not only is our average value higher than this but our data show a strong relationship with latitude. The difference in latitudinal effect may be explained by the fact that Smith and Kinsey report data for shallow seaward reef flats between 23°S and 11°N whereas our Hawaiian data were collected between 19°N and 28°N. In other words a "latitude effect" may not be apparent except near the extremes of reef growth. It is likely that water temperature and incident solar radiation are the variables responsible for the latitude effect. Future research is planned to sort out these relationships.

Looking at absolute values of $CaCO_3$ production, the Hawaiian data at the southeastern end of the chain are three to four times the 4.0 kg figure reported by Smith and Kinsey. Part of this difference may be due to the way in which growth of P. lobata was measured, i.e., along axes of maximum increase. Also, values for coral cover for all islands were taken from transects located in zones optimal for reef development. As pointed out above, the selection of optimal environments in which both coral growth and coral cover were measured produced estimates of reef development that might best be considered estimates of maximum potential gross production. The effect of this sampling design is especially pronounced at the southeastern end of the chain where the combination of physical factors associated with the leeward sides of high islands, particularly shelter from wave stress, result in areas extremely favorable for coral growth and high coral cover. Hence, our estimates of reef development (gross production) are not representative of mean values for entire high island reefs. Rather, they represent the maximum potential gross production for reefs in the high islands. This probably accounts for most of the discrepancy between our data at the southeastern end of the chain and values reported by Smith and Kinsey (1976).

At the northwestern end of the chain the discrepancy between our data and Smith and Kinsey's is in the other direction; i.e., our values are considerably lower. In this case, the effect of sampling optimal zones offshore produces little or no upward bias because seaward reefs on all sides of the islands are nearly homogenous presumably because differences in exposure to sea and swell are small. The data for the NWHI are therefore more representative than the data for the high islands.

Nevertheless because the most optimal areas were selected in the northwestern islands, the data for these islands represent the maximum potential for growth of seaward reefs.

In the NWHI the potential for coral and reef growth may be greater in the lagoons than on seaward reefs, since most of the lagoonal areas are sheltered from wave stress and water temperature is usually slightly higher than in nearshore areas (personal observations). Growth rates of Hawaiian corals are known to be strongly affected by temperature and the optimum for three species tested is near 26°C (Jokiel and Coles, 1977). The monthly mean temperature at Midway and Kure is generally below 26°C during nine months of the year (Robinson, 1976). In spite of the possibility that lagoon areas may support more active coral growth than seaward reefs, growth studies were conducted on seaward reefs because many islands, banks, and shoals in the archipelago lack lagoons. Furthermore, before lagoons can develop, seaward reefs must be capable of keeping pace with sea level changes. Therefore, in terms of understanding the factors which control atoll formation, the development of seaward reefs is of first order importance.

The estimated rates of reef accretion at Midway and Kure atolls are about 0.5 $kg/m^2/yr$. This rate is equivalent to an upward accretion rate of 0.3 mm/yr. Since Midway and Kure atolls are the last islands in the archipelago and are "followed" to the northwest by a series of drowned seamounts and guyots, the values of reef accretion for these atolls may represent a threshold value for atoll formation in the Hawaiian region. A threshold for atoll formation would be the carbonate production necessary to just offset losses due to mechanical, chemical, biological, and biochemical erosion plus the effects of eustatic changes in sea level and subsidence. The term Darwin Point is suggested as a name for such a threshold. This term seems appropriate in view of Charles Darwin's original theory of atoll formation, i.e., the upward growth of corals on subsiding foundations (Darwin, 1842).

An upward accretion rate of 0.3 mm/yr at Midway and Kure atolls is sufficient to offset known rates of subsidence (0.04 mm/yr) for this position of the Hawaiian Archipelago (Davies et al., 1972) but is somewhat less than rates of sea level change during the Pleistocene (1 mm/yr during the last 5,000 yrs, Chave et al., 1972). The 0.3 mm/yr rate is also somewhat less than erosion rates (1 mm/yr) which have been measured for at least intertidal limestones (Tracy and Ladd, 1974). The differences (0.3 mm gain versus 1 to 2 mm loss) may reflect carbonate production by other taxa such as coralline algae, mollusks, bryozoa, and foraminifera in the Hawaiian Archipelago.

Recent studies in plate tectonics have shown that the Hawaiian Islands are gradually subsiding and drifting northwestward on the Pacific plate (Van Andel, 1974; Schlanger and Gillett, 1976). As islands "pass" the latitude of the Darwin Point, coral growth and other sources of limestone production are apparently unable to keep pace with changes in sea level causing the islands to drown. Indeed, seismic reflection profiles show that the principal guyots in the Emperor Seamounts are capped by coral reefs (Greene et al., 1978). The processes of island formation, plate tectonic movement, subsidence, and atoll formation are schematically represented in Figure 3. The Darwin Point is shown at its present latitude of 28.4°N.

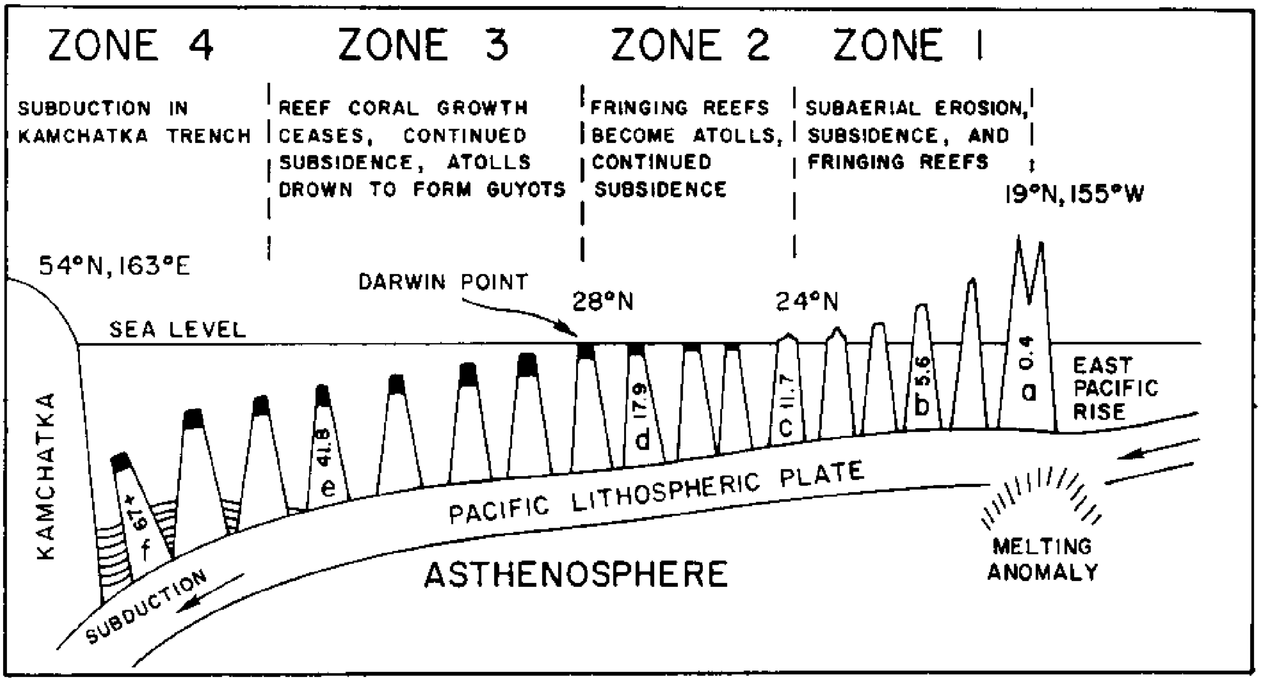

Figure 3. Schematic diagram showing evolutionary history of the Hawaiian Archipelago. The threshold for atoll formation of "Darwin Point" separates zones 2 and 3.

The latitude of the Darwin Point in the Hawaiian Archipelago appears to have been relatively invariant for millions of years. Taking into account horizontal movement of the Pacific plate, a reconstruction of the positions in the chain of the Emperor Seamounts when they sank below the surface of the sea shows that "drowning" has occurred consistently at latitudes between 27° and 31°N over the past 20 million years (Rotondo, 1979).

Our present and continuing work on this subject is centered on revealing the causative factors "contained" in latitude which control the growth of corals. Temperatures and light are the most likely candidates (Wells, 1957; Goreau and Goreau, 1959; Houck et al., 1977). The final step for this portion of the study is to characterize the physical conditions which control the development of coral reefs and their associated resources.

CORAL COMMUNITY STRUCTURE

Methods

A marine community is collectively all the organisms inhabiting a common environment, which interact with each other and with their inanimate surroundings (Pennak, 1964). The parameters used in this study to quantitatively characterize macroepibenthic coelenterate communities are species occurrence, species diversity (Shannon-Weaver Index), rank order of species abundance, and the degree of species dominance or conversely, equitability. Measures of these parameters are based on 25-meter long transects and qualitative surveys conducted at a variety of stations off each of the 14 major islands in the archipelago. At each station a transect line was placed on the bottom parallel to the bottom contour (isobath) at depths between 5 and 15 meters. A rectangular quadrat (0.67 m^2) with a camera mounted on a tripod was then placed over contiguous meter sections of the line. Data were recorded on film and by a second diver who recorded visual estimates of percentage of cover for each species present. In addition, at each station about 5,000 m^2 were surveyed in order to compile a more complete species list and more representative estimates of abundance. In the future, we plan to use existing charts and aerial photographs to fully characterize the areal coverage for a variety of habitats (seaward reefs, reef crests, patch reefs, and lagoons). Station data have been collected from all major islands, ranging between 2 and 8 stations per island. Plans call for collecting at least twice this amount of data.

Results

While there are no large differences in coral community structure within the Hawaiian Archipelago, there are small but rather significant variations. All offshore reef structures in the archipelago are morphologically similar in that they are characterized by fringing reef platforms. The morphology of patch reefs within lagoonal habitats are also similar throughout the chain. In terms of changes in species, there is no discernible significant trend from the southeast to the northwest. A priori, it was expected that species would gradually "drop out" progressively to the northwest as the average annual temperature gradually decreased. Instead, the largest number of coral species and highest coral species diversity occurred midway in the chain at French Frigate Shoals and Maro Reef (Figures 4 and 5). Most species of coral are present from one end of the archipelago to the other. It therefore appears that the development of reefs and reef ecosystems within the Hawaiian Archipelago is an all or none phenomenon. Preliminary data for algae and other invertebrates indicate that other reef taxa have similar patterns of distribution.

The differences in reef community structure that do exist within the archipelago are primarily related to the manner in which species abundance is organized and secondarily to differences that suggest different patterns of recruitment, i.e., sources of colonization. Considering the organization of coral species first, the most obvious difference

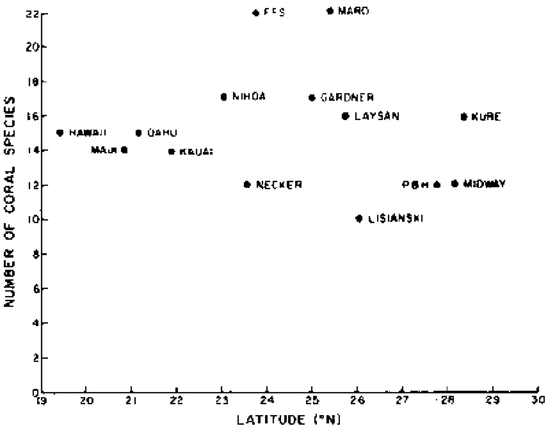

Figure 4. Number of coral species for all stations surveyed in the Hawaiian Archipelago

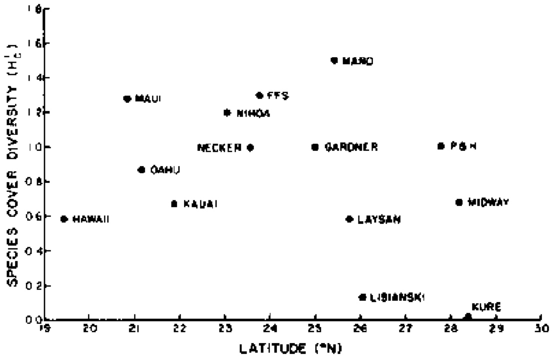

Figure 5. Coral species diversity for all stations surveyed in the Hawaiian Archipelago

between islands is the degree to which species are dominant (Figure 6). On 25-meter long transects off most islands, one or two species heavily dominate the coral communities. On others, however, such as Kauai, Nihoa, Necker, and Gardner Pinnacles, the abundance of species are distributed very equitably; no one species dominates.

Another difference in community organization between islands is the inconsistency of species dominance. Note in Figure 6, that the most abundant species is not the same on all 14 islands. *Porites lobata* is most abundant on 9 of 14 islands, *P. compressa* the most abundant on 4 of 14 islands, and *Palythoa tuberculosa* the most abundant on one island in the chain. Species which are less abudant (higher ranks in Figure 6) illustrate even more inconsistent patterns. Examples include *Pavona varians* which shows up as third in abundance off Hawaii and not at all after that on 25-meter long transects. Similarly the soft corals *Palythoa tuberculosa* and *Sinularia abrupta* are both very abundant at Nihoa Islands but are rare or absent on all other islands. *Pavona duerdeni* is second in abundance at Necker Island but generally much rarer on the other islands.

The presence of several species of *Acropora* in the Hawaiian Archipelago and their restricted patterns of occurrence (Figure 7) suggest that patterns of recruitment may not be the same for all islands. The appearance of several species of fish, (*Oplegnathus punctatus* and *O. fasciatus* (see paper by Hobson), in the northwestern half of the chain which have strong faunal ties to Japan, also is evidence that different patterns of recruitment exist within the archipelago. Differences in recruitment between islands do not appear to be a major factor affecting the community structure of reef ecosystems in Hawaii, but it clearly does account for some minor differences in the biota.

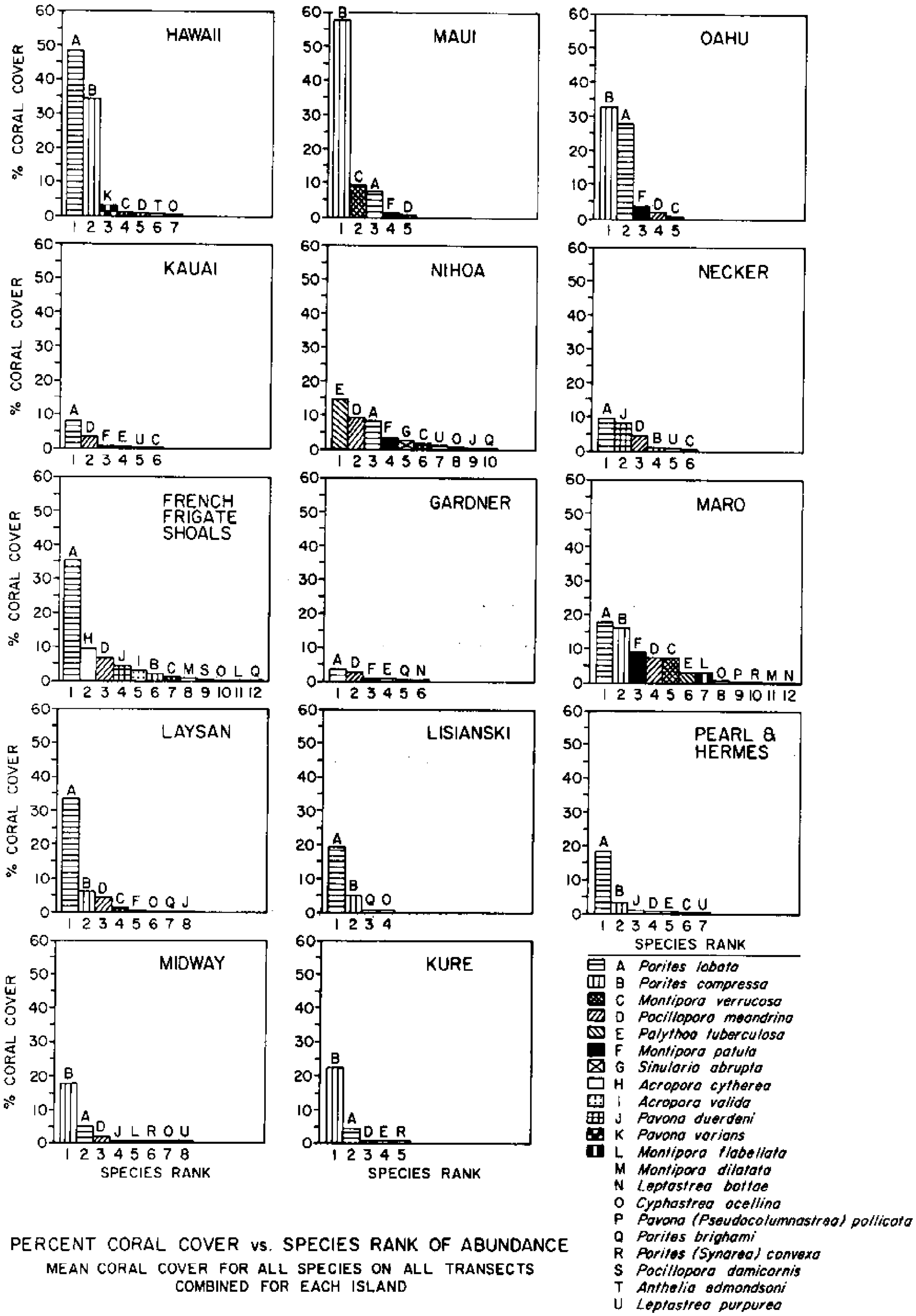

Figure 6. Community structure of reef corals in the Hawaiian Archipelago

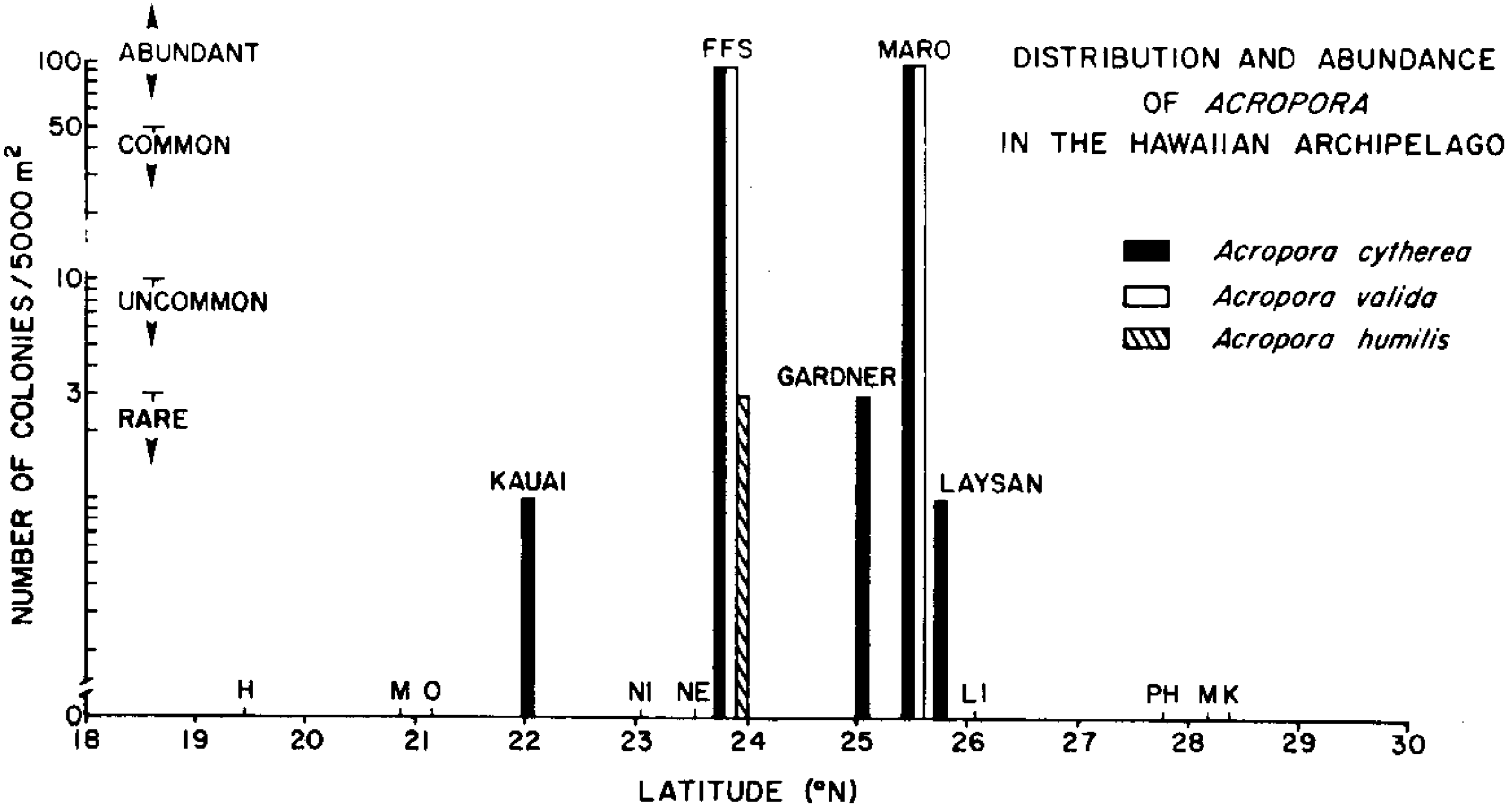

Figure 7. Distribution and abundance of Acropora spp. in the Hawaiian Archipelago

Most of the similarities and differences between reefs which have been described above support the hypothesis that physical conditions are more important in determining community structure than geographic position within the archipelago. Only those differences which appear to be due to geographic specific recruitment can be directly related to position in the chain. Otherwise physical conditions appear to be of overriding significance. This is clearly shown by the similarity in species composition between stations. Figure 8 is a dendrograph reduced from a similarity matrix that compares the abundance of each coral species on each transect with coral abundance on every other transect. The distance between any two transects on the vertical axis of the dendrograph is proportional to their dissimilarity. Similarity within groups or clusters is represented as distance along the horizontal scale. Major clusters corresponding to five physiographic zones are apparent and are indicated on the figure. Stations within groups do not share a common latitude. Rather, the frequency and magnitude of physical disturbance from waves appear to be the most important factors within clusters. For example, the optimal zone includes stations from Hawaii to Laysan Island. All of the stations within the optimal zone are frequently disturbed by minor wave stress. The monopolized zone contains a station from Midway next to a station from the island of Hawaii. Both are dominated by *Porites compressa*. And both are relatively well sheltered from wave stress.

Although quantitative data on wave climate and exposure for each island are presently lacking, a significant positive correlation appears to exist between the degree to which stations are exposed to waves and the equitability of the abundance of component species. This correlation may be related to the size and shape of the islands. For example, the smallest islands which are most exposed to sea and swell (Nihoa, Necker, and Gardner Pinnacles) are all characterized by coral communities with high equitability of species abundance (Figure 6). Kauai is the only large, high island with an equivalent degree of community equitability. It is rather round in shape and offers very little shelter in any area to tradewind and storm-generated swell. Other studies (Grigg and Maragos, 1974; Geister, 1977; Jokiel and Maragos, 1978; Smith and Jokiel, 1978; Dana, 1979) also suggest that water motion and exposure to waves are major factors controlling coral reef community structure, especially for seaward reefs. In more sheltered environments, especially in bays and estuaries, other factors such as turbidity, light, nutrients, salinity, and sedimentation may be of equal or greater importance.

The lack of continuous trends in community structure along the island chain may be because the exposure of islands to waves does not vary in any consistent manner from one end of the archipelago to the other, in spite of the fact that the islands are grouped into large, high islands at the southeastern end, rocky islets in the middle, and atolls at the northwestern end. The most exposed islands are the small rocky islets (Nihoa, Necker, and Gardner Pinnacles) which lie near the middle of the chain.

Island size is another factor that should be considered in the analysis of community structure of coral reefs. MacArthur and Wilson

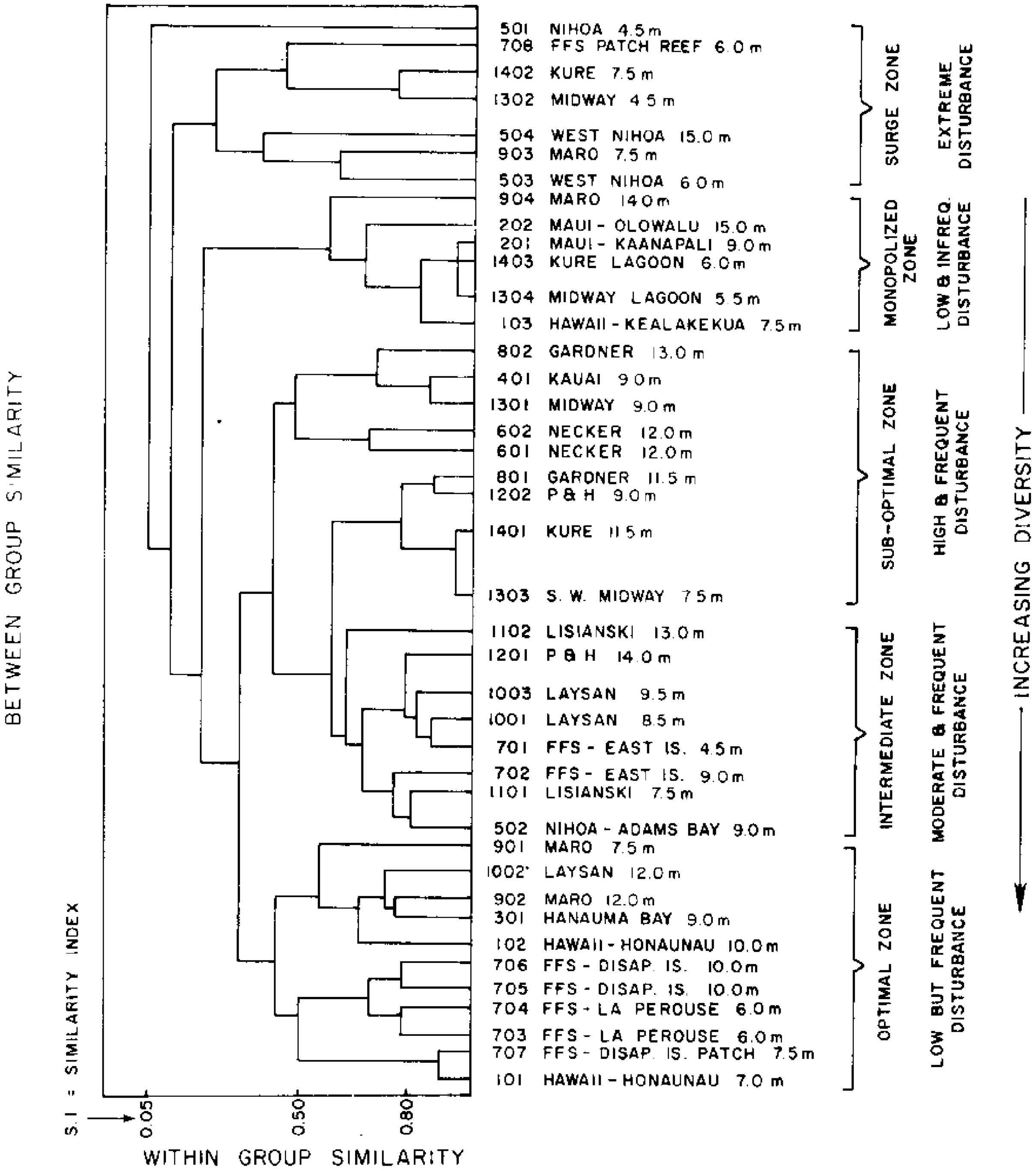

Figure 8. Dendrograph showing similarity between benthic transects based on species coral cover

(1967) have shown that island area is of major significance in determining species composition and community structure of terrestrial island biotas. Surprisingly, this does not appear to be the case, at least for Hawaiian coral reefs (Table 1). For example, Gardner Pinnacles which is less than 1% the size of French Frigate Shoals has almost as many species. What appears to be of greater significance than area *per se* is diversity of habitats. The greatest number of species occurs at French Frigate Shoals and Maro Reef which have only slightly greater reef area than the high islands but more importantly both contain a high diversity of habitats including lagoons, patch reefs, reef crests, reef flats, and seaward reefs. The high islands have, by and large, only seaward reefs and reef flats.

TABLE 1. CORAL SPECIES-AREA RELATIONSHIPS FOR THE HAWAIIAN ARCHIPELAGO

Island, Reef, or Atoll	Reef Area, km^2 (0 - 20 m)	Number of Coral Species
Hawaii	224.0	17
Maui	206.4	14
Oahu	287.8	15
Kauai	218.0	14
	0.6	17
Necker	2.1	12
FFS	509.6	23
Gardner Pinnacles	3.0	15
Maro	430.9	21
Laysan	57.3	16
Lisianski	325.3	10
Pearl and Hermes	359.0	12
Midway	101.2	12
Kure	54.9	16

Perhaps marine ecosystems are less affected by area than terrestrial island ecosystems because they are relatively less isolated. Terrestrial immigrants to islands must cross inhospitable barriers whereas marine forms more often are simply faced with bridging distances. Other things being equal, larval immigration rates to marine ecosystems would be expected to be higher than for island flora and fauna.

Islands further to the north such as Pearl and Hermes, Midway, and Kure have as much diversity of habitat as French Frigate Shoals and Maro Reef but at these extremes in latitude, a slight decline in species is found. This may reflect a slight decline in suitability as the Darwin Point is approached. Since the Darwin Point by definition is the threshold for reef development, one would expect it to be associated with some decrease in species diversity. Perhaps the most surprising result is that more species do not drop out as the Darwin Point is approached. The formation of a coral reef and all its associated flora and fauna appear to be, by and large, an all or none event. Where reefs can keep pace with erosion, subsidence, and sea level change, nearly the entire ecosystem appears intact.

In summary, most of the observed differences in species composition, diversity, and dominance appear to be related to differences in physical conditions. The most important factor appears to be exposure to waves. It has been shown by a variety of workers (Grigg and Maragos, 1974; Dollar, 1975; Loya, 1976; Jokiel and Maragos, 1978; and Dana, 1979) that the operational effect of wave exposure is mortality caused by physical disturbance. If this is true, it may be that differences in community structure between island coral reef ecosystems are due to differences in successional age which in turn are due to differences in frequency and magnitude of disturbance. Low diversity communities would result from severe and frequent disturbance in which few species survive the harsh conditions (surge zone, Figure 8), or from extremely favorable conditions in which disturbance rarely occurs and bottom resources are monopolized by one or two species (monopolized zone, Figure 8).

High diversity reef communities would be expected to occur where disturbance is frequent but not severe (optimal zone, Figure 8). Reef communities "held" at an intermediate successional stage by frequent but mild disturbance should be considered disclimax reefs. Such reefs should be characterized by inconsistencies in species composition and dominance since differences due to chance colonization would not have had time to be sorted out by competitive interactions. Frequent disturbance may in fact prevent or reduce competitive interactions by preventing resource (space) limitation. This may explain the inconsistencies in dominance noted for so many islands in the Hawaiian Archipelago. Hence, differences in community structure between Hawaiian reefs may be primarily due to differences in successional age which in turn appear to be due to differences in the frequency and magnitude of disturbance.

If correct, this conclusion has important implications for fisheries management. If differences in community structure are passed up the food chain, the patterns of abundance of species at higher trophic levels which depend upon reefs should also be different on different islands. Knowledge that supports this hypothesis is accumulating at the present time. Some islands are very "good" for some species but not for others. Fishermen and scientists consider Maro Reef and Necker Island to be best for lobsters, French Frigate Shoals for turtles, Brooks Banks for snappers, and Laysan Island for monk seals. As more data are gathered at all levels in the food chain, more coherent and explicit relationships should become apparent. In this regard, we are hopeful that the ecosystem model under development by NMFS will reveal new and previously unsuspected links between cause and effect. In this manner, we may begin to develop more intelligent and comprehensive management plans which take into account multispecies interactions.

CONCLUSIONS AND FUTURE RESEARCH PLANS

1. Corals and coral reefs exhibit declining trends in growth and development northwestward within the Hawaiian Archipelago.

2. Gross production of reef limestone at Midway and Kure atolls is about 0.5 kg $CaCO_3/m^2/yr$ or 0.3 mm/yr linear growth. These values appear to represent a threshold for atoll formation termed herein a "Darwin Point." The Darwin Point in the Hawaiian Archipelago appears to have existed at 29° ± 2°N latitude in the Pacific for the past 20 million years.

3. In general, species do not gradually drop out as the Darwin Point is approached. The formation of a coral reef ecosystem appears to be an all or none phenomenon.

4. Community structure of seaward reefs appears to be governed by the frequency and magnitude of physical disturbance primarily caused by wave forces. This suggests that differences in community structure are due primarily to differences in successional age. Latitude or position in the Hawaiian chain has little effect on community structure per se but does appear to account for some differences in species colonization patterns.

5. Differences in community structure of the benthos between islands may account for differences in species abundance patterns at higher trophic levels and may be useful indices for resource management.

Future research plans call for increased data collection to verify the above conclusions. We also hope to sort out the environmental factors which control coral growth and reef development such as light, temperature, and wave shock. Another goal is to more fully characterize the areal coverage of various habitats for each island and to relate these estimates to population measures for species of ecological or commercial importance. Because our investigation of benthic reef and shelf ecology of the Hawaiian Archipelago is only at a halfway point, the above conclusions must be considered preliminary.

ACKNOWLEDGMENTS

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BIOLOGY, DISTRIBUTION, AND ESTIMATES OF APPARENT ABUNDANCE OF THE SPINY LOBSTER, PANULIRUS MARGINATUS (QUOY AND GAIMARD), IN WATERS OF THE NORTHWESTERN HAWAIIAN ISLANDS:

PART I. DISTRIBUTION IN RELATION TO DEPTH AND GEOGRAPHICAL AREAS AND ESTIMATES OF APPARENT ABUNDANCE

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ABSTRACT

This paper describes the results of field surveys conducted by the Honolulu Laboratory on the spiny lobster, Panulirus marginatus, in the Northwestern Hawaiian Islands. Of 17 islands and submerged banks surveyed from October 1976 to November 1978, only Necker Island and Maro Reef had sufficiently large stocks of spiny lobsters to warrant commercial exploitation. The distribution of spiny lobsters in relation to geographical area and depth is also discussed. Future research needs are identified, including specialized data on the environment and the stocks to estimate their magnitude and potential yield, data on seasonal and spatial variation in stock distribution and abundance, and observations on behavior of spiny lobster in relation to biological and environmental conditions.

Northwestern Hawaiian Islands
spiny lobster
distribution
apparent abundance

INTRODUCTION

The Northwestern Hawaiian Islands (NWHI), often called the "Leeward Islands," are part of the Hawaiian Archipelago comprising a chain of small islands, islets, rocks, and shoals stretching 1,250 nmi west northwest of Niihau (Figure 1). All the land areas except Midway, which is a state-administered wildlife sanctuary and the site of a Coast Guard loran station, constitute the Hawaiian Islands National Wildlife Refuge and are seldom visited.

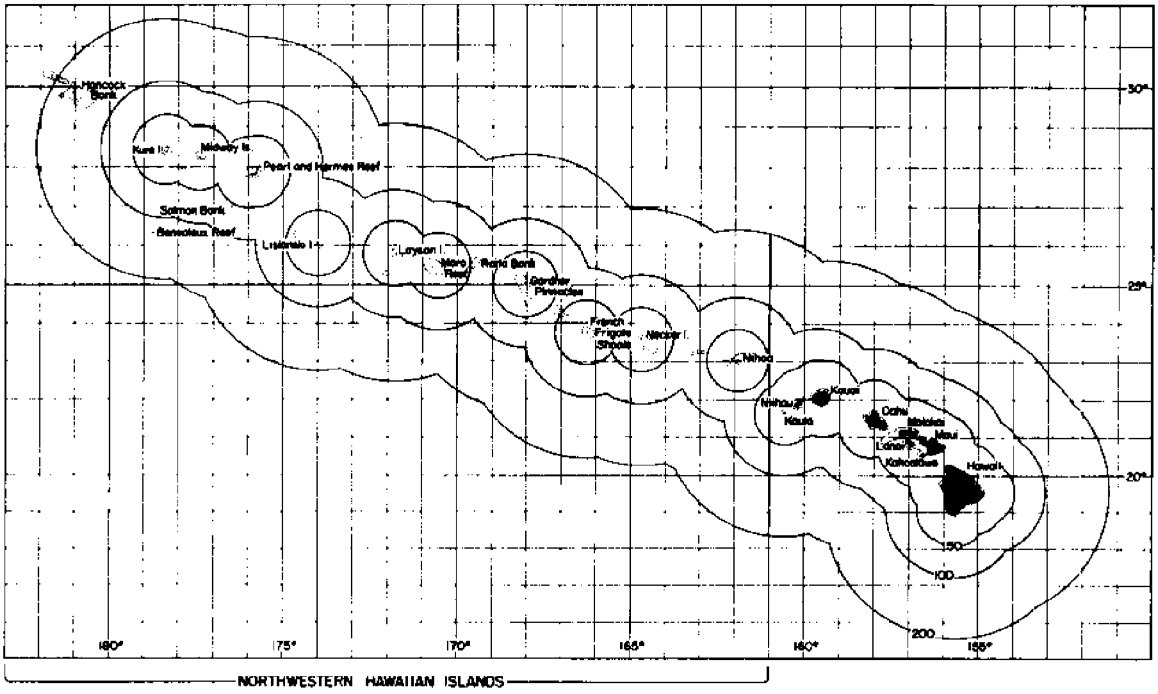

Figure 1. The Hawaiian Archipelago

In 1969, the Governor's Task Force on Oceanography of the State of Hawaii, recognizing the increase in fishing pressure being exerted on the fishery resources of Hawaii's main islands, recommended exploration and possible development of the fishery resources in waters of the NWHI (State of Hawaii, 1969, 1974). In response to these recommendations the Honolulu Laboratory of the Southwest Fisheries Center, National Marine Fisheries Service (NMFS), reconnoitered waters of the NWHI on a cruise of the NOAA ship David Starr Jordan in 1973 and followed that with two research cruises on the NOAA ship Townsend Cromwell in 1975.

In 1976, NMFS launched a full-scale investigation of the NWHI. Realizing that the extent of the investigation was beyond the capabilities of the staff and facilities of any single research agency in Hawaii, NMFS proposed a cooperative research effort with the Hawaii Division of Fish and Game (HDFG) and the U.S. Department of the Interior, Fish and Wildlife Service (USFWS). From the proposal evolved the Tripartite Cooperative Agreement which, in effect, gave responsibility for survey and assessment of the inshore fishery resources to the HDFG and for land-associated resources such as sea and land birds to the USFWS. The Honolulu Laboratory assumed responsibility for developing a quantitative fishery survey and assessment of the slope and coastal pelagic fish resources. A short time after the formation of the tripartite agreement, a fourth agency, the University of Hawaii Sea Grant College Program, became an active participant in the investigation.

Initially, very little was known about the slope and coastal pelagic resources in the NWHI; therefore, our objectives during the first two years of the investigation were simply to conduct exploratory fishing to determine the kinds of fish, shellfish, and molluscs present in waters of the NWHI, their spatial and temporal distribution, and their relative abundance in waters of the several islands and submerged banks. In this report, we summarize trapping results for the spiny lobster, *Panulirus marginatus*, from October 1976 to November 1978 aboard the *Townsend Cromwell* and a commercial fishing vessel chartered for two trips.

At the outset of our survey, we identified nearly 50 islands, submerged banks, and seamounts within 200 nmi of the NWHI. We have surveyed 17 of these for spiny lobster and this report covers what we found in waters around these islands and banks.

METHODS

Data used in this report were collected on six survey cruises of the *Cromwell* (TC-76-06, TC-77-02, TC-77-03, TC-78-01, TC-78-03, and TC-78-04) and on two NMFS-chartered cruises of the commercial fishing vessel *Easy Rider* (ER 77-02, Parts I and II) which operates out of Honolulu.

The standard gear used on all our lobster trapping operations was the California two-chambered lobster pot. In conjunction with our surveys of bottom fish resources, the large, Hawaiian-type fish trap was also used at the lobster trapping stations. Both the lobster pot and fish trap have been described in detail by Uchida and Hida (1977).

The fish traps were effective not only in capturing a wide variety of fish but also, as incidental catches, spiny lobsters. This report, however, covers only the data collected at our lobster trapping stations. Data on lobster catches made by the fish traps were used only to supplement that obtained on certain highly productive areas, to determine recruitment of juveniles, and for studies involving the length-frequency distributions of the stock(s).

To determine distribution and estimate relative abundance of spiny lobsters, banks were divided into a network of equal area squares or sampling units, measuring 0.1° to a side of latitude and longitude. Each square was identified by a six-digit code at the lower right corner. The first two digits give the whole latitude, the third identifies the 0.1° of latitude which is numbered from 0 to 9 starting at 00' of latitude. The fourth and fifth digits give the whole longitude minus 100, and the last digit identifies the 0.1° of longitude from 0 to 9 starting at 00' of longitude. For example, 220615 identified the square located at lat. 22°00'N and long. 161°30'W. When catches fell on a latitudinal line bordering a square, they were assigned to the square directly above; when they fell on a longitudinal line of a square, they were assigned to the square directly to the left (Figure 2).

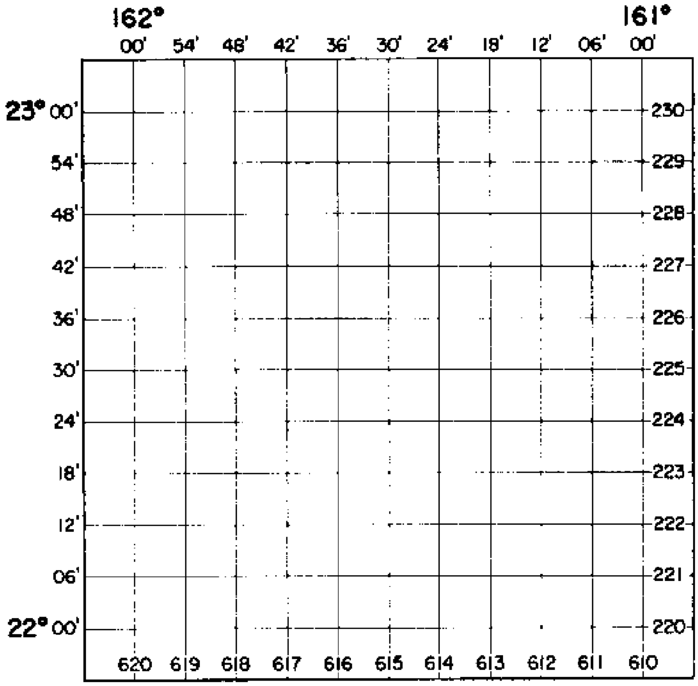

Figure 2. Codes for 0.1° squares established for the Northwestern Hawaiian Islands

RESULTS

Species composition

Our lobster trapping stations produced a great diversity of arthropods, molluscs, and fishes. Although Morris (1968) indicated that two species of spiny lobsters--P. marginatus and P. penicillatus--are commonly caught in waters around the major islands, our trapping stations produced none of the latter, primarily because it is essentially a shallow-water species that inhabits waters usually less than 5.5 m (3 fathoms) deep (De Bruin, 1962).

The second most important species caught in the lobster pots was the slipper lobster, Scyllarides squammosus.[1] Other commercially valuable species included the frog crab, Ranina ranina, octopus, Polypus marmoratus, pink snapper, Pristipomoides filamentosus, sea bass, Epinephelus quernus, amberjack, Seriola dumerili, and the thick-lip carangid, Caranx cheilio.

Distribution of fishing effort and apparent abundance

Confining our analysis to data collected with lobster pots during our survey and charter cruises between October 1976 and November 1978, 4,835 trap-nights were fished in waters of the NWHI producing 13,214

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[1] We were informed recently by Dr. Craig MacDonald, University of Hawaii, Department of Zoology, Honolulu, Hawaii that in addition to S. squammosus, a second species, S. haanii, may be present in Hawaiian waters.

spiny lobsters for an overall catch rate of 2.73 lobsters/trap-night (Table 1). Catch rates varied considerably among the areas visited, ranging from 0.00 at Middle Bank, Pioneer Bank, and at No-name Bank #8 to 4.72 lobsters/trap-night at Necker Island.

TABLE 1. THE POSITION OF THE ISLANDS, BANKS, AND REEFS, TOTAL NUMBER OF LOBSTERS CAUGHT, NUMBER OF TRAP-NIGHTS OF EFFORT EXPENDED, AND CATCH/TRAP-NIGHT OF ALL LOBSTERS INCLUDING LEGALS (8.25 CM OR MORE IN CARAPACE LENGTH), SUBLEGALS, AND BERRIED FEMALES IN THE NORTHWESTERN HAWAIIAN ISLANDS. CATCH DATA ARE FOR OCTOBER 1976-NOVEMBER 1978

Island or Bank	Position		Total Catch (No.)		
	Latitude (N)	Longitude (W)	Catch	Trap-Night	Catch/ Trap-Night
Middle Bank	22°42'	161°02'	0	40	0.00
Nihoa	23°03'	161°55'	255	178	1.43
Nihoa (west bank)	22°58'	162°14'	161	218	0.74
Necker Island	23°34'	164°42'	7,937	1,680	4.72
French Frigate Shoals	23°46'	166°18'	140	359	0.39
St. Rogatien Bank	24°25'	167°15'	41	59	0.69
Gardner Pinnacles	25°01'	167°59'	307	209	1.47
Raita Bank	25°35'	169°35'	169	92	1.84
Maro Reef	25°29'	170°35'	2,684	663	4.04
Laysan Island	25°42'	171°44'	575	341	1.69
Pioneer Bank	26°00'	173°25'	0	24	0.00
Lisianski Island	26°02'	174°00'	9	179	0.05
No-name Bank #8	26°17'	174°34'	0	24	0.00
Salmon Bank	26°56'	176°28'	2	48	0.04
Pearl and Hermes Reef	27°48'	175°51'	232	236	0.98
Midway Islands	28°12'	177°22'	576	280	2.06
Kure Atoll	28°25'	178°25'	158	240	0.66
Total			13,214	4,835	2.73

It is quite evident that spiny lobsters are distributed throughout the entire NWHI chain from Nihoa to Kure (Table 1 and Figure 3). The data also show that the shelves surrounding Necker and Maro Reef were the most productive during the survey period. Necker, because of its proximity to Oahu where the lobster fleet is based, received considerable trapping effort from the commercial boats only months after the Cromwell obtained catch rates as high as 17.80 lobsters/trap-night in some areas around the island during the October-November 1976 cruise. During our surveys, we expended 1,680 trap-nights at Necker and caught 7,937 lobsters or an average of 4.72 lobsters/trap-night.

Maro Reef, which was found to be almost as productive as Necker, was first visited and fished with significant amounts of effort during cruise TC-77-02 (Part III) in May-June 1977. In the course of our

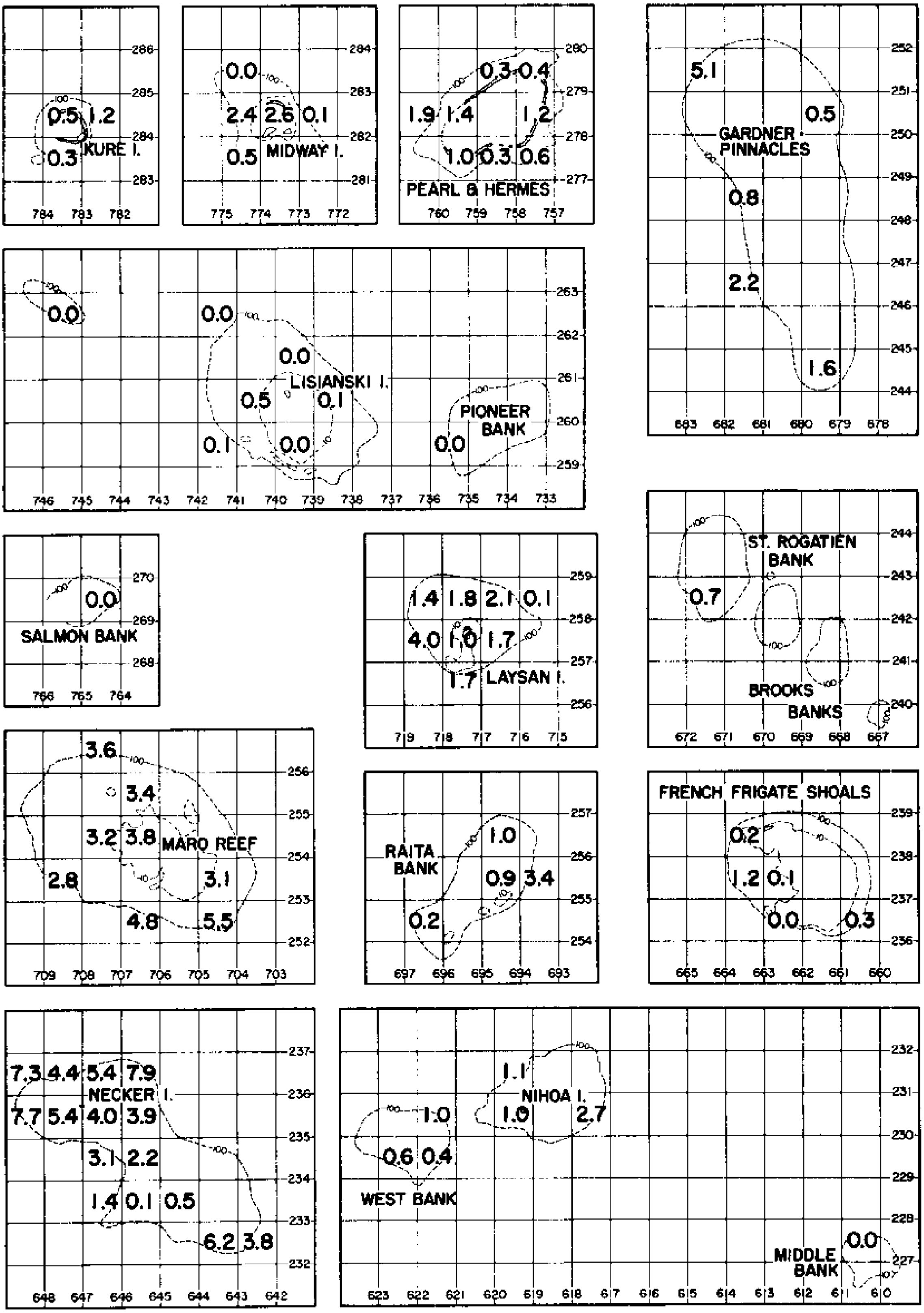

Figure 3. Distribution of spiny lobster catch rates, by 0.1° squares in the Northwestern Hawaiian Islands, October 1976-November 1978

surveys, we expended 663 trap-nights and caught 2,684 lobsters or an average of 4.04 lobsters/trap-night (Table 1).

Gardner Pinnacles, Raita Bank, and Laysan were other islands and banks that showed some highly productive areas; however, the overall catch rates never approached the magnitude we found for Necker and Maro Reef. These areas all require additional surveys to determine their productivity.

Relation between catch per trap-night and depth

Panulirus marginatus has been reported to occur at depths ranging from a few meters to 183 m in the Hawaiian Islands (McGinnis, 1972). To examine the relative abundance of this species with respect to depth in the NWHI, we grouped the catch data into 9-m (5-fathom) strata for each of the islands and banks. The relative abundance of *P. marginatus* at the lower end of the NWHI chain was higher at depths between 37 and 64 m (21 and 35 fathoms); however, in the middle and higher latitudes particularly from Gardner Pinnacles to Kure, there was a tendency for the catch/trap-night to be higher usually in waters 10 to 36 m (6 to 20 fathoms), except at Midway where the relative abundance of spiny lobsters was highest at 37 to 45 m (21 to 25 fathoms) (Figure 4). The relatively low catch rates we observed in waters deeper than 64 m (35 fathoms) in the northern part of the chain may be the consequence of differences in temperature regime from north to south.

Data from XBT casts made during two cruises of the *Cromwell* were examined for differences in the surface and subsurface (0-140 m) temperature at Necker and Midway (Table 2). It is evident that during both summer and winter, there is a pronounced cooling of the subsurface waters around Midway. Also of interest is the depth of the mixed layer, which is relatively shallow in summer and deep in winter. These data are similar to the results obtained by Seckel (1962) who studied the oceanographic climate of the Hawaiian Islands region.

DISCUSSION AND CONCLUSIONS

The pattern that emerges from our trapping results in the NWHI is one of uneven distribution of spiny lobsters with heavy concentrations located only at Necker and Maro Reef. There are, however, other sites such as Gardner Pinnacles, Raita Bank, and Laysan that show potential, but only additional surveys or commercial fishing at these locations will provide sufficient data to verify the potential. Furthermore, because fishing is still in its infancy, it is extremely difficult to draw inferences about catch rates. Catch/trap-night for spiny lobsters is influenced by dominance behavior of the large adults, of adult males, and perhaps by reproductive condition of the females.

Another interesting aspect of the distributional pattern of *P. marginatus* is its relationship to depth and possibly subsurface temperatures prevailing over the substrate. Whereas the catch/trap-night was relatively high in depths between 37 and 64 m around islands and banks southeast of Gardner Pinnacles, there was a trend for catch/trap-night

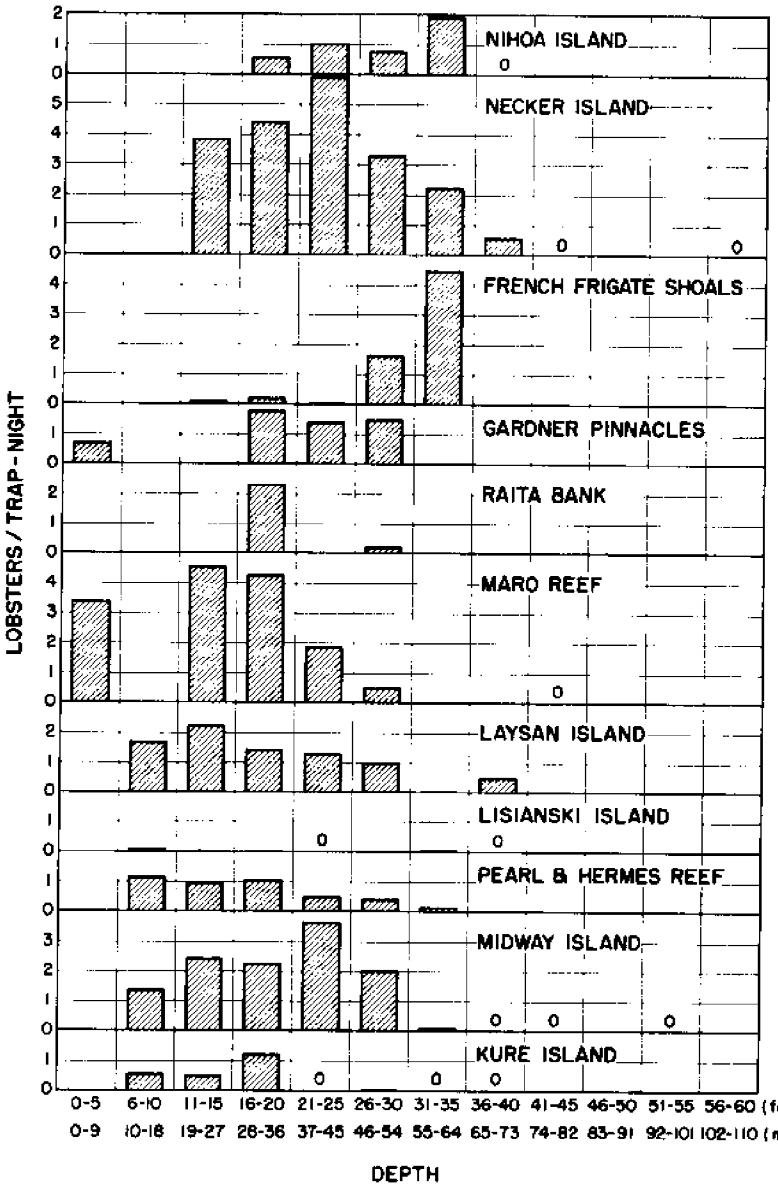

Figure 4. Distribution of spiny lobster catch rates, by depth, in the Northwestern Hawaiian Islands, October 1976-November 1978

to be higher at shallower depths between Gardner Pinnacles and Kure. In addition to the possible effects of subsurface temperatures on the depth distribution pattern of spiny lobsters, other factors such as substrate type and location of feeding or browsing pastures may also influence habitat selection.

At this time, nothing is known about the pattern of larval recruitment in the NWHI. Johnson (1968) reported catching spiny lobster phyllosoma in plankton samples at a number of locations in the Hawaiian Archipelago. Whereas the phyllosoma of both _P. marginatus_ and _P. penicillatus_ was collected around Oahu and in waters to the southwest

TABLE 2. SURFACE AND SUBSURFACE TEMPERATURES IN WATERS AROUND NECKER AND MIDWAY ISLANDS DURING THE SUMMER AND FALL MONTHS IN 1976-77

	Summer Temperature °C		Winter Temperature °C	
Depth (m)	Necker (May 17, 1977)	Midway (May 30, 1977)	Necker (Oct. 17, 1976)	Midway (Nov. 2, 1976)
0	24.9	24.9	25.8	26.1
10	24.7	24.4	25.7	26.1
20	24.4	23.9	25.7	26.1
40	24.2	22.8	25.7	26.1
60	23.9	21.2	25.7	26.1
80	23.1	20.4	25.3	23.6
100	22.2	19.6	23.1	21.6
120	21.9	19.2	22.0	21.3
140	21.7	18.7	21.0	18.5

of the main islands, Johnson found only P. marginatus phyllosoma at French Frigate Shoals. Thus, the distribution of these phyllosoma corresponds to some extent to the distributional pattern of the adults.

FUTURE RESEARCH NEEDS

Exploratory fishing to determine species composition and initial catch rates has been completed for most of the larger islands and banks in the NWHI. Several areas for future research include a need for specialized information on the environment and the stocks to estimate their magnitude and potential yield. Catch and effort data from commercial vessels are needed to calculate more precise catch rates. Additional studies are needed to determine how catch rates can be expected to change with increasing fishing pressure. We need a sufficiently large data base to be able to predict seasonal and spatial variation in stock distribution and year-to-year fluctuation in stock abundance or availability.

More research is also needed on the relationship between lobster behavior and changes in biological and environmental parameters, on predation of lobsters by large predators such as sharks and carangids, on gear competition, on ghost fishing, and on escape gaps.

The results of all these studies will assist us in making crucial decisions on the management of the fishery and will influence decisions of investors.

SUMMARY

The results of exploratory surveys conducted by the NMFS show that the spiny lobster, P. marginatus, is unevenly distributed throughout the NWHI. Two locations--Necker and Maro Reef--showed the highest concentrations; Gardner Pinnacles, Raita Bank, and Laysan showed signs of having good potential.

The study also revealed that the concentrations of lobsters are stratified by depth. South of Gardner Pinnacles, the highest catch rate occurred within 37 and 64 m, but around islands and banks to the north, the highest catch rate occurred between 10 and 36 m.

The exploratory phase of the NWHI investigation is well toward completion and future research needs are being considered.

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BIOLOGY, DISTRIBUTION, AND ESTIMATES OF APPARENT ABUNDANCE OF THE SPINY LOBSTER, PANULIRUS MARGINATUS (QUOY AND GAIMARD), IN WATERS OF THE NORTHWESTERN HAWAIIAN ISLANDS:

PART II. SIZE DISTRIBUTION, LEGAL TO SUBLEGAL RATIO, SEX RATIO, REPRODUCTIVE CYCLE, AND MORPHOMETRIC CHARACTERISTICS

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ABSTRACT

Population structure in terms of size, legal to sublegal ratio, sex ratio, and reproductive cycle is defined for the spiny lobster, Panulirus marginatus, in the Northwestern Hawaiian Islands. Trapping operations were conducted in waters of the Northwestern Hawaiian Islands from October 1976 to November 1978. Striking differences were noted in average sizes of lobsters among the various islands and banks surveyed. At Necker Island, where catch rates were estimated to be the highest in the island chain, the average sizes of males and females were the smallest. The proportion of legal lobsters in the catch was relatively high in most areas and males usually predominated. Egg bearing among females showed marked seasonality with peaks in early summer and fall. The length-weight relationship showed that, up to the 65-mm carapace length, males usually weighed more than females, but beyond this size females were heavier than males of equivalent sizes. Future research will be directed toward collection of data to define the reproductive cycle.

Northwestern Hawaiian Islands
spiny lobster
population structure
morphometric

INTRODUCTION

This report deals with studies on several aspects of the biology of the spiny lobster, Panulirus marginatus, caught in waters of the Northwestern Hawaiian Islands (NWHI) between October 1976 to November 1978. It represents an expansion of the preliminary analyses of data collected on P. marginatus by the Honolulu Laboratory of the Southwest Fisheries Center, National Marine Fisheries Service (NMFS) (see papers by Honda; Polovina and Tagami; and Uchida et al., part I).

METHODS

All data used in this study were collected during lobster and fish trapping operations on cruises of the NOAA ship Townsend Cromwell, TC-76-06, TC-77-02, TC-77-03, TC-78-01, TC-78-03, and TC-78-04 and on NMFS-chartered cruises of the RV Easy Rider, ER-77-02, parts I and II. The gear used--California two-chambered lobster pot and Hawaiian fish trap--has been described in Uchida and Hida (1977). The locations of the islands and banks are given in a separate paper (see paper by Uchida et al., part I).

The carapace length (CL), measured with a vernier caliper to the nearest 0.1 mm, is the distance along the mid-dorsal line from the transverse ridge between the supraorbital spines to the posterior margin of the carapace (McGinnis, 1972). All weights collected at sea were made on a beam scale to the nearest 10 g. Weights collected at the laboratory were recorded to the nearest whole gram using a single-pan balance. Tail weights were recorded when fresh (while at sea), and in the frozen and thawed states (on land).

RESULTS

Size distribution

The percentage frequency distribution of CL of male and female spiny lobsters caught during the surveys conducted from October 1976 to November 1978 are given by island and bank in Figure 1. The distributions are composites of all cruises and the data are grouped into 5-mm CL classes. Particularly striking are the differences in the means and variances of the size-frequency distributions among islands and banks and between sexes (Table 1).

The size-frequency distributions demonstrate that among all the areas sampled, the average sizes of the male and female lobsters at Necker were the smallest followed closely by those caught at French Frigate Shoals (Figure 1). At Necker, the relatively small size was evident even in October-November 1976 when our surveys first began and, therefore, does not represent a gradual reduction in size associated with increasing fishing effort and removal of the large dominant adults (Table 2).

The scarcity of juvenile lobsters smaller than 45 mm in CL suggests that they either occur in a different habitat or display different behavioral traits which affect their catchability. McGinnis (1972)

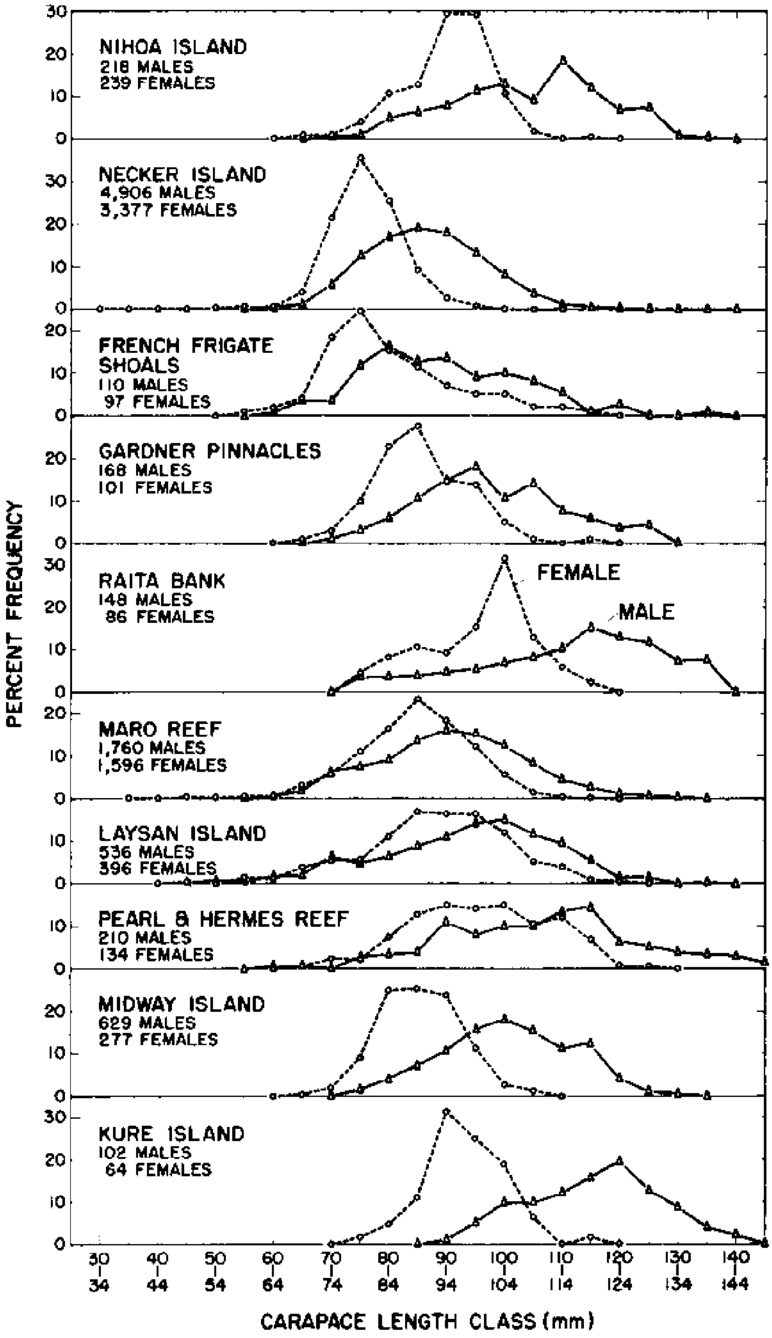

Figure 1. Percentage of frequency distributions of carapace lengths of male and female spiny lobsters sampled in waters of the Northwestern Hawaiian Islands, October 1976 to November 1978

TABLE 1. THE SIZE RANGE, MEAN CARAPACE LENGTH, STANDARD DEVIATION, AND VARIANCE OF MALE AND FEMALE SPINY LOBSTERS SAMPLED IN THE NORTHWESTERN HAWAIIAN ISLANDS, OCTOBER 1976-NOVEMBER 1978

Island or Bank	Male				Female			
	Size Range (mm)	Mean Carapace Length (mm)	Standard Deviation	Variance	Size Range (mm)	Mean Carapace Length (mm)	Standard Deviation	Variance
Nihoa	72-136	106.02	13.20	174.31	67-117	92.40	7.17	51.39
Necker	44-137	88.32	10.24	104.80	34-105	78.14	5.96	35.54
French Frigate Shoals	60-135	91.32	13.78	190.02	56-116	82.40	11.69	136.60
Gardner Pinnacles	72-128	99.96	12.49	155.96	68-117	87.61	8.00	64.08
Raita Bank	75-139	113.18	15.92	253.60	75-117	97.41	9.41	91.04
Maro Reef	47-133	92.97	12.71	161.47	44-119	86.67	9.77	95.54
Laysan	52-139	95.96	14.67	215.25	45-124	90.07	12.43	154.44
Pearl and Hermes	61-148	108.97	16.44	270.16	68-129	98.21	11.78	138.87
Midway	75-134	102.92	11.01	121.30	67-109	87.55	6.74	45.38
Kure	91-143	117.80	11.12	123.60	79-119	95.55	7.01	49.20

TABLE 2. THE SAMPLE SIZE, SIZE RANGE, MEAN CARAPACE LENGTH, STANDARD DEVIATION, AND VARIANCE OF MALE AND FEMALE SPINY LOBSTERS SAMPLED AT NECKER ISLAND, OCTOBER 1976-NOVEMBER 1978

Period	Male					Female				
	N	Size Range (mm)	Mean Carapace Length (mm)	Standard Deviation	Variance	N	Size Range (mm)	Mean Carapace Length (mm)	Standard Deviation	Variance
Oct.-Nov. 1976	690	48-118	87.03	10.47	109.62	233	59-97	77.22	5.70	32.44
May-June 1977	22	74-109	88.14	9.81	96.22	23	72-87	77.74	3.99	15.93
Sept.-Nov. 1977	466	49-137	91.08	12.86	165.47	372	50-105	80.94	8.19	67.14
Jan.-Mar. 1978	53	44-121	90.17	15.19	230.68	48	63-97	83.96	7.58	57.44
Oct.-Nov. 1978	268	52-111	86.97	9.70	94.13	183	34-93	77.70	8.06	64.96

reported that juvenile P. marginatus occur in inshore reef areas throughout the year. Furthermore, little is known about their behavior. One would expect, however, that at least greater numbers of lobsters smaller than the 45 to 49-mm length class would be caught in our fish traps, which are covered with 2.5-cm square wire mesh (as compared to the 5.1 x 10.2-cm mesh of our lobster pots). The low numbers of smaller size classes seen in the catch reflect either their scarcity on the trapping grounds or are simply not catchable; therefore, it can be expected that it is in the 45 to 49-mm size range that recruitment to the fishery is occurring.

There is no particularly striking trend in the average size of the lobsters geographically (Figure 1). The average size of the males was largest at Kure, at the northwestern tip of the NWHI chain followed by those caught at Raita Bank, which is located approximately halfway between Kure and Niihau. Among females, the average size was largest at Pearl and Hermes, followed by that at Raita Bank.

In all the areas sampled, the males were consistently larger than the females. The difference in average size between the sexes quite likely results from dimorphism related to egg bearing in females (Heydorn, 1969).

Proportion of legal-sized lobsters in the catch

In Hawaii, the regulation defines a legal-sized lobster as not less than 0.45 kg (1 lb) in weight or 8.25 cm in CL. During our surveys, we found a preponderance of legals in the overall lobster pot catches in the NWHI. Table 3 shows the breakdown of the legal and sublegal catches by sex, the male:female ratio among legals and sublegals, and the overall male:female and legal:sublegal ratios in 12 of the areas sampled. The ratios of legal:sublegal lobsters in the catch, by areas, varied widely between 53:47 at Necker and 99:1 at Kure Island with the overall arithmetic mean of the ratios reaching 85:15. The high proportion of legals in the catches, particularly at Raita Bank, Pearl and Hermes, Midway, and Kure can also be seen in Figure 1.

The percentage of sublegals caught by the lobster pots would tend to be relatively low, in part, due to various sampling artifacts. The mesh size used in the lobster pot construction usually permits most sublegals to escape or drop out during hauling. In addition, the effects of the molt cycle on the composition of the catches is unknown at present. McGinnis (1972) reported that juveniles of spiny lobsters molt more frequently than adults; therefore, newly molted juveniles would tend to remain secluded and, hence, not be subject to capture. Furthermore, the initial catch rates at any given locality would tend to include a large proportion of the large, older individuals, particularly males, because of their aggressive behavior.

Dominance hierarchy, which has been reported for the Australian lobsters (Chittleborough, 1974), exists in a natural environment for shelter and for food; however, in a fishery, the baited trap apparently becomes an object for which dominance behavior is displayed. This trait among large lobsters was quite evident in the changes in the proportion

TABLE 3. THE LEGAL TO SUBLEGAL AND MALE TO FEMALE RATIOS AMONG CATCHES MADE IN THE NORTHWESTERN HAWAIIAN ISLANDS, OCTOBER 1976-NOVEMBER 1978

	Legal			Male: Female Ratio	Sublegal			Male: Female Ratio	Total Male	Total Female[2]	Male: Female Ratio	Legal: Sublegal Ratio
	Male (No.)	Female[1] (No.)	Total (No.)		Male (No.)	Female[1] (No.)	Total (No.)					
Nihoa	104	81	185	56:44	5	8	13	38:62	109	146	43:57	93:7
Nihoa West Bank	86	46	132	65:35	3	3	6	50:50	89	72	55:45	96:4
Necker	2,909	465	3,374	86:14	1,175	1,841	3,016	39:61	4,084	2,963	58:42	53:47
French Frigate Shoals	51	24	75	68:32	20	31	51	39:61	71	55	56:44	60:40
Gardner Pinnacles	155	59	214	72:28	12	25	37	32:68	167	99	63:37	85:15
Raita Bank	106	60	166	64:36	2	1	3	67:33	108	61	64:36	98:2
Maro Reef	468	342	810	58:42	110	100	210	52:48	578	636	48:52	79:21
Laysan Island	295	193	488	60:40	33	32	65	51:49	328	247	57:43	88:12
Lisianski Island	2	5	7	29:71	2	0	2	100:0	4	5	44:56	78:22
Pearl and Hermes Reef	137	76	213	64:36	7	4	11	64:36	144	88	62:38	95:5
Midway Islands	370	110	480	77:23	14	28	42	33:67	384	152	72:28	92:8
Kure Island	97	53	150	65:35	0	2	2	0:100	97	60	62:38	99:1
Total	4,780	1,514	6,294	--	1,383	2,075	3,458	--	6,163	4,485	--	--
Arithmetic mean:				64:36				47:53			57:43	85:15

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

of legals in the catches at Necker. For example, in November 1976 when trapping operations first began, the ratio of legal to sublegal reached 60:40 but dropped to 43:57 by May 1977 and was only 34:66 in August 1977 (Table 4). The drop in the proportion of legals is attributable to heavy fishing pressure exerted by the commercial fishing vessels resulting in removal of large dominant lobsters from the stock.

TABLE 4. CHANGES WITH TIME IN THE PROPORTION OF LEGAL-SIZED LOBSTERS IN THE CATCHES AT ONE 0.1° SQUARE NORTH OF NECKER ISLAND

Date	Legal (No.)	Sublegal (No.)	Ratio of legal to sublegal
November 1976	114	77	60:40
May 1977	157	212	43:57
August 1977	194	383	34:66

Sex ratio

Dominance behavior exists not only among large lobsters over smaller ones but also between sexes (Table 3). Among the areas sampled, only Lisianski shows the proportion of legal males below 50:50 in the catch; however, the ratio probably is not representative of the population at Lisianski because of the very small numbers of lobsters, both legals and sublegals, caught at that location. Excluding Lisianski, then, the sex ratios of the catches of legals from all areas varied from 86:14 at Necker to 56:44 at Nihoa. Among sublegals, and excluding areas with less than 10 lobsters sampled, we found a preponderence of females in five of the eight areas sampled with sex ratios of male:female varying between 64:36 to Pearl and Hermes and 32:68 at Gardner Pinnacles. The overall sex ratios, which include legals, sublegals, and berried females, varied from 72:28 at Midway to 43:57 at Nihoa (excluding Lisianski). The ratio of male:female in all the catches made in the NWHI was 57:43.

Reproductive cycle

The frequency of berried lobsters among the females in the population can be used as an index of the reproductive cycle. To delineate the breeding cycle among females in the different stocks in the NWHI, the percentages of berried females were calculated for months in which the catch was made and are shown in Figure 2. Unfortunately, the observations in most of the areas are inadequate to construct consecutive monthly distributions of berried females. Time, distance, and area to be covered prohibited more frequent visits to the survey areas; however, the data that are available give us some evidence of a trend in the time of high incidence of berried females in the catch and, hence, in the reproductive period.

The incidence of berried females in the catches at Nihoa, Necker, and French Frigate Shoals appears to be concentrated in the late summer and fall, and possibly into the winter months. Moving northwestward

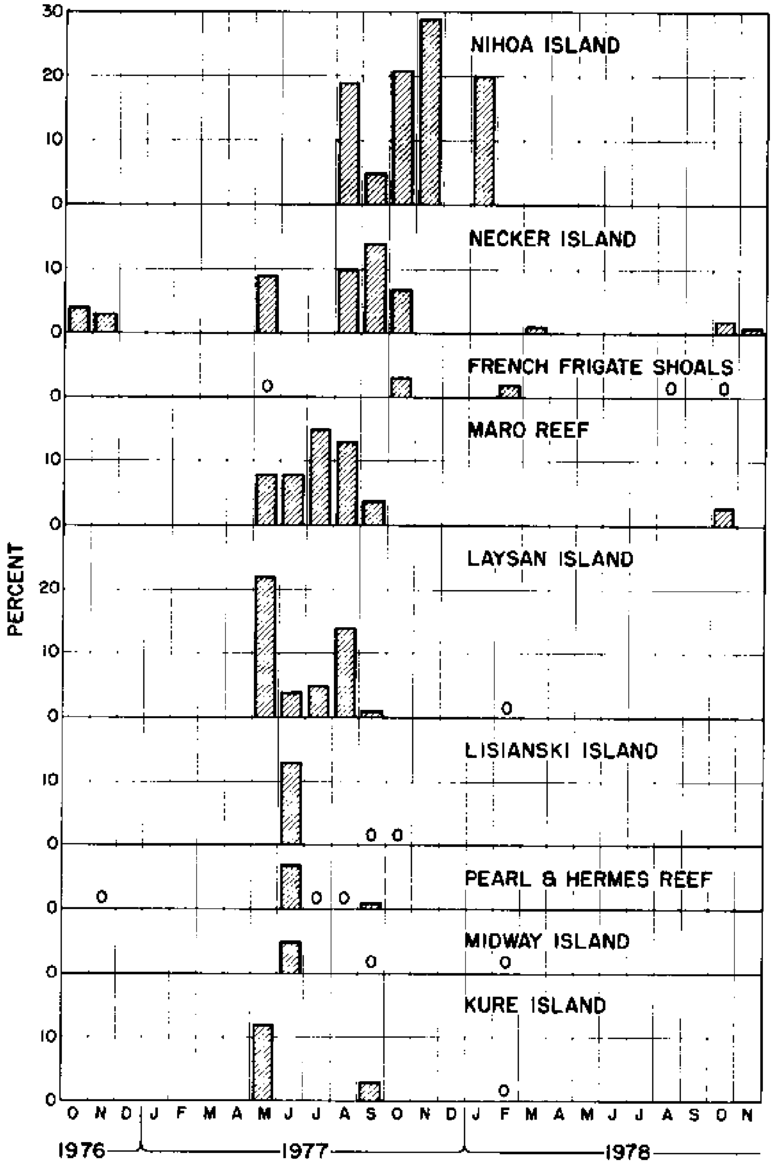

Figure 2. Percentage of berried females in the catches, by area, October 1976 to November 1978

along the chain, we found a gradual shift in the position of the monthly peaks to May and June. Comparison of our results with those obtained by MacDonald and Thompson (in preparation) at Midway shows good agreement with the peak numbers of berried females they found from May through August.

Relationship between carapace length and total weight

In the lobster fishery, both length and weight are used as criteria of harvest--the minimum legal size CL is used by the fishermen at sea, because this attribute can be measured more easily and accurately than weight, and weight is used as a criterion of harvest or total catch.

For the calculation of the relationship between CL and total weight, 605 measurements on lobsters caught at Necker, Maro Reef, and French Frigate Shoals during cruise TC-78-04 were used. For this preliminary report, data from all three areas were combined and calculations were made only for males and females, because it has been reported by Heydorn (1969) that growth is sexually dimorphic and that it may be related to egg bearing among females. All lobsters measured and weighed were intact with no appendages missing and none of the females was berried.

An exponential model, $W = aCL^b$, was fitted to the data for both male and female by the method of least squares. The 408 males ranged in size from 48.1 to 121.3 mm CL, whereas the 197 females ranged from 51.9 to 114.7 mm CL. The length-weight relationships for male and for female P. marginatus are as follows:

Males: $W = 0.00423\ CL^{2.6246}$
Females: $W = 0.00090\ CL^{2.9952}$

where W = weight in grams
CL = carapace length in millimeters
a and b = constants

The relationships are shown in Figure 3. For lobsters having a CL of 8.25 cm, the equations predict a total weight of 453.2 g (1 lb, 0 oz) for males and 496.0 g (1 lb, 1.5 oz) for females.

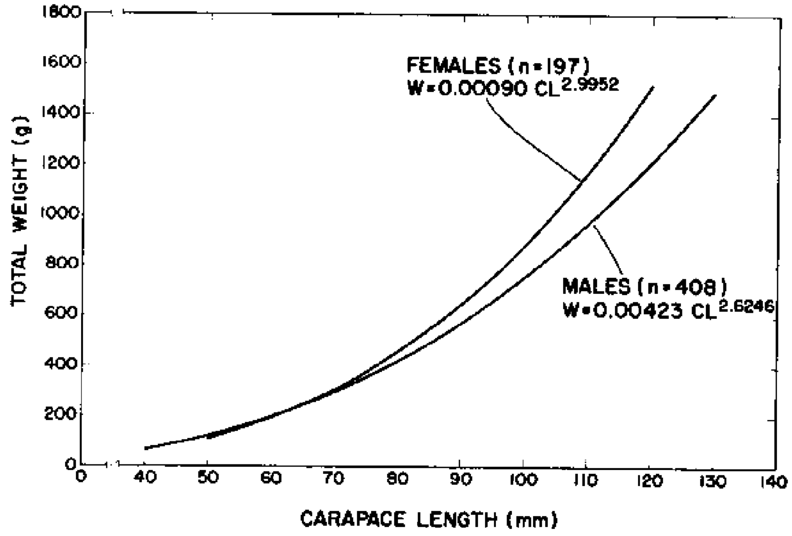

Figure 3. Length-weight relationship of male and female Panulirus marginatus determined from samples collected at Necker Island, French Frigate Shoals, and Maro Reef during cruise TC-78-04

It is interesting to note that males are slightly heavier than females at CL below 65 mm. At 65 mm CL, the males and females attain almost identical weights. From about 70 mm CL, the females are heavier, as compared with males of equivalent size and this difference can be attributed to an increase in tail weight in relation to total weight among females. Berry (1971) reported that elongation of the legs and enlargement of the cephalothorax among the South African lobster, P. homarus, accounted for the decrease in tail weight relative to total weight with increased size in males.

Relationship between carapace length and tail weight

Because accurate weighing of samples at sea is difficult due to the motion of the vessel, we believed it advisable to weigh the tails when fresh, frozen, and thawed to determine the variability when these attributes were regressed against CL. According to our preliminary analysis, frozen tail weight showed the least amount of variability about the line of best fit (i.e., had a higher correlation value). Furthermore, the differences in frozen and fresh weight, and frozen and thawed weight, were very small in almost all the samples collected. Therefore, in this report, frozen tail weight is used exclusively, because this attribute can be weighed rather precisely in the laboratory.

For enforcement purposes in situations where a vessel lands only frozen tails, it is useful to know the relationship between CL and frozen tail weight, provided that the former is used as a criterion for minimum legal size. During TC-78-04, 623 such measurements were collected. Carapace lengths of 402 males varied from 48.1 to 121.3 mm; for 221 females, CL varied between 51.9 and 114.7 mm.

An exponential model was fitted to the data for males and for females and the relationships are as follows:

$$\text{Males:} \quad TW = 0.00731\ CL^{2.2536}$$

$$\text{Females:} \quad TW = 0.00094\ CL^{2.7675}$$

where TW = tail weight in grams
CL = carapace length in millimeters

The equations predict that male lobsters with a CL of 8.25 cm would have a tail weight of 152.3 g (5.4 oz) and that female lobsters of minimum legal size would have a tail weight of 190.3 g (6.7 oz).

DISCUSSION AND CONCLUSIONS

The analysis by Uchida and co-workers indicated that the spiny lobster is distributed widely from Nihoa to Kure in the NWHI. Data on CL collected during our surveys showed striking differences in the average sizes of the unexploited population among the areas visited. Necker Island, for example, which had the highest catch rates, had the smallest average sizes among both males and females. Considering that the average sizes were small even at the outset of the survey, it is possible that there is a density dependent effect of stock size on growth rate caused by intraspecific competition. Such an effect could produce a larger population and may account for the high catch rates at Necker Island.

Because *P. marginatus* is endemic to the Hawaiian Archipelago and has been reported only from Johnston Atoll outside the Hawaiian chain, the resident population in the NWHI must be regarded as the source of larval recruits. Unfortunately, very little is known about the pelagic existence of the phyllosoma larvae of *P. marginatus* and the current patterns around the NWHI. It is possible that phyllosoma larvae emerging in waters of the Hawaiian Islands are carried out to sea by the prevailing surface currents only to be redeposited on substrates around the Hawaiian Archipelago. It is also possible that most of the phyllosoma larvae remain in coastal waters with little or no long-distance movement involved and that local repopulation is occurring. Whatever the mechanism, it is quite apparent that the distribution and abundance of the adults are dependent, to a large extent, on adaptation of the larvae to prevailing oceanographic conditions.

FUTURE RESEARCH NEEDS

To monitor changes in the population structure, we need to continue sampling at banks where relatively little fishing effort has been expended in order to expand our data base on distribution, apparent abundance, CL, weight, and other morphometric characteristics. There is also a need to continue collection of data on berried females to delineate the reproductive cycle.

To study the occurrence of the puerulus, we have built Withan larval collectors, which will be placed at selected sites, and we will also expand our night-light observational program. Traps with enlarged openings are presently being used in attempts to capture individuals larger than 14 cm CL, which have been taken in our traps only infrequently.

SUMMARY

The present study elucidated several aspects of the unexploited populations of *P. marginatus* in the NWHI and some of the results appear to be particularly significant. Analysis of our data showed that there were striking differences in the average sizes of lobsters among the various islands and banks surveyed. The stock at Necker Island, in particular, presented an interesting contrast to that found elsewhere in the NWHI chain. At Necker, our surveys revealed that the average size of both males and females was the smallest and this phenomenon was evident even during our first survey at this island.

Our initial surveys also revealed that the proportion of legal-sized lobsters was relatively high in most areas and that males predominated in the catch. Data on egg-bearing females in the catch disclosed that there is a marked seasonality in reproduction with peaks in early summer to fall.

The length-weight relationships predicted that an 8.25 cm CL lobster would weigh 453.2 g for males and 496.0 g for females. This differential growth between the sexes was attributed to an increase in tail weight in relation to total weight among females as a result of egg bearing. The relationship between CL and tail weight predicted that legal-sized males would have a tail weight of 152.3 g as opposed to 190.3 g in females.

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PRELIMINARY RESULTS OF STUDIES ON FECUNDITY OF THE SPINY LOBSTER, PANULIRUS MARGINATUS, IN THE NORTHWESTERN HAWAIIAN ISLANDS

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ABSTRACT

Part of an investigation of the marine resources of the Northwestern Hawaiian Islands includes studies on the biology of the spiny lobster, *Panulirus marginatus*. This paper deals with the fecundity of *P. marginatus* collected from Necker Island and Maro Reef during 1978-79. Estimates of fecundity were made on 34 egg-bearing females. The number of eggs carried generally increased in relation to an increase in carapace length (CL). The smallest female (56.7 mm CL) in the sample carried an estimated 129,000 eggs. The largest female (104.6 mm CL) was found to have an estimated 454,000 eggs.

Northwestern Hawaiian Islands
Panulirus marginatus
fecundity

INTRODUCTION

The spiny lobster, *Panulirus marginatus*, which is endemic to the Hawaiian Archipelago and Johnston Atoll (Brock, 1973), is of great importance in the sport and commercial fisheries in the major Hawaiian Islands. Trapping surveys in the Northwestern Hawaiian Islands (NWHI) indicate that this species is taken at depths greater than 28 m (10 fathoms) (see paper by Uchida et al., part I).

One of the biological parameters of interest in the management of the resources is fecundity. Fecundity of *P. marginatus* caught off Oahu was previously estimated by Morris (1968) and by McGinnis (1972). However, no estimates have been made for *P. marginatus* caught in the NWHI; therefore, a study was initiated to determine their fecundity and also to examine whether significant differences occured in fecundity among lobsters caught at different localities throughout the archipelago.

METHODS

The material used in this report was collected at Necker Island and Maro Reef during cruises of the NOAA ship Townsend Cromwell (TC-78-04 and TC-79-02) during October 20-27, 1978 and March 31-June 6, 1979. The lobsters were caught in the California two-chambered lobster pot (Uchida and Hida, 1977). The traps were baited and set in the late afternoon and picked up the next morning. Thirty-four egg-bearing or "berried" females were collected during these cruises.

The carapace length, defined as the distance along the mid-dorsal line from the transverse ridge between supraorbital spines to the posterior margin of the carapace, was measured to the nearest 0.1 mm. In the field, egg masses were collected by carefully stripping the setae of pleopods on which the egg masses were attached. The egg masses collected from each pleopod were then frozen separately for later examination in the laboratory.

In the laboratory, the egg masses from each pleopod were preserved in a solution of 4% formaldehyde and seawater and allowed to harden for about 30 days. Before processing the egg masses, they were blotted with paper towels for 15 minutes and weighed to the nearest 0.001 g. Total weight of the egg masses was derived by summing the weight of the egg mass on each pleopod. A sample of eggs weighing approximately 0.125 g was then taken from each pleopod to make up a sample of 1 g. All the eggs in this sample were counted. The total number of eggs carried was then calculated by simple proportion:

$$\frac{\text{Weight of sample}}{\text{No. of eggs in sample}} = \frac{\text{Total weight of eggs}}{\text{Total no. of eggs carried}} \qquad (1)$$

RESULTS

Although the upper and lower size ranges of lobsters were inadquately represented in the sample, the results showed that the number of eggs carried by a female increases in relation to an increase in carapace length ($r = 0.810$; $df = 33$; $P < 0.01$) (Table 1). The relationship between the number of eggs carried and carapace length (Figure 1) is expressed by the equation:

$$Y = -226399 + 5541.3X^{*} \qquad (2)$$

where X = carapace length in millimeters
Y = number of eggs carried

*Additional samples collected recently from females larger than 104.6 mm CL indicate that the relationship may be curvilinear.

TABLE 1. CARAPACE LENGTH AND THE ESTIMATED NUMBER OF EGGS CARRIED BY SPINY LOBSTER, *PANULIRUS MARGINATUS*, CAUGHT AT NECKER ISLAND AND MARO REEF

Carapace Length (mm)	Estimated No. of Eggs	Carapace Length (mm)	Estimated No. of Eggs
56.7	129,266	85.6	133,350
58.6	96,602	86.3	339,289
58.8	94,053	86.6	235,003
60.9	60,101	86.7	330,095
61.8	136,534	86.7	242,887
63.0	160,196	86.8	193,560
64.7	166,897	87.2	228,322
67.9	171,607	87.5	178,780
67.9	143,005	88.3	299,581
68.9	105,767	88.8	246,068
71.5	161,370	89.0	257,692
71.6	166,050	89.9	303,233
73.4	202,428	91.4	161,562
77.8	237,730	93.4	389,552
78.0	194,075	96.8	315,518
81.2	207,247	99.4	282,183
82.4	240,533	104.6	454,362

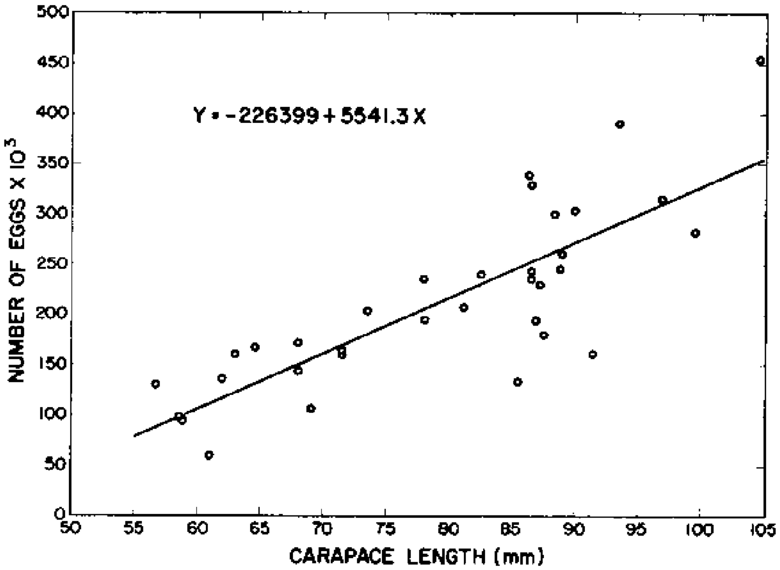

Figure 1. Relationship between the number of eggs carried and carapace length in the spiny lobster, *Panulirus marginatus*

DISCUSSION AND CONCLUSION

To determine whether the estimates obtained from this study differed from those provided by other investigators, comparisons were made for certain sizes for which estimates were available either in tabular form (Morris, 1968) or graphic form (McGinnis, 1972) (Table 2).

TABLE 2. CARAPACE LENGTH AND THE NUMBER OF EGGS CARRIED BY FEMALE <u>PANULIRUS MARGINATUS</u> AT OAHU, NECKER ISLAND, AND MARO REEF

Carapace Length (mm)	Estimated Number of Eggs Carried		
	Oahu*	Oahu†	Necker Island and Maro Reef§
54	--	--	72,831
69	134,000	--	155,951
70	--	140,000	161,492
80	--	210,000	216,905
81	261,000	--	222,446
83	228,000	--	233,529
87	271,000	--	255,694
89	280,000	--	266,777
90	--	280,000	272,318
93	328,000	--	288,942
95	263,000	--	300,024
98	--	--	316,648
100	--	410,000	327,731
101	440,000	--	333,272
101	431,000	--	333,272
101	467,000	--	333,272
102	--	--	338,814
102	--	--	338,814
105	495,000	--	355,438
110	--	575,000	--
111	--	--	--

*Data from Morris (1968).
†Data from McGinnis (1972).
§Data from this study and estimated by the regression equation.

Comparison of data from Morris (1968) with those obtained from this study showed rather good agreement at the lower size range. Morris estimated that a female of 83.0 mm CL caught off Oahu carried 228,000 eggs compared to an estimated 233,529 eggs carried by a female of similar size caught in the NWHI. At a larger size of 101 mm CL, however, the discrepancy was larger; this study estimated 333,272 eggs whereas Morris estimated from 431,000 to 467,000 eggs.

The egg counts for <u>P. marginatus</u> were also similar at the lower size range to counts obtained by McGinnis (1972) for specimens also caught around Oahu. For example, McGinnis found that <u>P. marginatus</u> of 70 mm CL produced about 140,000 eggs. In comparison, a 70-mm CL female in this study was estimated to carry 161,492 eggs. At larger sizes, however, the counts by McGinnis on Oahu lobsters were higher. His data showed that a 90-mm CL female carried about 280,000 eggs, whereas the equation calculated for this study predicts that at 90 mm CL, the number of eggs carried by a female is 272,318.

The estimates of the number of eggs carried obviously vary with the accuracy and precision of the sampling, weighing, and counting. Kensler (1967) found that the number of eggs in a gram sample can vary from 6,453 to 8,341 for Jasus verreauxi. Morgan (1972) reported that fecundity can be calculated with some degree of accuracy by basing egg counts on individual females and by not averaging counts based on several specimens of different sizes.

Apparently, P. marginatus is less fecund than other members of the genus. Berry (1971) showed that a 70 mm CL P. homarus of South African waters carried 309,907 eggs. Ino (1950) estimated that a 71 mm CL P. japonicus carried 524,000 eggs. Berry (1973) reported that a female Palinurus delagoae carried far fewer eggs for its size than any of the other members of Palinuridae. Apparently, the smaller number of eggs carried by the females of this species is associated with the comparatively large egg size. Berry added that like many other deepwater crustaceans, P. delagoae produces relatively few large eggs which have a prolonged incubation period. The extended incubation produces larvae which when hatched are in an advanced stage of development. Egg size, then, appears to be an important consideration when studying fecundity.

FUTURE RESEARCH NEEDS

Additional samples, particularly in the lower size ranges below 60 mm CL and in the upper size ranges beyond 90 mm CL, are needed to extend the range and improve the estimates already obtained. As more data are accumulated, comparisons will be possible to determine variations in fecundity estimates among the islands and banks sampled.

SUMMARY

Egg counts were made on 34 female Panulirus marginatus caught at Necker Island and Maro Reef. The smallest female (56.7 mm CL) carried an estimated 129,000 eggs whereas the largest female in the sample (104.6 mm CL) carried an estimated 454,000 eggs. The study also showed that the number of eggs carried increases relative to an increase in CL. A comparison of estimates of the number of eggs carried by female spiny lobsters caught off Oahu shows relatively good agreement with those obtained for the females caught at Necker Island and Maro Reef.

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POPULATION ESTIMATES AND YIELD-PER-RECRUIT ANALYSIS FOR THE SPINY LOBSTER, PANULIRUS MARGINATUS, AT NECKER ISLAND

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ABSTRACT

Data from commercial fishermen and research sampling for lobster fishing at Necker Island are examined. The abundance of lobster appears to be very heterogeneous with the greatest abundance in the northwestern part of the Necker bank. Estimates of virgin population size and catchability for this region are 125,000 legal lobsters and 3.94×10^{-5} per trap-night, respectively. The estimated range of sustainable yield from the northwest region based on the minimum legal size of 8.25-cm carapace length and the present population size is 10,000 to 21,000 legal lobsters per year. Yield-per-recruit analysis indicates that substantially greater yields may be possible if the minimum legal size is reduced from 8.25 cm. However, this latter result is based on strong assumptions about recruitment which can only be confirmed by field tests.

Necker Island
spiny lobsters
sustainable yield
yield per recruit

INTRODUCTION

Commercial spiny lobster, *Panulirus marginatus*, fishing began on a regular basis off Necker Island in the Northwestern Hawaiian Islands in November 1976. Seven commercial fishing vessels from Honolulu reported lobster catches during the period from November 1976 through April 1979. Some of these vessels trapped in the area frequently while others trapped only occasionally.

This report analyzes and summarizes commercial and research data for the *P. marginatus* fishery off Necker Island during the period from November 1976 through April 1979. Estimates of virgin population size, catchability, and sustainable yield are obtained and a yield-per-recruit analysis is performed. The commercial data consists of monthly totals of the number of legal lobsters caught and the effort expended (Table 1).

TABLE 1. TOTAL MONTHLY CATCH (IN NUMBERS) AND EFFORT (IN TRAP-NIGHTS) IN THE COMMERCIAL FISHERY FOR LEGAL LOBSTERS AT NECKER ISLAND, OCTOBER 1976-APRIL 1979

Date	Region I		Region II		Total	
	Catch	Effort	Catch	Effort	Catch	Effort
1976						
Oct.	107	73	--	--	107	73
Nov.	616	156	--	--	616	156
Dec.	984	276	--	--	984	276
1977						
Jan.	10,030	1,656	1,599	1,081	11,629	2,737
Feb.	--	--	--	--	--	--
Mar.	--	--	--	--	--	--
Apr.	--	--	--	--	--	--
May	15,588	3,480	67	53	15,655	3,533
June	7,132	1,936	461	122	7,593	2,058
July	9,727	2,447	24	75	9,751	2,522
Aug.	5,404	1,832	678	534	6,082	2,366
Sept.	10,524	2,944	293	120	10,817	3,064
Oct.	2,901	916	58	120	2,959	1,036
Nov.	1,885	600	--	--	1,885	600
Dec.	2,485	824	--	--	2,485	824
1978						
Jan.	1,314	254	203	92	1,517	372
Feb.	978	300	--	--	978	300
Mar.	3,687	1,482	54	60	3,741	1,600
Apr.	3,022	719	398	112	3,420	831
May	3,160	687	--	--	3,160	687[1]
June	2,940	1,260	--	--	3,849	1,724
July	2,167	603	--	--	2,167	603
Aug.	2,014	585	--	--	2,014	585
Sept.	202	246	--	--	202	246
Oct.	1,574	606	1,373	401	2,947	1,007
Nov.	116	56	5,222	2,349	5,338	2,405
Dec.	--	--	7,040	3,139	7,040	3,139
1979						
Mar.	1,563	658	--	--	1,563	658
Apr.	1,925	958	--	--	1,925	958

[1] Two stations with no positions.

A legal lobster is defined as a lobster with a carapace length equal to or exceeding 8.25 cm. These data were collected by National Marine Fisheries Service (NMFS) observers aboard commercial vessels or were reported in catch reports submitted by the vessels' owners. The unit of effort is measured as one baited trap fished on the lobster ground for one night, henceforth referred to as a trap-night. The research data consist of total number and effort, as well as length and sex, for lobsters caught at sampling sites from the RV Townsend Cromwell.

Necker Island is surrounded by a large bank (Figure 1). The commercial catch by position indicates that the fishermen have primarily trapped in the northwest region of this bank, indicated as Region I in Figure 1. There were 90,368 legal lobsters trapped in Region I from January 1977 through April 1979; only 17,740 legal lobsters were trapped on the rest of the bank (Region II) during the same period (Table 2). The catch per unit effort (CPUE) in Region II (Figure 2) shows considerable variation, and some of the more recent values for CPUE approach those for Region I (Figure 3). However, because of the lack of a longer series of catch and effort data for Region II, this report will focus only on Region I. By isolating Region I for study, we are making the assumption that the lobster population in this region is closed. This may not be an unreasonable assumption for adult lobsters because tagging experiments by NMFS indicate minimal migration. However, in the case of larval recruitment this may not be the case and for the long term, the assumption of a closed population in Region I may not be valid.

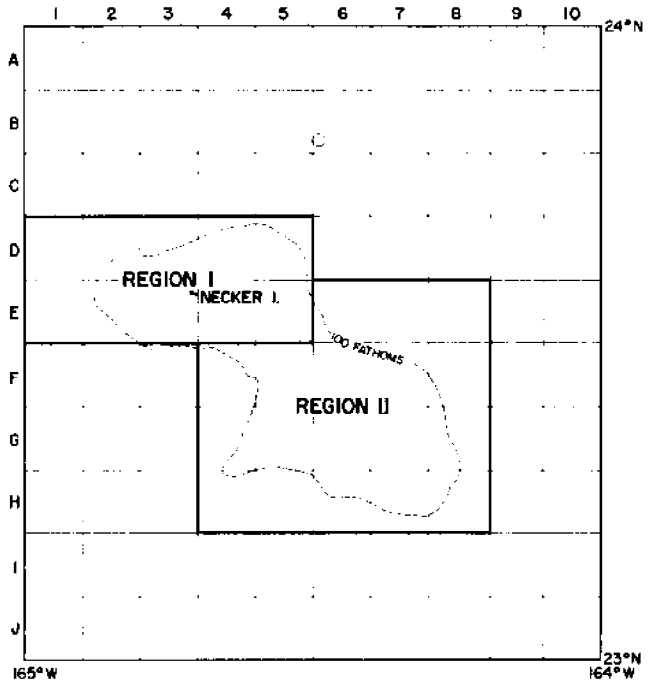

Figure 1. Necker bank

TABLE 2. THE ANNUAL CATCH (IN NUMBERS OF LOBSTERS), EFFORT EXPENDED (IN TRAP-NIGHTS), AND CATCH PER UNIT EFFORT FOR LEGAL LOBSTERS AT NECKER ISLAND BY COMMERCIAL VESSELS FROM JANUARY 1977-APRIL 1979

Year	Catch	Effort	Catch Per Unit Effort
Region I			
1977	65,676	16,635	3.95
1978	21,201	6,798	3.12
1979 (1/1-4/30)	3,491	1,616	2.16
Region II			
1977	3,180	2,105	1.51
1978	14,290	6,153	2.32
Combined (Regions I and II)			
1977	68,856	18,740	3.67
1978	35,491	12,951	2.74

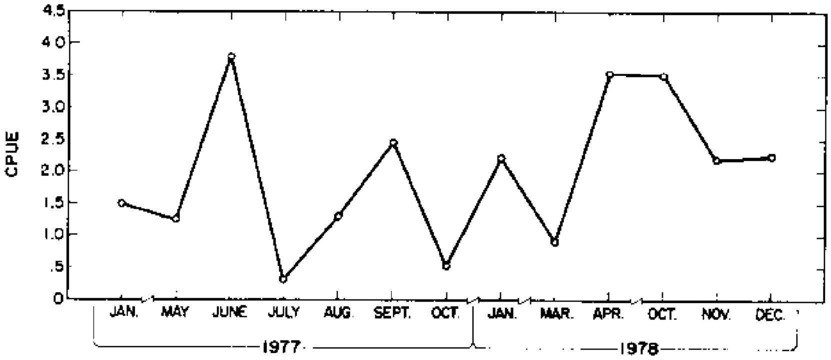

Figure 2. Catch per unit effort (in legal lobsters per trap-night) from Region II at Necker Island

RELATIVE ABUNDANCE

Catch per unit of effort provides a measure of relative abundance. Changes in CPUE over time can result from changes in population structure and size, as well as changes in fishery methods and gear. In the case of the lobster fishery at Necker between November 1976 and April 1979, the changes in fishing methods and gear have been minimal. A graph of CPUE for legal lobsters from Region I on a monthly basis is presented in Figure 3. Considerable month-to-month variation as well as a declining trend is apparent.

One reason for some of the month-to-month variation in CPUE is that the monthly CPUE is computed by pooling the catch and effort for all the

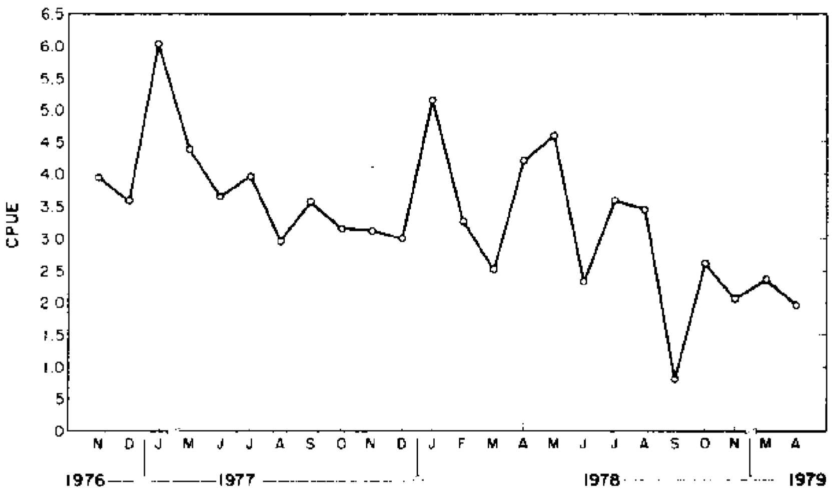

Figure 3. Catch per unit effort (in legal lobsters per trap-night) from Region I at Necker Island

vessels reporting trips to Necker during the month. These vessels are not always the same vessels but a subset of the seven commercial vessels which comprise the fleet.

Catch per unit effort computed on an annual basis has declined each year from 1977 to 1979, although the 1979 figure should be treated with caution because it is based on only an effort of 1,616 trap-nights and may change when more 1979 data are available (Table 2).

A regression of CPUE against month, weighted by effort, indicates that at the 5% level the decreasing trend in CPUE for 1977 is significant while the trend in 1978 is not. The CPUE for January 1977 and January 1978 represents a sharp increase from the preceding and following months indicating a possible seasonal trend which should be examined as more data become available.

The percentage of legal lobsters in the total lobster catch provides an index of the proportion of legal lobsters in the population to the total lobster population. A decrease in this index could mean that the number of legal lobsters in the population has been reduced and/or the number of sublegal lobsters in the population has increased due to increased reproduction, survival, or immigration. We found that the percentage of legal lobsters in the catch for the RV Townsend Cromwell decreased from 54.2% in November 1976 to 23% in May 1979 (Table 3).

POPULATION ESTIMATES

The primary approach we selected to estimate population size was a method proposed by Allen (1966) (see Appendix 1). Basically, this method consists of a least squares procedure which estimates population size and catchability by minimizing the sum of squares between the actual catch and the predicted catch based on effort.

TABLE 3. THE AMOUNT OF EFFORT EXPENDED (IN TRAP-NIGHTS) AND PERCENTAGE OF LEGAL LOBSTERS CAUGHT AT NECKER ISLAND BY THE RV *TOWNSEND CROMWELL*

Date	Effort (Trap-Night)	% Legals in Catch
	Region I	
Oct.-Nov. 1976	145	54.2
May 1977	32	40.0
Oct. 1977	116	42.0
Mar. 1978	57	35.0
Oct.-Nov. 1978	104	37.1
May 1979	48	22.8
	Region II	
Sept.-Oct. 1977	234	62.6
Mar. 1978	61	81.0
Oct. 1978	52	67.0

We used the monthly commercial catch and effort data from November 1976 through April 1979 to estimate population size and catchability. Allen's model assumes natural mortality and recruitment operate in the population. In its most general form, this model assumes that the rate of natural mortality is constant while recruitment may vary over time. This most general form requires that the use supplies estimates of the natural mortality rate and the recruitment rates. We do not have any size and age data which might allow us to estimate these parameters and consequently, we used a simplified version of Allen's model. We assumed that the ratio of the rate of natural mortality to the recruitment rate ($e^{-M}/1-W_i$) in Appendix 1 is constant. Given effort, we then estimated this constant as the value which gave the best fit of predicted catch to actual catch. We feel the assumption that the ratio (rate of natural mortality to recruitment rate into the fishery) is constant may not be unreasonable for the 2-year period of our study. If it takes 6 or more years for a lobster to grow from larval stage to legal size, and if the majority of the mortality occurs during the early years of life, then even an intense reduction of the population of legal lobsters in 1977 will not have a major effect on the ratio of natural mortality rate to recruitment rate until 6 years later.

The plots of actual monthly catch and predicted monthly catch estimated by Allen's method are presented in Figure 4. The fit of the model to the data is good. Based on this method, we estimate that there were 132,406 legal lobsters in Region I at the beginning of November 1976. This number declined to 68,571 legal lobsters by April 1979. A plot of the monthly estimated population size is given in Figure 5. As could be expected from the catch and CPUE data, the population size of legal lobsters dropped severely during 1977 and decreased very slowly during 1978.

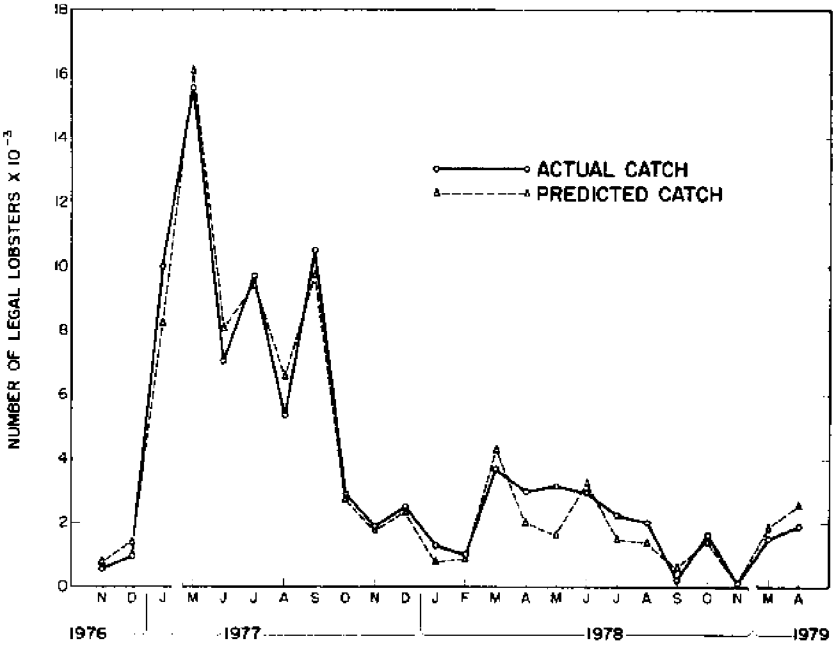

Figure 4. Catch predicted from Allen's model versus actual catch of legal lobsters from Region I at Necker Island

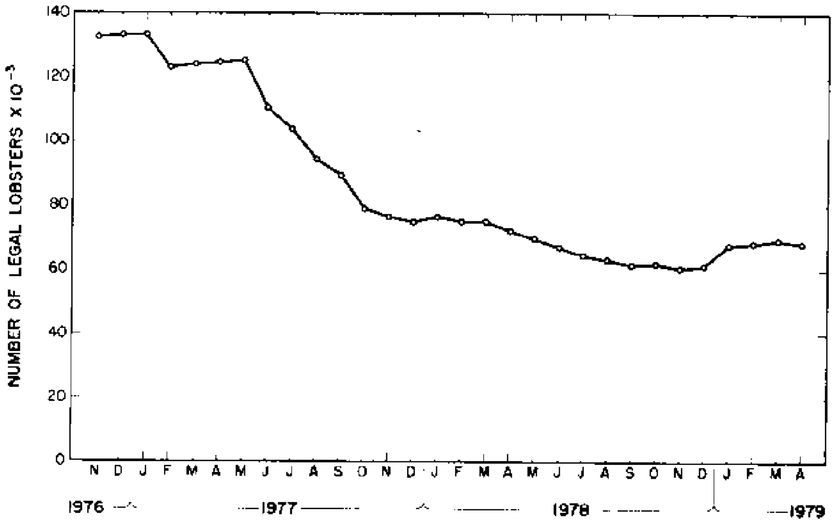

Figure 5. Estimated population size of legal lobsters from Allen's model for Region I at Necker Island

As an independent check on the results obtained by Allen's method, we used Leslie's method of population estimation. This method is used to estimate population size and catchability in situations where there has been intensive fishing of a closed population over a short period of time. Since this method applies to fishing over a short period of time, we assume that natural mortality and recruitment are negligible.

We noticed from Table 1 that trapping was very intense from May through August 1977. We used these data to estimate the population size of legal lobsters at the beginning of May 1977 and the catchability by Leslie's method. The estimated population size and catchability obtained from Leslie's method is in agreement with the estimates obtained by Allen's method (Table 4).

TABLE 4. A COMPARISON OF THE ESTIMATES FROM THE LESLIE AND ALLEN METHODS

	Leslie	Allen
N_{May}	127,000	125,000
q	3.58×10^{-5}	3.94×10^{-5}

N_{May} is an estimate of the number of legal lobsters in Region I beginning May 1977; q is the catchability coefficient.

Lobster yield-per-recruit analysis

We can explore the relationship between size at entry into the fishery (minimum carapace size) and yield with the Beverton-Holt equilibrium yield equation. We will assume that over the range of minimum legal sizes of interest, the number of recruits to a given size is constant, that the lobster growth can be approximated by a von Bertalanffy equation, and that the lobster weight can be expressed as: weight = a $(\text{length})^b$. We then write the yield per recruit into the fishery Y/R as:

$$\frac{Y}{R} = \left(\frac{F}{K}\right)\left(W_\infty\right)\left(e^{Zt_m}\right)\left[B\left(X,\ b,\ \frac{Z}{K}\right)\right]$$

where F is the fishing mortality, K is the growth coefficient for the von Bertalanffy curve, W_∞ is the asymptotic lobster weight, $Z = F + M$, M is the natural mortality, $t_m = t_{min} - t_0$, where t_{min} is the minimum age of entry into the fishery and t_0 is the age of zero length in the von Bertalanffy curve, and B(X, b, Z/K) is the incomplete beta function evaluated at $X = e^{-Kt_m}$, and b is the allometric coefficient.

We will evaluate Y/R at several levels of fishing effort and several minimum carapace lengths. We selected fishing effort (f) at the following levels (trap-nights): 2,500, 5,000, 7,500, 10,000, 12,500, and 15,000. Based on these values of f we can estimate F as F = qf where $q = 4 \times 10^{-5}$ from Allen's method. We selected the following values for the minimum legal carapace length: 6.75, 7.25, 7.75, and 8.25 cm. The value of t_m corresponding to these lengths can be estimated from the von Bertalanffy curve. We determined W_∞ to be 3,580 g and the coefficient b in the weight-length relationship as b = 2.6 from data in McGinnis (1972). There is not any one data set for lobster growth which appears sufficiently reliable. Results from tagging and modal analysis by NMFS gives the estimates: K = 0.26/yr and L_∞ = 12.5 cm. Observations by McDonald of an 18-cm carapace curve suggests L_∞ could be as high as 18 cm. We, thus, performed the yield-per-recruit analysis for the following sets of K and L_∞ values: (K = 0.05, L_∞ = 18 cm), (K = 0.1, L_∞ = 15 cm), (K = 0.2, L_∞ = 12 cm). We used the relationship:

$$\frac{F + M}{K} = \frac{(L_\infty - \bar{l})}{\bar{l} - l_{min}}$$

where l_{min} is the minimum carapace length, $\bar{l}$ is the mean carapace length of the population above l_{min}, and F and M are the fishing and natural mortality, respectively (Beverton and Holt, 1956).

We are able to estimate the ratio M/K by taking a length-frequency distribution from a sample of the population taken from Necker Island in November 1976--before any substantial fishing effort was applied to the region. This sample, consisting of 744 lobsters, estimated M/K at approximately 3.5 for L_∞ = 12 cm. For the yield-per-recruit analysis, we used values for M/K as 2, 3, and 4.

From the results of the yield-per-recruit analysis, we determined the carapace length from among the set 6.75, 7.25, 7.75, and 8.25 cm, which gave the greatest yield (Table 5). In most situations, a minimum carapace length of 6.75 cm achieved the maximum yield per recruit. Only when M and M/K are low and L_∞ is large is the yield per recruit achieved with a minimum carapace length greater than 6.75 cm.

TABLE 5. CARAPACE LENGTH (IN CENTIMETERS) AT WHICH THE MAXIMUM YIELD PER RECRUIT (IN GRAMS) IS OBTAINED

		Fishing Effort					
		2,500	5,000	7,500	10,000	12,500	15,000
$\frac{M}{K} = 2$	K = 0.05, L_∞ = 18	7.75	8.25	8.25	8.25	8.25	8.25
	K = 0.1, L_∞ = 15	6.75	6.75	6.75	7.25	7.25	7.75
	K = 0.2, L_∞ = 12	6.75	6.75	6.75	6.75	6.75	6.75
$\frac{M}{K} = 3$	K = 0.05, L_∞ = 18	6.75	6.75	7.25	7.25	7.75	7.75
	K = 0.1, L_∞ = 15	6.75	6.75	6.75	6.75	6.75	6.75
	K = 0.2, L_∞ = 12	6.75	6.75	6.75	6.75	6.75	6.75
$\frac{M}{K} = 4$	K = 0.05, L_∞ = 18	6.75	6.75	6.75	6.75	6.75	6.75
	K = 0.1, L_∞ = 15	6.75	6.75	6.75	6.75	6.75	6.75
	K = 0.2, L_∞ = 12	6.75	6.75	6.75	6.75	6.75	6.75

An examination of the yield-per-recruit results suggest that an adoption of a 6.75-cm minimum carapace length could, in the worst case ($K = 0.05$, $L_\infty = 18$, $M = 0.1$, and $F = 15,000$), result in a 15% decrease in yield per recruit from the minimum carapace length of 8.25 cm, and at best ($K = 0.2$, $L_\infty = 12$, $M = 0.8$, $F = 1,500$), achieve a 167% increase in yield-per-recruit over an 8.25-cm minimum carapace length (Table 6). Clearly, these results should be interpreted cautiously because we have no evidence to suggest that the level of recruitment will remain unchanged when the minimum carapace length is lowered to 6.75 cm. However, the magnitude of the possible increase in yield which may be achieved with a reduction from the existing minimum carapace length should serve as impetus for further study and testing.

TABLE 6. YIELD-PER-RECRUIT (IN GRAMS) AS A FUNCTION OF FISHING EFFORT (IN TRAP-NIGHTS) AND MINIMUM LEGAL CARAPACE LENGTH (IN CENTIMETERS) FOR SELECTED GROWTH AND MORTALITY PARAMETERS

	Fishing Effort					
l_{min}	2,500	5,000	7,500	10,000	12,500	15,000
$\frac{M}{K} = 4$, $K = 0.2$, $L_\infty = 12$						
6.75	124	216	287	343	388	425
7.25	90	157	210	252	286	314
7.75	64	112	150	180	205	226
8.25	44	78	105	126	144	159
$\frac{M}{K} = 3$, $K = 0.1$, $L_\infty = 15$						
6.75	210	305	355	384	402	415
7.25	194	285	334	364	383	397
7.75	177	262	310	340	360	373
8.25	160	239	284	313	332	346
$\frac{M}{K} = 2$, $K = 0.05$, $L_\infty = 18$						
6.75	318	339	335	327	321	315
7.25	321	351	351	347	342	338
7.75	321	358	363	361	349	356
8.25	319	362	371	372	371	370

CONCLUSIONS

The analysis of commercial catch and effort data indicating the decline in CPUE from 3.95 in 1977 to 3.12 in 1978 strongly suggests that a population size of 65,676 legal lobsters is not sustainable with a CPUE of 3.90. This is further supported by the decline in the percentage of legal lobsters per trap from the Cromwell sampling data. The fact that we do not reject the hypothesis that CPUE did not decline during 1978, based on the test of the slope of the regression line, suggests that a yield of 21,201 legal lobsters per year may be sustainable with a CPUE of about 3.00. We can use the result of Allen's model to compute the surplus production which can be harvested without reducing the population size. This value is obtained by multiplying the population size of legal lobsters by the ratio of the natural mortality rate to the recruitment rate for legal lobsters and subtracting the initial population size. We estimated the population size at the beginning of 1979 to be 67,766 legal lobsters and the ratio of the monthly rate of natural mortality to recruitment to be 1.0116. Consequently, for 1979, we estimate that slightly over 10,000 legal lobsters can be harvested for the year without reducing the population size of legals. Thus, based on the data presented here, the annual surplus production of legal lobsters in 1979 is estimated to be between 10,000 and 21,000.

Finally, due to the results of our theoretical yield-per-recruit analysis, it is suggested that future research undertake field trials to ascertain the impact of a lower legal size on yield per recruit.

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APPENDIX 1

Allen's population estimation procedure

A method developed by Allen (1966) was used to estimate population size at time t (N_t), catchability (q) given effort at time t (X_t), and catch (C_t). M is the natural mortality, W_i is the proportion of the new recruits in the exploited stock for the ith season, and A is the ratio of the number of animals that die per month to the number of animals that are recruited per month. The essential relationships of this model are given below:

Year 1 Initial population $= N_1$

Survival to beginning of next season $= (N_1 - C_1)e^{-M}$

Expected catch $= \left(N_1 - \frac{C_1}{2}\right)qX_1$

Year 2 Initial population $= N_2 = \frac{(N_1 - C_1)e^{-M}}{1 - W_2}$

Survival to beginning of next season $= \left[\frac{(N_1 - C_1)e^{-M}}{1 - W_2} - C_2\right]e^{-M}$

Expected catch $= \left[\frac{(N_1 - C_1)e^{-M}}{1 - W_2} - \frac{C_2}{2}\right]qX_2$

Continuing in this way we can show that at the beginning of year t the population equals

$$N_t = \frac{e^{-(t-1)M}}{\prod\limits_{i=2}^{t}(1-W_i)}\left[N_1 - C_1 - \frac{C_2(1-W_2)}{e^{-M}} \cdots \frac{C_i\prod\limits_{j=2}^{i}(1-W_j)}{e^{-(i-1)M}} \cdots \frac{C_{t-1}\prod\limits_{j=2}^{t-1}(1-W_j)}{e^{-(t-2)M}}\right]$$

$$= A_t\left[N_t - f(C)_{t-1}\right],$$

where

$$A = \frac{e^{-(t-1)M}}{\prod\limits_{i=2}^{t}(1-W_i)}$$

and

$$f(C)_{t-1} = C_1 + \sum_{i=2}^{t-1}\frac{C_i}{A_i}\ .$$

about 3.00. We can use the result of Allen's model to compute the surplus production which can be harvested without reducing the population size. This value is obtained by multiplying the population size of legal lobsters by the ratio of the natural mortality rate to the recruitment rate for legal lobsters and subtracting the initial population size. We estimated the population size at the beginning of 1979 to be 67,766 legal lobsters and the ratio of the monthly rate of natural mortality to recruitment to be 1.0116. Consequently, for 1979, we estimate that slightly over 10,000 legal lobsters can be harvested for the year without reducing the population size of legals. Thus, based on the data presented here, the annual surplus production of legal lobsters in 1979 is estimated to be between 10,000 and 21,000.

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Year 2 Initial population $= N_2 = \frac{(N_1 - C_1)e^{-M}}{1 - W_2}$

Survival to beginning of next season $= \left[\frac{(N_1 - C_1)e^{-M}}{1 - W_2} - C_2\right]e^{-M}$

Expected catch $= \left[\frac{(N_1 - C_1)e^{-M}}{1 - W_2} - \frac{C_2}{2}\right]qX_2$

Continuing in this way we can show that at the beginning of year t the population equals

$$N_t = \frac{e^{-(t-1)M}}{\prod_{i=2}^{t}(1-W_i)}\left[N_1 - C_1 - \frac{C_2(1-W_2)}{e^{-M}} \cdots \frac{C_i\prod_{j=2}^{i}(1-W_j)}{e^{-(i-1)M}} \cdots \frac{C_{t-1}\prod_{j=2}^{t-1}(1-W_j)}{e^{-(t-2)M}}\right]$$

$$= A_t\left[N_t - f(C)_{t-1}\right],$$

where and

$$A = \frac{e^{-(t-1)M}}{\prod_{i=2}^{t}(1-W_i)} \qquad f(C)_{t-1} = C_1 + \sum_{i=2}^{t-1}\frac{C_i}{A_i} .$$

POPULATION BIOLOGY OF SPINY LOBSTERS IN THE LAGOON AT KURE ATOLL - PRELIMINARY FINDINGS AND PROGRESS TO DATE

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ABSTRACT

This study is primarily aimed at collecting and evaluating the most critical information identified by the Western Pacific Regional Fishery Management Council, National Marine Fisheries Service, and the Hawaii Division of Fish and Game for improving state and federal management plans for spiny lobsters in Hawaii. The standing stock of the lobster population at the Kure Atoll lagoon study site has been estimated by two techniques. Visual counts of lobsters by divers indicated there were upwards of 1,000 lobsters at the study site. Over the same period a total of 1,620 lobsters were collected in traps and tagged in the same area. Catch per unit effort (CPUE) based on 791 trap-nights, averaged 0.611 ± 0.277 (mean and standard deviation). Trap catches do not seem to have been influenced by a dominance hierarchy based on size, and CPUE does not seem to have been influenced by seasonal or lunar factors. Examination of size frequency distributions obtained from diver-caught animals and those obtained from commercial-style traps shows that the latter failed to capture lobsters with less than about 7-cm carapace length. Modified traps made of smaller mesh appeared to provide unbiased samples of lobsters over their entire size range which coincide with diver catches. Population structure in terms of size composition varied during the year in apparent response to seasonal recruitment of lobster larvae. A total of 306 puerulus lobster larvae was recruited primarily in June-October and recruitment seemed heavier during the new moon and first quarter lunar phases. A high level of spatial overlap of juveniles and adults has been observed in the lagoon at Kure Atoll. Juveniles tend to occur as members of groups in dens; adults (> 6-cm carapace length) tend to be found as solitary occupants.

spiny lobsters
Hawaii
population biology
stock assessment

INTRODUCTION

Interest is currently increasing in harvesting lobsters in the Northwestern Hawaiian Islands (NWHI) especially since lobster stocks in the southern inhabited islands are now low. Two species of spiny lobster occur throughout the Hawaiian Archipelago, but only one, *Panulirus marginatus* is fished throughout the island chain and is the primary subject of the developing lobster fishery in the NWHI. In this paper only *P. marginatus* is considered.

The fisheries and biological data presently available for *Panulirus marginatus* in Hawaii are not sufficient for planning and management. In part, this is because it is not yet known how catch per unit effort of fishing is related to standing stock in Hawaii and we do not know how catchability differs over time. Consequently there is no measure of the reliability of present estimates of population size and sustainable yield based on catch per effort data. Additionally, nothing is known about the population biology of young lobsters before they enter the fishery. The complete lack of information detailing patterns of larval recruitment further confounds management of the resource. Finally, there is a complete lack of understanding of movements and use of space by spiny lobsters.

This study is designed to produce accurate estimates of population size, rates of growth, natural mortality, and movement largely from mark-recapture techniques. It is also intended to assess the extent of stock autonomy and the annual pattern of larval recruitment. Such data will enable the Western Pacific Regional Fishery Management Council (WPRFMC) to decide what maximum sustainable yield is appropriate within the NWHI and whether or not that fishery can be expanded. Additionally, this information will assist the Hawaii Division of Fish and Game (HDFG) in evaluating their existing management policy for spiny lobsters around the eight major Hawaiian Islands at the southern terminus of the archipelago and in the nearshore waters within their jurisdiction throughout the island chain. Finally, the results of this study are certain to be of value to the U.S. Fish and Wildlife Service in making critical habitat decisions that pertain to the Hawaiian monk seal which is a predator of lobsters and to be of general use in wildlife refuge management in the NWHI.

The results that we present in this paper are mostly preliminary. This is particularly true of our analysis of catch rates by traps and the study of larval recruitment since we are only ten months into our two-year sampling program. The patterns that have emerged to date, however, should be particularly useful to government agencies in the design of future sampling programs for spiny lobsters and in the resolution of uncertainties inherent in some of the existing data.

Selected results that pertain to general patterns of lobster distribution and abundance, catch rates, population size distribution, recruitment of puerulus larvae, and use of shelter by juveniles and adults are summarized in this report.

METHODS

The study is being conducted in the lagoon at Kure Atoll. Kure is the northernmost emergent land in the Hawaiian Archipelago and is part of the Hawaii State Wildlife Refuge. Samples were collected primarily between June 1979 and May 1980. The investigation uses several standard techniques for the study of spiny lobster population biology. The basic procedures include (1) trap sampling, (2) diving sampling, (3) mark-recapture, and (4) lobster larvae sampling.

Fifty commercial-style lobster traps have been positioned at permanent locations in the lagoon for the duration of the study. They are dispersed over an area of about 2 km^2 and sample a representative range of lobster habitats and densities. Ten of the traps are completely covered by a 0.65-cm mesh screen. These modified traps can retain the entire size range of lobsters at Kure. Twenty of the commercial-style traps and five of the modified traps are fished one night each week, based upon a stratified-random sampling design. At all other times the traps are unbaited and access lids are secured open. In this condition, these traps do not retain lobsters that may inadvertently enter them during the night. Catch per unit effort is calculated as the number of lobsters caught per trap per night. Catches from commercial-style and modified traps are combined and all sizes of lobsters are included in the CPUE estimates.

Sampling by diving is conducted during January, June, and September. This schedule provides representative seasonal coverage. Sampling is performed by diving over the entire study area using SCUBA. An attempt is made to capture every lobster sighted. A number of workers have stated that the size distribution of lobsters in natural populations can best be represented by diver-caught samples (Pollock and Beyers, 1979). Reef structures which afford shelter to one or more lobsters are referred to as "dens." The total number and appfoximate size of all lobsters in each den is recorded and a tail snare (Kanciruk and Herrnkind, 1976) is used to extract as many lobsters as possible. All shelters are permanently numbered (approximately 560 to date) and all lobsters are returned to their original shelter by divers. All measurements and tagging are done by other personnel aboard an outboard skiff that closely accompanies the divers.

All lobsters caught are either tagged or individually marked, and immediately released. The western Australian spiny lobster tag (Chittleborough, 1974) is used to identify all adults. Juveniles are marked by punching holes in the telson (tail fan) of the lobster according to a set of binary codes. In addition, all lobsters are marked by clipping the distal portion of each pleopod (swimmeret). The particular pleopod to be clipped differs each month. This provides a time-specific mark to assess the extent of tag loss.

Puerulus lobster larvae are collected using improved "Witham" collectors (Witham et al., 1968; Little, 1977). Twenty of these collectors are buoyed up at the surface and moored at permanent stations up to several hundred meters apart in the lagoon at Kure. Larval collectors were deployed in June 1979. The collectors are checked once each week and any larvae present are counted and removed. The species of puerulus larvae are discernible using biochemical-genetic techniques (J. Shaklee, Department of Zoology, University of Hawaii, Honolulu, personal communication). The species of larvae that were caught in the collectors, however, have not yet been determined and the results to date could include larvae of two species.

RESULTS

Estimation of lobster abundance

Visual counts of lobsters made by divers during the three initial surveys indicated that the standing stock of *P. marginatus* within the study area was upwards of 1,000 lobsters. Over the initial ten months of the study, diving and trapping resulted in the collection of a total of 1,620 *P. marginatus* over a wide range of carapace lengths (1.8 to 15.5 cm). About 28% of those collected were recaptures. Estimates of absolute abundance will be derived from mark-recapture techniques.

Analysis of catch-rates

Catch per unit effort for the lagoon population was generally lower than expected when compared with the range of catch rates encountered in the commercial fishery. The average catch rate in the study area at Kure Atoll was 0.611 ± 0.277 (mean and standard deviation). This mean catch rate was based on 791 trap-nights of fishing distributed over 10 months.

Many factors could influence CPUE and the influence of two of these is being examined. CPUE apparently did not differ much with either season or moon phase but did vary greatly through the sampling period (Figure 1). The pattern was less clear during October to November when sampling was repeatedly interrupted by severe storms (dashed line in Figure 1). It is clear, however, that the range in July did not differ markedly from that in January. The variability observed in the CPUE is ascribed to random fluctuations.

Water temperature varied markedly over the year at Kure Atoll (range from 17° to 29°C). It is surprising that this and other environmental factors such as day length and food availability evidently did not exert any seasonal influence on the catch rate given that, in other studies, CPUE is associated with seasonal molt cycles and water temperature changes (Morgan, 1974; Pollock and Beyers, 1979). CPUE varied broadly over all moon phases (Figure 1). This was also unexpected because the moon is known to influence the CPUE of certain other commercial species of spiny lobster through the apparent influence it exerts on the level of foraging activity (Sutcliffe, 1956; Morgan, 1974).

Comparison of size frequency distributions

Lobsters caught by divers are widely believed to more nearly represent an unbiased sample of the size frequency distribution of the population than lobsters caught by other methods. This assumption was tested by comparing the carapace length frequency distributions of lobsters caught and measured with those based upon the estimated length of

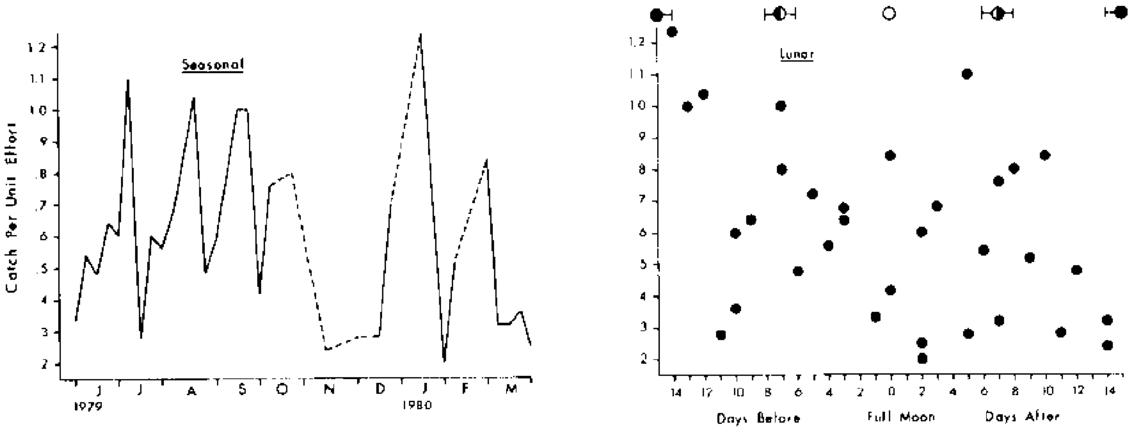

Figure 1. Changes in catch per unit effort over seasonal and lunar cycles

all lobsters seen by divers (Figure 2). The shaded area in Figure 2 represents males; the unshaded area represents females. Small lobsters are ≤ 7 cm, medium lobsters are 8 to 11 cm, and large lobsters are ≥ 12-cm in carapace length. Overall, divers caught about 50% of the lobsters they found. Frequency distributions based upon measurements and estimates of length corresponded closely in each season. Samples of lobsters collected by divers are concluded to be largely free of bias.

Carapace lengths of lobsters sampled by commercial-style traps, modified traps, and divers were compared to determine whether or not trap samples give a biased estimate of the population size distribution (Figure 3). Samples were pooled over sex and season. Traps identical to those commonly used in the commercial lobster fishery in the NWHI did not catch small lobsters less than about 7-cm carapace length. The results from the modified traps indicate that small lobsters probably entered the commercial-style traps, but were not retained by their larger mesh size. The results from the modified traps did not differ much from the results based on diver catches or diver estimates. Therefore, lobsters caught in modified traps appear to constitute a representative sample over the entire range of carapace lengths of juveniles and adults. The correspondence between the size distribution obtained with modified traps and that from diver catches or estimates suggests that there is no dominance hierarchy based on carapace length that significantly influences the catch of traps. Commercial-style traps evidently catch the larger individuals selectively solely because of their large mesh openings.

Annual changes in size frequency distributions and larval recruitment

The population size distribution did not remain constant throughout the year (Figure 2). Large lobsters were relatively more abundant in January. Small lobsters were relatively more abundant in June and September. Males tended to be more abundant than females in each season and predominated in the large size classes (Figure 2). The seasonal differences in size distribution indicate that larval recruitment to the population is seasonal beginning in spring and continuing at least through the summer. The virtual absence of 4 to 5-cm lobsters in January and their

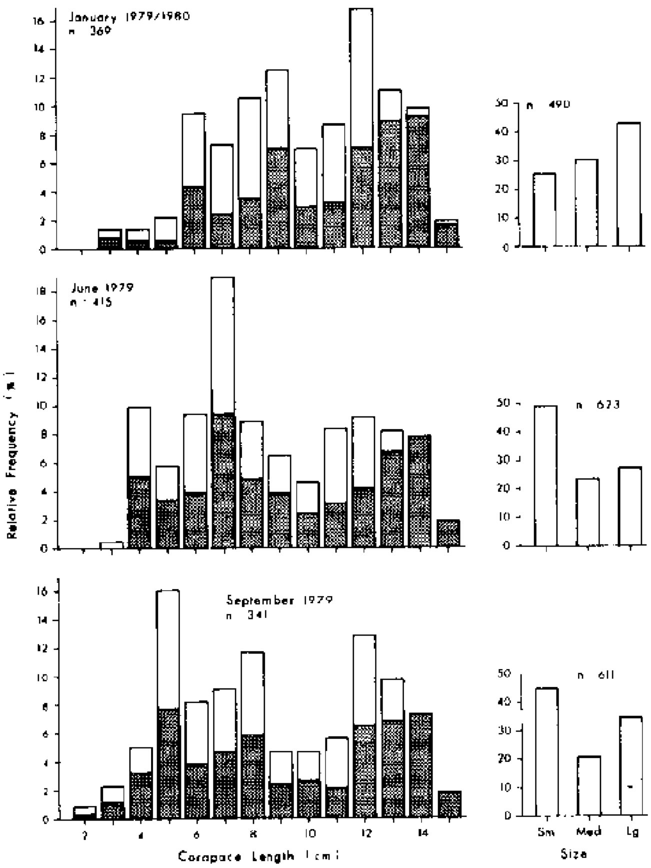

Figure 2. Seasonal comparison of carapace length distributions of lobsters caught by divers and measured versus distributions of size classified by divers while underwater

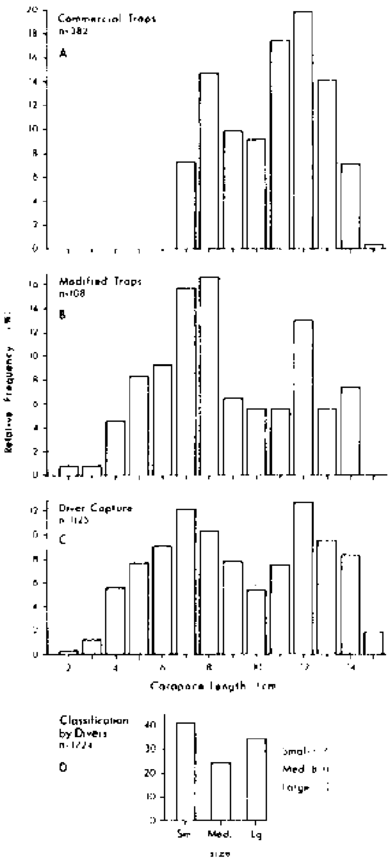

Figure 3. Comparison of size distributions based on different sampling methods

pronounced increase by June and September is indicative of a high rate of growth during the first year after the puerulus larval state. Puerulus larvae were about 1-cm carapace length upon settling. A progression of modes produced by the growth of individuals is suggested by some of the peaks below and at 9-cm carapace length. The rate of growth that this could indicate, however, seems unreasonably high based on preliminary examination of molt increments derived from the recapture of tagged lobsters.

Puerulus larvae were recruited to collectors from June to October but not from October to March (Figure 4). Unanalyzed data recently obtained further indicate that larvae were also recruited from March to May, thus recruitment was strongly seasonal at Kure. A total of 306 puerulus larvae were collected. Although storms interrupted the sampling series at different times during late fall and winter (dashed line in Figure 4), we can be quite certain that larvae did not recruit on days that were not sampled. Puerulus larvae of other species of spiny lobster apparently remain on

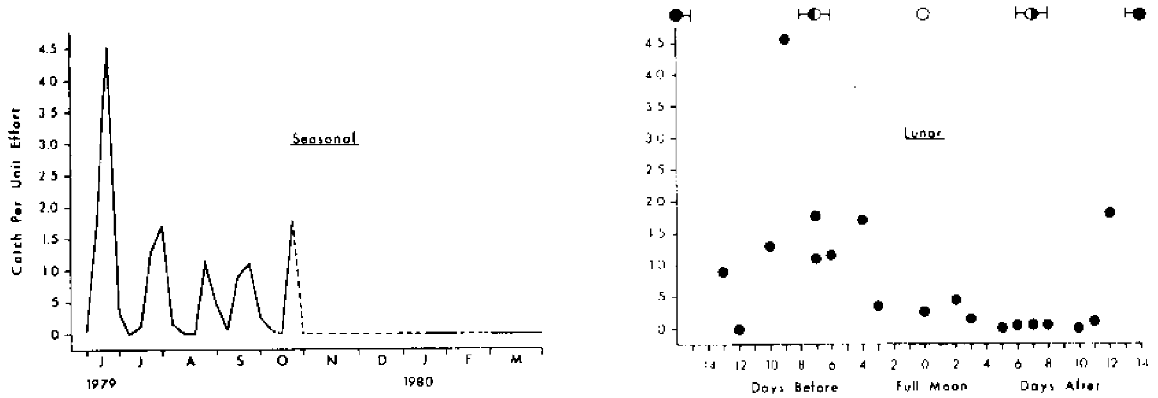

Figure 4. Pattern of recruitment by puerulus larvae over seasonal seasonal and lunar cycles

collectors for a period of at least a month (Phillips, 1972; Booth, 1979). Collectors at Kure were always checked at intervals of three weeks or less and if larvae had settled one or two weeks earlier they probably would have been present when collectors were examined. This seasonality in larval recruitment confirms the earlier expectations that were based upon the seasonal changes in population size distribution of juveniles and adults. There is also strong seasonality in the reproduction of females; ovigerous females only occur during May to September.

Puerulus larvae were recruited most frequently during the new moon and first quarter phases (Figure 4). Our sample size is relatively small but will increase as sampling continues. The phase of the moon exerts a similar influence on the pattern of puerulus larval recruitment of several other species of spiny lobster that have been studied (Phillips, 1972; Little, 1977).

Examination of shelter patterns

The den occupancy pattern in each season was characterized by a high frequency of solitary lobsters (Figure 5). The sexes are combined in this comparison. Pairs and larger groups (maximum of 40+ in one den) occurred with lesser frequency. This general pattern of shelter-use was constant throughout the year. Overall, the proportion of dens with one lobster was 57% whereas the proportion of dens with more than one lobster was 43% (Table 1). In terms of animals, however, more than 80% of the lobsters residing in the various habitats were found in the company of one or more other lobsters. These results are similar to related information from shallow habitats in the Caribbean for Panulirus argus (Herrnkind et al., 1975).

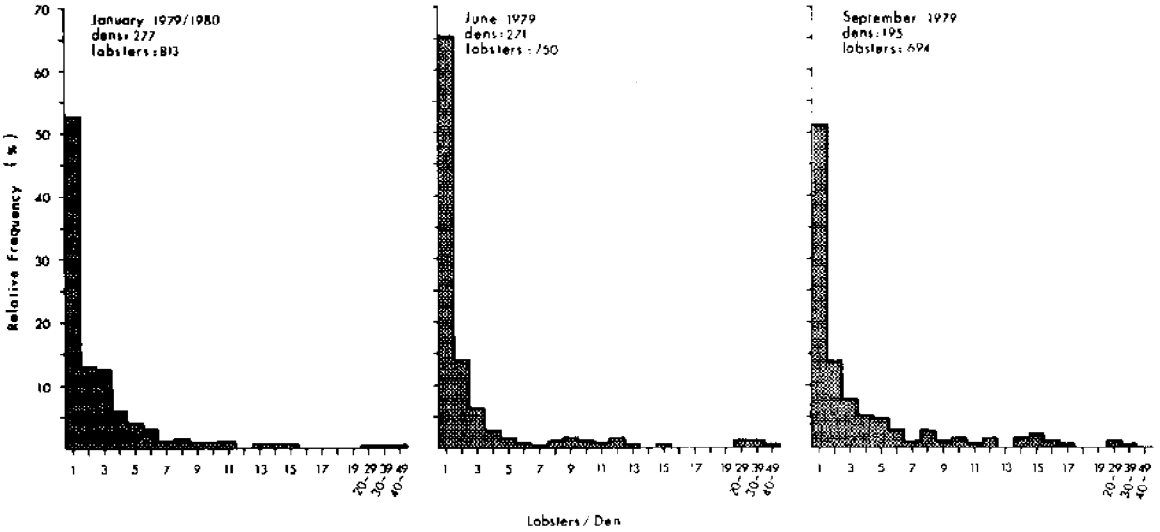

Figure 5. Seasonal comparison of den occupancy patterns

TABLE 1. LONG-TERM SHELTER PATTERNS AT KURE ATOLL

Class	Occupancy (%)		
	Single	Multiple	n
Dens	56.9	43.1	743
Lobsters	18.7	81.3	2,257

Juvenile and adult lobsters of both sexes frequently share the same den (Figure 6). The shaded blocks in Figure 6 represent males; the unshaded blocks represent females. Juvenile lobsters (less than about 6 cm in carapace length) seldom occurred by themselves and the sexes evidently did not differ in this regard. The number of data points in any lobster/den class can be less than indicated by the class designation because not all lobsters in the den were always caught. Figure 6 is based on 402 lobsters that were captured and measured. The results presented are for June but are typical of the results based on measurements of lobsters collected by divers in September and January as well. The relationship between carapace length and den occupancy pattern was more noticeable when the relative frequency of small, medium, and large lobsters obtained from records of divers estimates was compared across all levels of den occupancies (Figure 7). The sexes were combined in this comparison and sample sizes are indicated in Figure 7. The general relationship between carapace length and den occupancy did not vary much seasonally but was more apparent in June and September than in January.

Other progress

The rate of dispersal of P. marginatus is slow and individual movements have not exceeded distances of several hundred meters. Juveniles especially appear to move much less than adults.

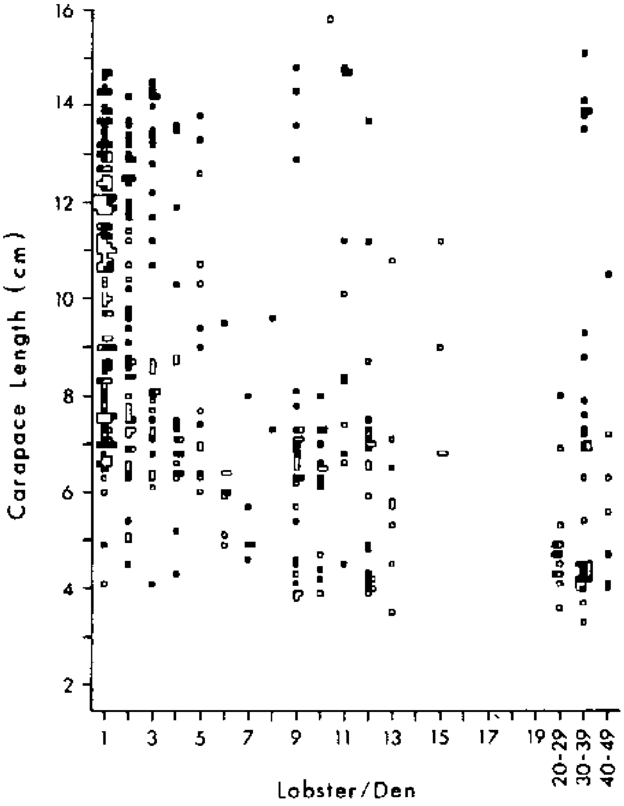

Figure 6. Relationship between carapace length and den occupancy pattern by sex

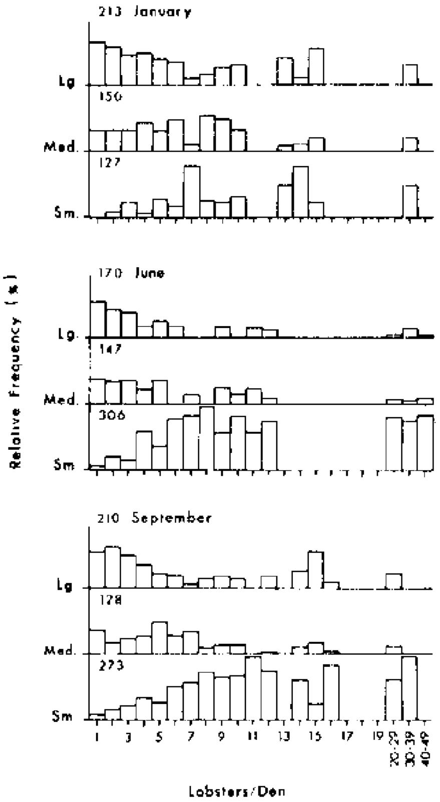

Figure 7. Relationship between size of lobsters classified by divers and den occupancy

This study has been expanded to include two species of slipper lobster, *Scyllarides squammosa* and *S. haani*, which have accounted for 63% of our total trap catches. *S. squammosa* and *S. haani* are sympatric with *P. marginatus* throughout the Hawaiian Archipelago and account for less than 10% of the commercial lobster catches in the NWHI. Nothing is known about the biology of *S. squammosa* and *S. haani* and the population biology of slipper lobsters in general is poorly understood. A total of 1,017 slipper lobsters with a wide range of carapace lengths (3.8 to 14.8 cm) was collected by diving and trapping. About 28% of those sampled were recaptures. At the beginning of September, a few slipper lobster larvae entered the puerulus larvae collectors. It was not previously known with certainty that *S. haani* occurred in Hawaii.

DISCUSSION AND CONCLUSIONS

Juvenile and adult *P. marginatus* are not segregated geographically or by habitat within Kure lagoon. There are no specific nursery areas in which juveniles reside apart from adults during the first few years of their benthic life. This is in noted contrast with what is generally known of other commercially important species of spiny lobster. In other species, juveniles tend to reside in shallow nearshore areas and move offshore as they grow and become sexually mature (Witham et al., 1968; Chittleborough, 1970; Berry, 1971; Olsen et al., 1975). Assuming that juvenile and adult lobsters behave similarly in offshore areas, i.e., they do not segregate geographically or by habitat, small lobsters are probably at greater risk of capture by commercially fished traps in Hawaii than at other locations where there are discrete nursery areas and where small and large lobsters are less likely to occur together on commercial fishing grounds. Consequently, the problems associated with handling and releasing sublegal lobsters, such as incidental damage and reduced survivorship, are of greater potential magnitude in Hawaii than elsewhere.

Shelter is used differently by juveniles and adults throughout the year. Results of the study of den occupancy patterns by P. marginatus demonstrated that juveniles were more likely to reside in multiple-occupancy dens than solitary dens. The limited data presently available indicate that juveniles maintain greatly restricted home ranges and that larger lobsters tend to range more widely. These data suggest that multiple-occupancy dens serve as refuges for juveniles until they have grown large enough to successfully forage more widely within an enlarged home range or to become slightly nomadic in their movements.

Although commercial-style lobster traps do not catch the smaller juveniles, they do catch sublegal animals that are less than the minimum legal carapace length (8.25 cm). This finding strengthens the need for a regulation that requires means of escapement of sublegal lobsters by designating either mesh size or the dimensions and location of escape gaps. Our findings that catches from modified traps tend to represent unbiased samples of the population size distribution is of considerable practical importance because it suggests that modified traps may provide the means to randomly sample the entire size range of lobsters on the commercial fishing grounds where the depths are too great and conditions are too hazardous for the use of SCUBA. Modified traps would be particularly useful to monitor trends in growth rates and survivorship of juveniles on the commercial fishing grounds since these parameters may vary in direct response to increased pressure as fishing effort intensifies. Rates of juvenile growth and mortality are important variables that are used to estimate levels of fishing production.

Data for almost one year indicate that recruitment of puerulus larvae is seasonal at Kure Atoll. Reproduction at Kure is also seasonal. The larvae of other species of spiny lobster are known to have long planktonic residence times of 8 to 11 months (Johnson, 1974). The larvae recruited at Kure during any one year are probably from reproduction in the previous year. The use of biochemical-genetic techniques by Shaklee indicates that lobsters at Kure and several other widespread geographic locations in the Hawaiian Archipelago are indistinguishable (J. Shaklee, Department of Zoology, University of Hawaii, Honolulu, personal communication). This suggests there may be sufficient mixing of the larvae while in the plankton that larvae produced around one island may recruit elsewhere in the island chain.

Recruitment of puerulus larvae at Kure coincides with the period when the northern boundary of the north Pacific central water "type" is expected to pass Kure in its annual northward and southward shift in location (Seckel, 1962). According to this model, the Hawaiian Archipelago is predominantly bathed by the north Pacific central water system which changes location in association with the seasonal variation in the intensity and position of surface currents around its boundary. This may mean that the seasonal availability of puerulus larvae will be determined to a large extent by an island's position relative to the northern and southern boundaries of the north Pacific central water type. If so, recruitment should occur more or less regularly throughout the year at islands centrally located in the Hawaiian Archipelago. Recruitment at the southernmost islands such as Oahu, however, should be seasonal and should occur at the opposite time of the year than at Kure because of the northward displacement of the north Pacific central water type from around Oahu during April to October (Seckel, 1962). This prediction will be tested in part over this next year by deploying larval collectors at Oahu which will be monitored concurrently with the larval collectors at Kure.

FUTURE RESEARCH NEEDS

The major goal of the present management policies of the WPRFMC and the HDFG for P. marginatus is to protect females with eggs and juveniles so as to maximize yield and to protect reproductive potential. Regulations designed to meet these goals include the release of all females with eggs and all lobsters less than 8.25-cm carapace length. Although sublegal lobsters and females with eggs must be released according to law, they are seldom returned to their origin of capture under existing commercial fishing practices. There is no information to decide whether displacement from a given area of reef increases natural mortality and whether or not displaced lobsters return to their home reef. In fact, it is not known whether these regulations achieve their stated goals of protecting females with eggs and sublegal lobsters so that they may respectively reproduce or survive and grow to a harvestable size.

Knowledge of the success of these regulations is critical because these measures are the only ones presently invoked to manage the fishery in the NWHI. If natural mortality subsequent to release is high, the level of production realized may be less than what could be obtained by retaining these lobsters and instead curtailing entry and possibly limiting effort particularly when the sustainable yield becomes known. The question of the success of these regulations is particularly pertinent in view of recent findings by other workers that the yield per recruit is highest when lobsters are harvested at carapace lengths of 7 cm or even less (J. Polovina, Southwest Fisheries Center Honolulu Laboratory, National Marine Fisheries Service, NOAA, Honolulu, and G. Marten, East-West Center, University of Hawaii, Honolulu, personal communications). Also, females are more likely to reproduce only during the summer months in the NWHI so that at Midway Islands, for example, 50 to 70% of all females caught during June to August would have to be released (MacDonald and Thompson, unpublished manuscript). Commercial fishing in the NWHI is most intense during this period because unfavorable weather interferes with or prevents fishing at other times during the year. Additionally, regulations that protect females with eggs will probably increase the fishing mortality of males. As a result, females with eggs may eventually come to constitute an even greater proportion of the total catch in the future, thereby increasing any negative economic impact associated with significantly increased mortality of lobsters that were handled and released.

SUMMARY

Catch per unit effort varied over the ten months for which we have data (June 1979 to March 1980), but seasonal and lunar influences were not apparent. Deviations from the mean were ascribed to random fluctuations.

The size frequency distribution of lobsters obtained from diver catches was concluded to be free of bias. Commercial-style traps undersampled small lobsters less than 7-cm carapace length apparently due to escapement. Modified traps sampled lobsters in a manner similar to divers, indicating that if a dominance hierarchy existed based on size, it did not significantly influence trap catches. The population size distribution varied during the year evidently in response to the seasonal recruitment of puerulus larvae. Large lobsters were predominant in January whereas small lobsters were predominant in June and September.

Puerulus lobster larvae were recruited seasonally and were influenced by moon phase. Larvae were recruited from June to October but not from October to March. Unanalyzed data recently obtained further indicate that larvae were also recruited from March to May. Puerulus larvae were apparently recruited most frequently during the new moon and first quarter phases.

Juveniles and adult P. marginatus were not segregated geographically or by habitat in Kure Atoll lagoon. Juveniles seldom occurred by themselves and the size of the lobsters in multiple-occupancy dens tended to decrease with increased number of occupants. More than 80% of the lobsters residing in the various habitats were found in the company of one or more other lobsters although more than half of the dens were occupied by solitary individuals. This general pattern of shelter-use remained the same throughout the year.

ACKNOWLEDGMENTS

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TROPHIC STUDIES OF SHALLOW-WATER FISH COMMUNITIES IN THE NORTHWESTERN HAWAIIAN ISLANDS

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ABSTRACT

This is a preliminary report on the first six months of a two-year program. The central objective of this program is to determine the general outlines of trophic relationships among major fish species and between major fish species and invertebrate groups in the lagoon area of two sites in the Northwestern Hawaiian Islands: French Frigate Shoals and Midway Islands. Estimates of population size of fish groups at certain trophic levels will be integrated with other NWHI projects, particularly ecosystem modeling. Field work has concentrated on a reconnaissance of all NWHI sites, extensive shark fishing at French Frigate Shoals, and two intensive survey and collection expeditions to French Frigate Shoals and Midway Islands. To date over 119 carcharinid sharks and 100 carangids have been collected, as well as over 4,500 reef fishes. Age determination has begun for the carcharinid species. Intensive data analysis is planned for the summer and fall of 1980.

INTRODUCTION

It is important at the outset to point out that the information contained herein is preliminary and that this project is still in progress. No definitive conclusions can be reached at this point; data gathering and analysis are still underway.

The guiding objectives of these studies are the following:

1. Determine the general outlines of trophic relationships among major fish species and between major fish species and invertebrate groups in the reef/lagoon area

2. Estimate composition and abundance of important invertebrate prey groups as they occur naturally in typical fish feeding areas

3. Identify instances where diet overlap, species abundance, and feeding ecology suggest that important competitive relationships may exist among fish, seabirds, seals, man, or some combination thereof

4. By comparing this type of trophic information in (a) a relatively pristine NWHI situation, (b) an experimentally "fished" NWHI situation, and (c) a high island situation, assess the effects of top carnivore predation on community trophic structure

5. If possible, identify the routes and rates of movement of reef/lagoon fish production out to deeper water

6. Determine local, short-term effects of fishing pressure on top predators and the fish community

7. For top pelagic predators of the reefs and shoals, obtain basic quantitative estimates of population size and age structure that relate to trophic role and response to fishing

The information from this study will provide a reasonable understanding of the trophic structure of an important segment of the NWHI fishery resource. This will permit an appreciation of the basis for life support of species present and of their interactions. From this knowledge, and comparing fished and unfished areas, sources of present or potential conflict for resources among species--including endangered seals and turtles, as well as fish, seabirds, and man--can be identified. Predictions can be made of the effects of various exploitation strategies in this nearly pristine area. Population and trophic information, especially on high trophic level predators, will permit planning the wise use of these economically important species. The basic understanding gained of how trophic systems are structured and what controls the structure will be of value in all future study and management of such resources.

METHODS

Collection of animals and qualitative and quantitative data are made on periodic research trips to the NWHI. To date, cruises on the chartered vessel Easy Rider have been made in September and November 1978; and March, June, and October-November 1979. Work has been done at Necker, Nihoa, French Frigate Shoals, Gardner Pinnacles, Maro Reef, Laysan Island, Lisianski Island, Pearl and Hermes Reef, and Midway. An intensive diving survey and collection project has just been completed at Midway. Brief field and logistic reconnaissance has been done at Kure Atoll.

Field procedures include: (1) visual census of shallow-water demersal fish communities; (2) visual reconnaissance, mapping, and quantitative recording of substrate and sessile macro-animals; (3) general, rough visual inventory of certain pelagic fish species, especially top carnivores; (4) collection of pelagic carnivores by longline and pole-and-line or handline fishing; (5) collection of shallow-water demersal fish community by all appropriate fishing methods (e.g., nets, traps, spears); (6) collection of mobile benthic invertebrates by use of an air-lift suction device or collection of substrate (consolidated or unconsolidated).

Laboratory (or deck) procedures include: (1) taking morphometric and meristic data on fishes and weight of all except for the largest species; (2) extracting fish otoliths or vertebrae for age determination; (3) checking fish gonads for sex and reproductive condition; (4) identifying and quantifying diet items from gut contents; (5) extracting benthic invertebrates from the collected substrate, and identifying and quantifying them; (6) analyzing all the above data to determine the trophic structure of the community and meet the stated objectives. Later phases of the project will involve more specific field manipulations and more intensive studies directed at specific groups.

The difficulty of access to most Northwestern Hawaiian Islands sites and the limited time available for extensive studies at any one site have dictated that intensive field studies be concentrated at two localities, French Frigate Shoals and Midway Islands. To date much of the project research has been done operating with small craft from these shore bases for periods of about three weeks at a time. The location at the extreme northwest end and French Frigate Shoals afford a comparison of two ends of the low-lying islands in the northwestern chain.

Data acquisition and analysis have been divided into four sub-areas and these will be treated individually in this report. These sub-areas are: biology of top carnivores (large sharks and the dominant species of carangid); benthic fauna; reef fish surveys; and diet analysis of selected species of reef fish. At present work is in progress on both data collection and analysis of samples collected during 1979 and March-April 1980.

Biology of top carnivores

Studies have concentrated on six species of carcharhinid sharks and the carangid species *Caranx ignobilis*. Sharks were collected using 16- and 32-hook longline techniques described in Taylor and Naftel (1978). Carangids were fished using handline techniques with catch per unit effort recorded as fish/man-hour. Age determination of sharks has begun successfully using methods modified after Stevens (1975). Population estimates of sharks will be made using analysis of changes of catch per unit effort over time (Braaten, 1969). Attempts to estimate population size of *Caranx ignobilis* by tag and recapture methods have proven unsatisfactory due to the dearth of fishing effort in the French Frigate Shoals/Midway areas for this species. Analyses of shark and ulua gut contents are in progress; a reference collection for identification of the various food items available is being assembled. Percentage of occurrence of food items ingested by sharks and ulua will be compared to the relative abundance of food items available as indicated by the benthic sampling and reef fish survey samples.

Reef fish surveys

Reef fish surveys have been conducted to record the fish assemblages at the specific collection sites identified for this project. These surveys allow a comparison of the relative abundance of fishes available for consumption by sharks and ulua. Data from other surveys of workers involved in the cooperative NWHI study, such as E.S. Hobson and personnel of the Hawaii Division of Fish and Game, are used as ancillary information. However, it is important to conduct surveys of reef fishes during the same time periods and at the same locations in which they and large carnivores are sampled. To date, preliminary fish surveys have been made at every Northwestern Hawaiian Islands location, but intensive fish surveys have been limited to French Frigate Shoals and Midway.

To characterize the reef fish assemblages under study at French Frigate Shoals, eleven visual surveys of fish populations were conducted in the four habitat types where collections were made. A modification of the "Brock method" (1954) was used. For each survey, a 25-m transect line was set and, to delimit the survey area, cork floats were placed 5 m from each side of the line at approximately 10-m intervals. In areas where the habitat was sufficiently homogeneous, two 25-m transect lines were set end to end. To minimize disruption to the fish community, surveys were begun 20 minutes after the line had been set. Two observers swam abreast, one on each side of the line, and recorded by species name each individual fish seen within 5 m of their side of the line. During transcription of the data, the observers' counts were combined to obtain the total number of fish of each species seen within 250 m^2. Following completion of the survey, additional species and schools of fish occurring outside the survey area were noted. At each transect location, the benthic habitat was mapped and the identity and abundance of corals and macro-invertebrates were recorded.

A total of eleven surveys were conducted in the four habitat types where French Frigate Shoals collections were made: (1) patch reefs with 85% live coral cover, mainly *Porites compressa* and *Porites lobata*; (2) limestone pavement with 25% live coral cover, mainly *Porites lobata*, *Pocillopora meandrina*, and small patches of *Leptastrea* sp. and *Montipora* sp.; (3) limestone pavement with 15% live coral cover, mainly *Pocillopora eydouxi*, *Pocillopora damicornis*, *Pocillopora meandrina*, *Porites lobata*, and *Porites lichen*; and (4) coral rubble consolidated by coralline algae with 30% live coral cover, mainly *Porites lobata*, *Porites lichen*, and *Porites compressa*.

Analysis of gut contents of selected species of reef fish

To date gut content analysis has been limited to samples from French Frigate Shoals. Complete analysis has been accomplished for only a single species. It is reported herein as an example of the techniques. The data presented are strictly preliminary.

Fish were collected from several specific sites in the 2 to 10 m depth range from the northern part of French Frigate Shoals in October/November 1979 and from several sites distributed over much of Midway lagoon in March/April 1980. Most were taken by spearing with a Hawaiian sling. Collections were also made with gill nets and fish traps.

Speared fish were placed immediately in plastic bags and placed on ice to await transport to a shoreside freezer and then frozen for later examination in the laboratory.

In the laboratory, fish were thawed individually and standard length, fork length, and total length measurements were taken. The fish were then weighed, gutted, and sexed. The viscera were immediately preserved in a 10% formalin solution. Complete identification awaits the establishment of a reference collection now in progress. Displacement volume was taken on the full and empty gut and the volume of the diet items was computed.

Benthic fauna

Coral samples were collected in June by divers using SCUBA. Coral heads were enclosed in plastic bags and broken off using a hammer and chisel. The bags were then sealed and taken to the surface where the coral was (1) preserved in 10% formalin for transporting to the Honolulu laboratory or (2) soaked in dilute formalin to draw out live animals, then broken up and preserved in 10% formalin.

October samples were taken using a drop net approximately 1 m in diameter to enclose an area of coral. Coralline material and infauna were then removed using hammer and chisel and an air lift suction device. Samples were frozen and transported to Honolulu.

Coralline material was processed in the laboratory by one of three methods: (1) the coral was thoroughly washed over a .15-mm sieve which collected all organisms washed off; (2) the carbonate fraction was dissolved with nitric acid using the method of Brock and Brock (1977); and (3) the coral was broken into very small pieces with a hammer and chisel and washed through a .15-mm sieve to collect infauna. After processing by one of these methods, the animals were sorted, identified, and counted.

The June sand samples were collected by coring with a 2,000-ml coffee can. In October/November and March/April sand samples were obtained using a "macrocorer" and coffee cans. The "macrocorer" consists of a metal tube approximately 67 cm in diameter which is forced into the sand to a depth of as much as 12 cm. A metal plate is then slid under the base so that an intact cylindrical slice of the substratum can be removed. The October/November and March/April samples were frozen and the June samples preserved in 10% formalin for transporting to Honolulu. At the laboratory the sand was sieved through a series of sieves (2 mm, 1 mm, .335mm, and .15 mm).

None of the sand or coral samples taken at French Frigate Shoals in October or at Midway in March/April has been processed.

RESULTS

The following discussion is based on preliminary results.

Reconnaissance dives (26 total) were made at several islands in the leeward group in June 1979: French Frigate Shoals, Gardner Pinnacles, Maro Reef, Laysan, Lisianski, and Pearl and Hermes. Work included general observations of shallow-water fish communities and characterization of habitats. A total of eight visual fish censuses and six species lists of areas were selected for more intensive later study. We determined that there are reasonable representative sites, in terms of habitat and fish fauna, at French Frigate Shoals and Miday at which most of the remaining work of the project can be concentrated.

Other individual results of the June cruise included: (1) sighting of a marked monk seal at Maro which gave important evidence of inter-island movement (Laysan-Maro at least) and some estimate of rate of movement; (2) observation of a large, tightly milling aggregation of female gray reef sharks in a very shallow reef area at Laysan; (3) first sighting of the taape, Lutjanus kasmira, at Laysan; (4) collection and return to the Waikiki Aquarium of several masked angelfish, Genicanthus personatus (only seven specimens have ever been seen or collected previously in the state; no males had been taken alive.)

An adult specimen of the shallow-water snapper, toau (Lutjanus fulvus = vaigiensis) was collected at French Frigate Shoals. This is apparently the first report that this species, introduced to the high islands, has moved so far up the archipelago.

Results of top carnivore sub-section

The catch record for sharks and ulua is given in Table 1. The three most abundant shark species caught are the gray reef shark, Carcharhinus amblyrhynchos; and Galapagos shark, Carcharhinus galapagensis; and the tiger shark, Galeocerdo cuvier. Most fishing effort has been at French Frigate Shoals and is reflected in the larger sample size from the area. Many more Caranx ignobilis were caught at Maro Reef however, and this may be due to a real difference in abundance in comparison to French Frigate Shoals where much more effort was expended.

TABLE 1. SUMMARY OF TOP PREDATORS CAUGHT (NUMBER OF FISH WITH IDENTIFIABLE GUT CONTENTS)

Island Species	Nihoa	Necker	FFS	Maro	Laysan	Lisianski	P & H	TOTAL
Carcharhinus amblyrhynchos	4 (1)	7 (3)	22 (14)	7 (4)	2 (0)	0	0	42 (22)
C. galapagensis	4 (1)	4 (1)	14 (4)	19 (8)	0	0	1 (1)	42 (15)
C. limbatus	0	0	2 (1)	2 (0)	0	0	0	4 (1)
C. milberti	0	0	2 (1)	0	0	0	0	2 (1)
C. obscurus	0	0	2 (0)	0	0	0	0	2 (0)
Galeocerdo cuvier	5 (3)	3 (2)	14 (12)	4 (3)	0	0	0	26 (20)
Sphyrna lewini	0	0	1 (1)	0	0	0	0	1 (1)
Caranx ignobilis	0	5 (3)	8 (6)	51 (27)	0	10 (6)	15 (14)	89 (56)
Caranx melampygus	0	1 (0)	2 (1)	1 (1)	0	1 (0)	0	5 (2)
Seriola dumerili	0	0	0	0	0	0	2 (1)	2 (1)

Table 2 gives the results of preliminary gut content analysis for top carnivores. *C. amblyrhynchos* appears to be a piscivore, although it does eat a significant amount of cephalopods. *C. galapagensis*, on the other hand, has cephalopods occurring more frequently than fish. This species also seems to be eating more of the slower-moving fish (e.g., puffers and eels) than the gray reef shark.

The tiger shark seems to be a more opportunistic feeder. Seabirds make up the largest single item in the gut contents, and there is photographic documentation of these sharks taking seabirds in the water. Tigers seem to show a definite preference for slower moving organisms, such as pufferfish, turtles, lobsters, octopuses, and floating seabirds.

The analysis of *Caranx ignobilis* gut contents shows this species to be also highly piscivorous. Scarids, eels, and pufferfish comprise a large part of their diet. Crustaceans and cephalopods also contribute significantly.

Results of preliminary attempts at age determination in the *Galeocerdo cuvier* are portrayed in Figure 1. The regression made from 12 vertebral samples and one point representing the average length of 24 fetal sharks is $L = 21.44T + 40.35$ cm ($r = 0.981$), where T is the number of vertebral rings. This compares with Stevens' (1975) data for the blue shark *Prionace glauca*, $L = 18.41x + 23.18$ cm ($r + 0.987$) where x is the centrum radius in millimeters. It has not been ascertained whether the vertebral rings in Hawaiian *Galeocerdo cuvier* are annual or are correlated with some other time period.

Reef fish surveys

A total of 79 species from 21 families were recorded. The data presented in Table 3 were compiled from all four habitat types to provide a broad overview of the fish population under study at French Frigate Shoals. The relative abundance for each family is the percentage which that family represented of all individual fish counted along all transect lines. Fish of 61 species belonging to six families comprised 90% of the individuals counted during all transects. The family Labridae had the highest relative abundance, accounting for 24% of the total number of individuals observed.

Population densities of wide-ranging pelagic species could not be censused in transects. An indication of the relative abundance of species of the family Carangidae was obtained by recording sightings while occupied with various diving tasks. In 73 man-hours of SCUBA and skin diving, 92 *Caranx ignobilis* approximately 1.0 m in total length and 100 *Caranx melampygus* approximately 0.5 m in total length were observed.

Similarly, species of the family Carcharhinidae were not seen during transects but were observed at other times. During 18 days of field work, 12 *Carcharhinus amblyrhynchos*, 3 *Carcharhinus melanopterus*, and 1 *Triaenodon obesus* were sighted.

Trapping provided incomplete but suggestive data on cryptic and nocturnal species. In 235 trap-days, 47 eels of the genus *Gymnothorax* were collected.

TABLE 2. PERCENTAGE OF OCCURRENCE OF FOOD ITEMS IN TOP PREDATORS (ALL ISLANDS POOLED)

Prey Items	*Carcharhinus amblyrhynchos*	*Carcharhinus galapagensis*	*Galeocerdo cuvier*	*Caranx ignobilis*
Monachus shauinslandi	-	-	10	-
Stenella longirostris	-	-	5	-
Aves	-	-	70	-
Chelonia mydas	-	-	25	-
Chondrichthyes	-	-	10	-
Anguilliformes	23	13	5	23
Muraenidae	-	6.7	-	9
Gymnothorax eurostus	-	-	-	1.8
Gymnothorax moluccensis	-	-	-	1.8
Congridae	4.5	-	-	9
Ariosoma sp.	4.5	-	-	1.8
Conger sp.	-	-	-	3.6
Ophicthidae	4.5	-	-	-
Myrichthys maculosus	4.5	-	-	-
Beloniformes				
Cypselurus sp.	-	-	5	-
Gastereosteiformes				
Aulostomus chinensis	4.5	-	-	-
Mugiliformes				
Sphyraena sp.	-	-	5	-
Perciformes	64	13	20	75
Apogonidae	-	-	5	-
Priacanthidae				
Priacanthus sp.	-	-	-	3.6
Carangidae	-	-	5	-
Scaridae	-	13	-	18
Scarus sp.	-	6.7	-	3.6
Calotomus sp.	-	6.7	-	1.8
Acanthuridae	4.5	-	-	1.8
Acanthurus nigroris	4.5	-	-	-
Cottiformes				
Scorpaenidae	-	6.7	-	-
Tetraodontiformes	4.5	13	20	9
Balistidae	-	-	5	-
Monocanthidae	4.5	6.7	5	1.8
Pervagor spilosoma	4.5	-	5	1.8
Ostraciontidae	-	-	-	7
Diodontidae	-	6.7	10	-
Diodon sp.	-	6.7	10	-
Chilomycterus affinis	-	-	5	-
Decapoda	-	-	40	18
Dardanus punctulatus	-	-	-	1.8
Heterocarpus sp.	-	-	5	-
Palinuridae	-	-	30	5
Panulirus marginatus	-	-	15	3.6
Panulirus pencillatus	-	-	-	1.8
Scyllaridae	-	-	20	-
Scyllarides squammosus	-	-	15	-
Stomatopoda	-	-	-	3.6
Cephalopoda	32	53	25	25
Octopus sp.	27	47	20	7
Teuthoidea	9	20	25	18
Charonia tritonis	-	-	10	-
Holothuroidea	-	-	-	1.8
	N = 22	N = 15	N = 20	N = 56

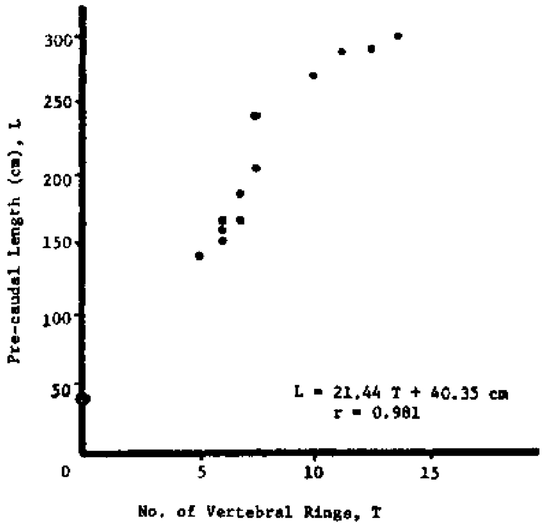

Figure 1. Length vs. number of vertebral rings for <u>Galeocerdo cuvier</u>

TABLE 3. THE SIX FISH FAMILIES MOST FREQUENTLY RECORDED DURING ELEVEN 250 m^2 TRANSECTS AT FRENCH FRIGATE SHOALS

Family	No. Individuals recorded per 250 m^2	Relative Abundance*
Labridae	47	24%
Acanthuridae	39	20%
Pomacentridae	33	17%
Scaridae	28	14%
Mullidae	19	10%
Chaetodontidae	11	5%

*The relative abundance for each family is the percentage which that family represented of all individual fish counted during all transects.

During the recent field work at Midway, fourteen 25-m transects were conducted. The data obtained from these surveys have not yet been analyzed.

Analysis of gut contents of selected reef fish

To date, large numbers of specimens have been analyzed for only a single species, the endemic wrasse <u>Thalassoma ballieui</u>. Data reported here are preliminary and are presented for exemplary purposes only.

Work is continuing on sorting and identifying the various food items in the fish guts from all collected reef fish. Identifiable gut contents are separated by systematic group and stored for later specific identification. All fish samples obtained on the June 1979 cruise and some of the fish from the October cruise have been worked up in this manner. None of the March-April 1980 samples have been examined.

Approximately 20 specimens of *Thalassoma ballieui*, taken from site 3 at French Frigate Shoals during October, have been examined in detail. Preliminary investigations on this species indicate that it is an opportunistic carnivore, feeding primarily on decapod crustaceans, prosobranch gastropods, and occasionally on echinoids, ophiuroids, and small fish.

Benthic surveys

Results are given in Table 4 for coral taken at one site at French Frigate Shoals, combining numbers from all three processing methods. The most abundant taxa are Polychaeta (30.38%), Copepoda (19.45%), Amphipoda (13.82%), Isopoda (10.18%), and Mollusca (13.58%). Decapod crustaceans comprise less than 3% by number of the total fauna. Other organisms found include Nematoda, Sipunculida, Foraminifera, and encrusting and filamentous algae. Gastropod molluscs were the dominant taxon (58.79%) in sand samples from French Frigate Shoals; 20.61% of the infauna were crustaceans and 17.23% polychaetes (Table 4).

Invertebrates noted in the transects at French Frigate Shoals included the echinoid species *Echinometra mathaei* and *Echinothrix diadema*, holothuroids, and the gastropod *Trochus intextus*. A number of larger hermit crabs were collected in fish traps at French Frigate Shoals in October. Echinoids and ophiuroids have been found in other benthic samples not included in accompanying figures.

No polychaetes were found in the gut contents of the wrasse, *Thalassoma ballieui*, but a high percentage of fish had decapod crustacean fragments (Figure 2). While polychaetes are very abundant in both coral and sand, decapods comprise less than 3% of the benthic fauna. This disparity may indicate selective feeding by *T. ballieui*, or it could be due to various other reasons. The absence of stomatopods in the benthic material (19% of the diet of *T. ballieui*) shows that some species have been missed in these samples.

DISCUSSION

Because this project is still in the data collection stage and data analysis has barely begun, it is premature to state conclusions at this time. The initial reconnaissance of the northwestern chain and the initial baseline collections at French Frigate Shoals and Midway are important accomplishments in fulfilling project objectives. We presently have solid data on sharks and a good beginning on carangid information in the NWHI. Collections of other shallow-water reef fishes should prove adequate to make substantial progress on an initial description of the trophic structure.

TABLE 4. RELATIVE NUMERICAL ABUNDANCE OF BENTHIC FAUNAL ELEMENTS FROM FRENCH FRIGATE SHOALS

Taxa	% of total number of organisms	
	sand	coral
Polychaeta	18	30
Crustacea	20	56
Amphipoda	5	14
Isopoda	11	10
Copepoda	3	19
Decapoda	1	3
Cirripedia	0	8
Mollusca	61	14
Gastropoda	59	12
Bivalvia	2	2
Echinodermata		
Ophiuroida	.5	0

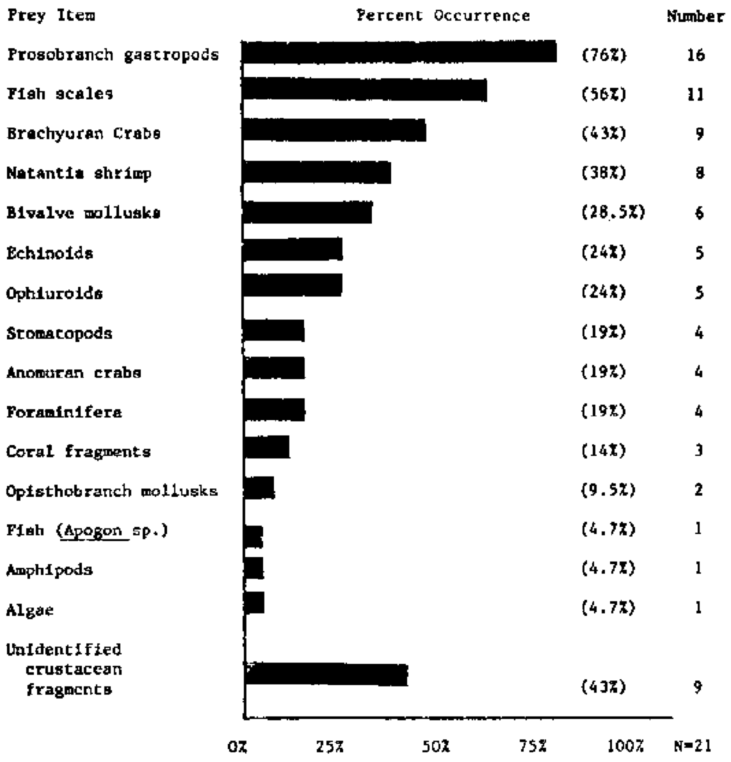

Figure 2. Percentage of occurrence of food items in Thalassoma ballieui

Preliminary data analysis suggests that the vertebral ring method of age determination in sharks could prove successful for the shark species which we are examining. Diet analysis and initial data on relative abundance of food items suggest some selectivity in certain top level carnivores and there are also indications of overlap among species in certain diet categories, particularly spiny lobster.

FUTURE RESEARCH NEEDS

Of particular importance is the completion of the reference collection of invertebrates and fish skeletons that is essential to identifying stomach contents. This reference collection will also include a photographic record of fish scales. The remaining benthic material from the October 1979 cruise and the March/April Midway cruise will be analyzed for invertebrates.

Continued shark sampling will be necessary to obtain additional vertebral samples to permit age determination. The development of additional methods of examining vertebral rings will be explored, including the use of scanning electron microscope and densitometer scans.

An expansion of the program of tagging tiger sharks at French Frigate Shoals to verify growth rates will be undertaken, and growth rate determination of captive sharks at the Waikiki Aquarium and Sea Life Park will be integrated into our program. It is also necessary to explore methods which will confirm that vertebral rings are annual.

This project is now less than eleven months into what should be at least a three or four-year effort. Three major research cruises are complete; three more (two to French Frigate Shoals, one to Midway) are scheduled before the end of Sea Grant Year 13 (1980-81). Cruises to date have provided an overall reconnaissance of the major Northwestern Hawaiian Islands and very substantial sized first samples of the fish and invertebrate communities at two important, representative locations, widely separated and well located in the chain. Future cruises to Midway and French Frigate Shoals will permit making seasonal comparisons at established study stations and filling data sets on fish and invertebrate communities more completely. The top predator collection program will continue with emphasis on collecting close to reef fish study sites and trying to examine the trophic ties between these groups more closely. During and after these cruises, a major shift in emphasis will be to more specific and intensive studies, e.g., experimental manipulation such as predator removal at small study stations. These studies will be facilitated by maintaining a few investigators at the field sites for longer periods of more intensive monitoring and experimentation.

In the laboratory a great deal of material remains to be analyzed for information on fish, the identification and quantification of naturally occurring benthos, and the recognition and quantification of feeding relationships from gut contents. This will be a major, continuing effort, and the specific direction of future emphasis in the study will be influenced by continuing feedback from these analyses. Analysis of the population biology of top predators, particularly sharks, will be intensified. Work to date has laid the groundwork for accelerated progress in estimating age, growth, and population size.

We hope to put these kinds of laboratory results on both major groups of top pelagic predators together with an accumulating body of observations from intensive field studies to gain a good understanding of the nature and importance of this predator-prey relationship that may be very significant to the ecology of these island communities.

The project is basically on schedule, although the loss of a planned cruise to Midway in January 1980 was a minor setback. Some original objectives have required modification. It was originally believed that some limited areas at Midway and/or French Frigate Shoals had received enough local recreational fishing pressure to provide ready-made experimental "fished" NWHI situations. It now appears unlikely that this type of situation with a long history of adjustment to fishing will be available. As mentioned above, the tagging program for a population estimate of jacks seems unworkable due to low tag recovery (low fishing effort). It now seems less feasible than it did originally to get useful diet information from deeper-water fishes taken in other segments of the NWHI program. Therefore, it is not clear how much can be done in establishing the link between the shallow-water communities and deeper communities.

The scope of the project and the large data base involved make it imperative to place major emphasis on field work early. The great volume of laboratory analysis required to produce much of the data indicates that major quantitative results and firm conclusions are still a good many months away.

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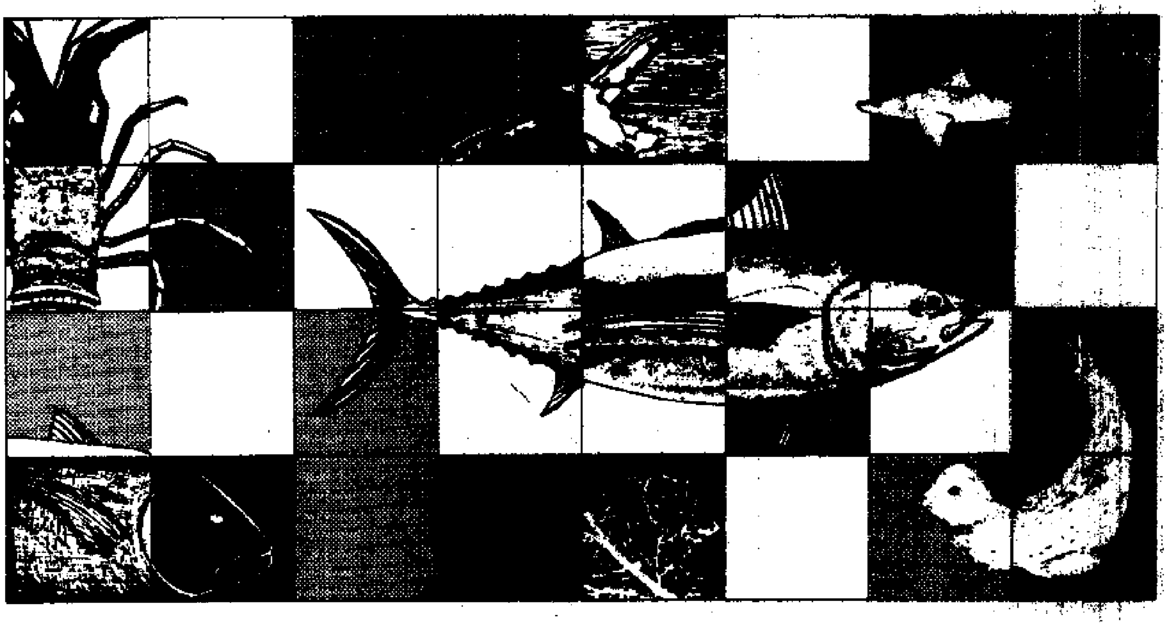
Offshore Research



DISTRIBUTIONS OF PLANKTON STOCKS, PRODUCTIVITY, AND POTENTIAL FISHERY YIELD IN HAWAIIAN WATERS

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ABSTRACT

An investigation on the hydrography, distributions of plankton stocks and particulate matter, level of primary productivity, and potential fishery yield in the epipelagic zone of Hawaiian waters was carried out in 1979 at several stations between Hawaii and Midway Islands. While a few important differences exist between subareas of the high Hawaiian Islands and the low Northwestern Hawaiian Islands regarding water temperature structure and taxa of fish larvae, the physical-chemical environment and the abundance of planktonic stocks are strongly uniform and have low variability in both space and time. Although the oceanic habitat is relatively uniform along the archipelago, waters around the Northwestern Hawaiian Islands have slightly higher average amounts of plankton stocks (10 to 30%) and daily primary productivity (40%) than the Hawaiian Islands. The best estimate of potential fishery yield from Hawaiian waters is 50 to 100 kg $km^{-2}yr^{-1}$ of live biomass, or about 2 to 4 times the average annual catch of tunas in Hawaiian waters in the past two decades.

Hawaiian Archipelago
potential fishery yield
primary and secondary productivity

INTRODUCTION

Research on the distributions of plankton stocks, primary productivity, and calculated potential fishery yield in the Hawaiian Archipelago has been carried out to resolve whether any significant differences exist for these variables between the northwestern and eight Hawaiian Islands. The focus on this primary objective for the present study was taken to help determine whether or not any fundamental biological differences in the lower trophic levels between these two subareas in the Hawaiian chain can account for or are manifest in the apparent greater abundance, stocks, and larger sizes of certain high-order, pelagic carnivores in the Northwestern Hawaiian Islands. These subarea differences in the abundance and size composition of large pelagic predators may be attributed to three primary factors: (1) basic physical-chemical habitat differences such as currents and hydrographic structure, a greater level of underlying primary productivity in the water column, or differences in the composition of organism sizes and taxa in the plankton; (2) time-varying patterns in the migration routes of these large pelagic fish; (3) a much greater level of fishing effort and degree of stock exploitations in the Hawaiian Islands. Thus, most of the research effort has been a search for pattern in spatial and temporal distributions of several key variables in the epipelagic zone of Hawaiian waters. The variables measured and sampling plan for the present study are described below.

METHODS

The planned field sampling design for oceanographic components in the epipelagic zone of Hawaiian waters was based on two cruises of eight transects each (four per subarea in the Hawaiian Islands, A to D, and Northwestern Hawaiian Islands, E to H) with three stations per transect on a windward-leeward alignment (Figure 1). For each variable of interest, this station plan would enable statistical comparisons for seasonal changes (winter versus summer), differences between subareas, and differences between stations along the transects. Thus, the ideal sampling grid covered 24 stations per cruise, whereas the actual sampling density averaged 20 stations per trip.

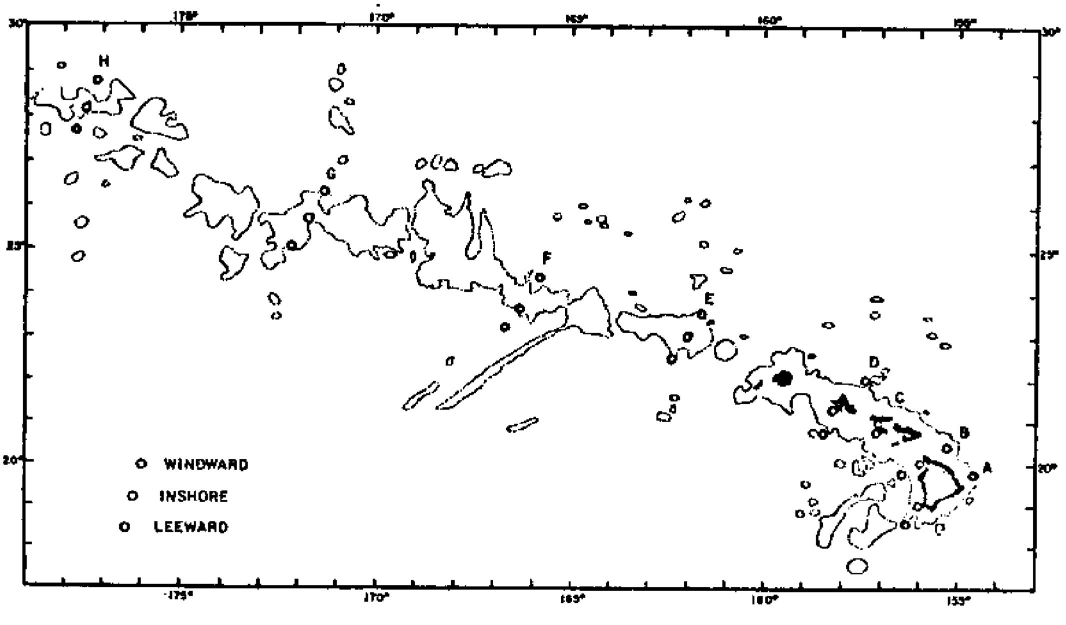


Figure 1. Sampling transects and stations occupied in the Hawaiian Archipelago from Hawaii (A) to Midway Islands (H) in 1979. The dotted lines enclose the 3,660 m depth contour.

Field sampling measurements of several environmental and biological variables were carried out in the upper 200 meters during each cruise in 1979, the first one being in late winter (2 to 29 April) and the other in summer (21 June to 9 July). The data and samples collected for analyses and study include incident light and vertical light attenuation, profiles of temperature and salinity, plant nutrients (nitrate + nitrite), particulate carbon (PC) and nitrogen (PN), chlorophyll *a* and phaeopigments, daily primary productivity, depth-average night and day zooplankton stock, the mean dry weight and percentage of carnivorous taxa by numbers in the macrozooplankton catch, and the taxonomic composition and abundance of epipelagic fish larvae.

The analyses of samples and data collected were carried out with only minor modifications to established procedures. The light data were obtained using LICOR (Lambda Corp., Lincoln, NE) quantum sensors and meters (model 190S atmospheric sensor, model 550 printing digital integrator, model 185A meter and model 192S submarine 2 pi hemispheric sensor), with Secchi disc depth readings taken near noon each day. Temperature and salinity data were obtained from bucket samples for the surface, from CTD (conductivity-temperature-depth) casts and XBT drops to a maximum of 450 m, and from seawater samples for conductivity calibrations from hydrocasts at each station. Sigma-t values were calculated from CTD temperature and salinity values using Knudsen's tables (Knudsen, 1901). From the samples of each hydrocast, determinations of nitrate plus nitrite, PC and PN, plant pigments and daytime (sunrise to sunset period) ^{14}C uptake were carried out by conventional methods outlined in Strickland and Parsons (1972) with the following exceptions. PC and PN were measured using procedures and facilities given by Hirota and Szyper (1976), and the daytime primary productivity was calculated from *in situ* incubations to depths of 150 to 175 m from sunrise to about local apparent noon. The net-collectable macrozooplankton stock was sampled and assessed during both daytime and nighttime with a standard 0.7-m diameter bongo net in oblique tows to about 200 m and by a 0.7-m wide by 0.35-m high rectangular mouth neuston net, both nets being of 0.18-mm aperture (Hirota and Szyper, 1976). From the oblique bongo net collections, a small aliquot was taken from each preserved sample and the total number of macrozooplankters and the number of individuals which are carnivorous (viz., chaetognaths, siphonophores, other cnidarians, ctenophores, fish larvae, and several taxa of crustaceans, including many copepod genera) were counted by dissecting microscope at low (10 to 40X) power. From these data and the total macrozooplankton stock as dry weight, it is possible to estimate the average plankter dry weight (Mullin et al., 1975) and the percentage of carnivores of total numbers. Collections of ichthyoplankton were made at each station with four types of nets, but all with the same 0.5-mm mesh apertures. The neustonic ichthyoplankton were collected in both daytime and nighttime with a 1-m wide by 0.5-m high rectangular mouth net. The epipelagic taxa were collected only at night in oblique tows to about 100 m primarily with a 2-m by 2-m square mouth larval fish trawl and a 1-m diameter ring net on cruise I with a 20-m (6-ft) Isaacs-Kidd Plankton Trawl (IKPT) during cruise II (IKPT mouth area ca. 2.4 m^2). Because of this change in collection gear during the ichthyoplankton part of the study (due to a break in the 2-m by 2-m net frame), differences in the abundance data of fish larvae must be viewed with caution.

RESULTS

Data from the 1979 survey of the hydrography, particulate matter, and productivity of Hawaiian waters show that for most variables there are small mean differences (ca. 10 to 40%) in either space or time (Table 1). The physical-chemical environment of the tropical ocean and these biotic components show a strong uniformity and low variability of average values (coefficient of variation in percentage is the sample standard deviation expressed as a percentage of the mean), except for the mixed layer depth.

TABLE 1. A COMPARISON OF TEMPORAL AND SPATIAL VARIATIONS IN MEAN VALUE OF TEN SELECTED VARIABLES (COEFFICIENT OF VARIATION IN PERCENT) ALONG THE HAWAIIAN ARCHIPELAGO IN 1979

Variable	Temporal Changes		Spatial Changes	
	Winter (April) 1979	Summer (June-July) 1979	Hawaiian Islands	Northwestern Islands
1. Quantum flux, Ei $m^{-2}d^{-1}$	54.7 (1.7)	51.6 (2.5)	51.8 (9.9)	57.0 (3.8)
2. Surface temperature, °C	23.1 (1.1)	25.6 (0.3)	24.8 (0.5)	23.6 (0.8)
3. Mixed layer depth, m	130 (5.6)	50 (12.8)	108 (9.1)	83 (10.0)
4. Euphotic zone, m (1% I_o)	111 (2.6)	104 (4.0)	110 (4.5)	106 (3.9)
5. Total nitrate-nitrite, mg-atN m^{-2} 0 to 200 m	285 (9.1)	256 (13.0)	265 (14.9)	282 (14.9)
6. Total particulate N, mgN m^{-2} 0 to 200 m	648 (3.2)	707 (6.0)	604 (5.0)	732 (5.0)
7. Chlorophyll _a_, mg m^{-2} 0 to 200	9.89 (5.0)	9.88 (5.5)	9.10 (9.6)	10.6 (4.3)
8. ^{14}C uptake, mgC $m^{-2}d^{-1}$ 0 to 175 m	80 (10.5)	101 (10.8)	73 (16.2)	102 (11.8)
9. Nighttime neustonic macrozooplankton stock, mg dry wt m^{-2}	2.40 (12.0)	3.49 (14.0)	2.47 (15.9)	3.21 (19.4)
10. Nighttime average macrozooplankton stock, mg dry wt m^{-3} 0 to 200 m	6.42 (5.5)	7.15 (6.1)	6.09 (8.4)	7.23 (7.4)

When the plant nutrient data from all the stations in each season are plotted against the water density (Figure 2), it is evident that the main part of the nutricline is consistently between 24.5 and 26 sigma-t units and that there is very little seasonal change in the nutrient concentration-density structure of the upper 200 m. Thus, these data clearly show that the Hawaiian Islands and Northwestern Islands subareas are not very heterogenous, the differences of mean values being much less than a factor of two.

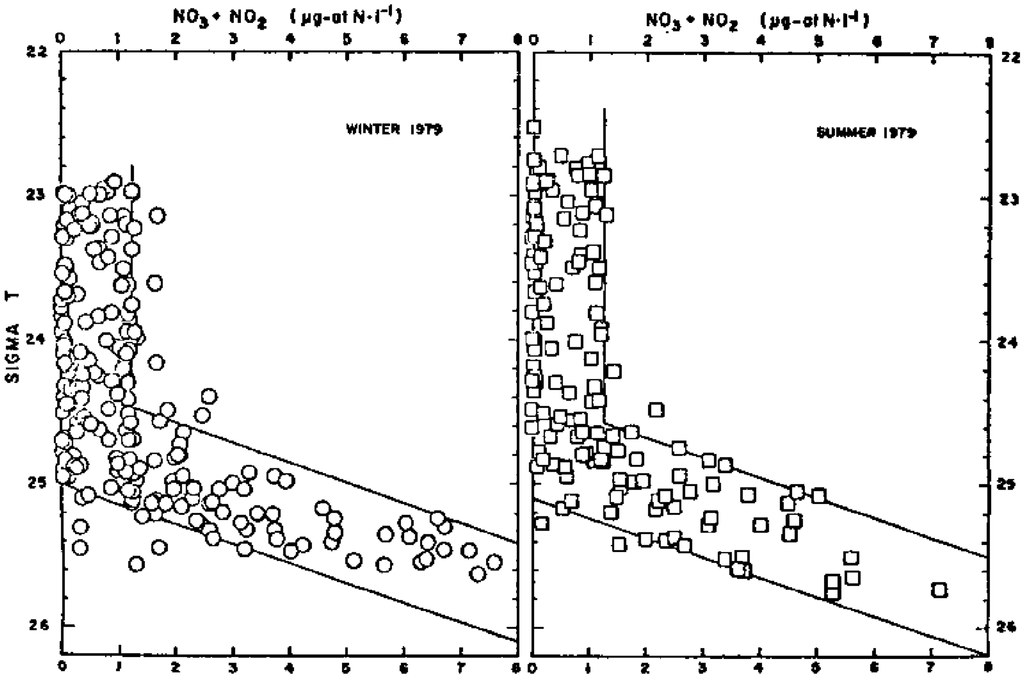


Figure 2. Seasonal variation in the nutrient concentration-density structure of the epipelagic zone in Hawaiian waters, with data from all stations being combined for each cruise.

For each of several parameters, results from this study were separated into data sets of Hawaiian versus Northwestern Hawaiian Islands subareas and tested statistically for median and mean differences (Table 2). Only the PN and primary productivity values are significantly different (p, the probability of equal medians due to change, being less than 0.05). Other parameters which do not show a significant difference, but which suggest a trend are the plant pigments, percentage of carnivorous macrozooplankters, and the abundance of total ichthyoplankton (Table 2). Note that the significant median difference for daily primary productivity ($p < 0.01$), for all stations taken together is due to higher level of productivity at inshore stations ($p < 0.05$), since oceanic windward and leeward station levels are not significantly different between subareas ($p = 0.2$).

The observed variations in primary productivity in Hawaiian waters for 1979 appear best related to the upward flux of nitrogenous plant nutrients ($NO_3 + NO_2$) inferred from the vertical gradient of the nutricline (Figure 3, $N = 13$, $r = 0.73$, $p < 0.01$). Note that this positive correlation applies only to those stations at which the top of the nutricline is deeper than the photic zone (1% of surface light). This relationship only holds for about one-third of the stations sampled (13 of 38), and whenever the nutricline depth is within the photic zone the

TABLE 2. RESULTS OF STATISTICAL TESTS FOR 16 PARAMETERS MEASURED IN HAWAIIAN WATERS DURING WINTER AND SUMMER CRUISES IN 1979

Parameter	Hawaiian Islands		Northwestern Islands		U-test	t-test
	N	Median	N	Median	p	p
Depth of mixed layer (m)	18	115	19	70	0.12	0.12
$NO_3 + NO_2$ ($mg\text{-}atN \cdot m^{-2}$)	18	279	20	294	0.71	0.70
PC ($mg \cdot m^{-2}$)	18	5740	20	5750	0.99	0.53
PN ($mg \cdot m^{-2}$)	18	586	20	732	0.0008**	0.0014**
C/N ratio	18	9.23	20	7.90	0.0007**	0.0019**
Chlorophyll a ($mg \cdot m^{-2}$)	18	9.33	20	10.3	0.077^{+}	0.065^{+}
Phaeopigments ($mg \cdot m^{-2}$)	18	8.57	20	8.98	0.68	0.71
Chl. a/Chl. a + Phaeo. ratio	18	0.493	20	0.523	0.099^{+}	0.098^{+}
Primary Production ($mgC \cdot m^{-2} \cdot day^{-1}$)	18	65.6	20	101	0.013*	0.025*
Inshore station	7	61.1	7	104	0.030*	0.030*
Leeward and windward	11	71.6	13	97.9	0.22	0.32
Zooplankton dry weight ($mg \cdot m^{-3}$)	28	4.44	40	5.39	0.25	0.88
Animal dry weight ($\mu g \cdot animal^{-1}$)	28	11.8	40	11.2	0.99	0.88
% carnivores (%)	28	6.40	40	7.48	0.082^{+}	0.095^{+}
Total larval fish ($no \cdot m^{-3} \cdot 10^{-3}$)	14	135	19	242	0.056^{+}	0.23
Total tuna spp. ($no \cdot m^{-3} \cdot 10^{-3}$)	14	2.67	19	0.70	0.44	0.84
Inshore reef larval fish ($no \cdot m^{-3} \cdot 10^{-3}$)	14	19.9	19	24.6	0.39	0.27
% reef taxa (%)	14	8.42	19	8.60	1.00	0.89

Note: Null hypotheses are that no difference exists between subareal medians or means of the parameter. P is probability of a significant difference due to random sampling variability. * and ** indicate probability less than 0.05 and 0.01, respectively, and a + is for p less than 0.1.

level of productivity is more variable and is not related to the nutricline gradient. These results are interpreted to mean that the level of ^{14}C fixation in the water column is limited by the vertical flux or supply of new inorganic nitrogen (nitrate) to plants in the photic zone, and this relationship (Figure 3) is consistent with the findings of other studies in tropical-subtropical habitats (Eppley et al., 1979; King and Devol, 1979; Herbland and Voituriez, 1979). From the ^{14}C and chlorophyll a data (using a PC/Chl a ratio of 60) the specific growth rate of the phytoplankton in the water column is 0.15 per day (range ca. 0.3 to 0.05 per day), or a doubling time of about 5 days.

A hypothetical nitrogen mass balance description for the epipelagic zone in Hawaiian waters (Figure 4) shows the presumed relationships for steady state vertical transport: upward flux of dissolved "new" inorganic nutrient (nitrate), uptake and consumption-transformation by plankton, and downward loss to sinking. The importance of hydrographic structure and processes controlled by zooplankters is evident in their relationship to abundance and productivity of the phytoplankton. The general relationship of nitrogen mass balance in the vertical direction for tropical, permanently stratified environments seem simple enough to verify by measurement, but the frequency of departures from a steady state and the importance of storms and changes in weather will require documentation.

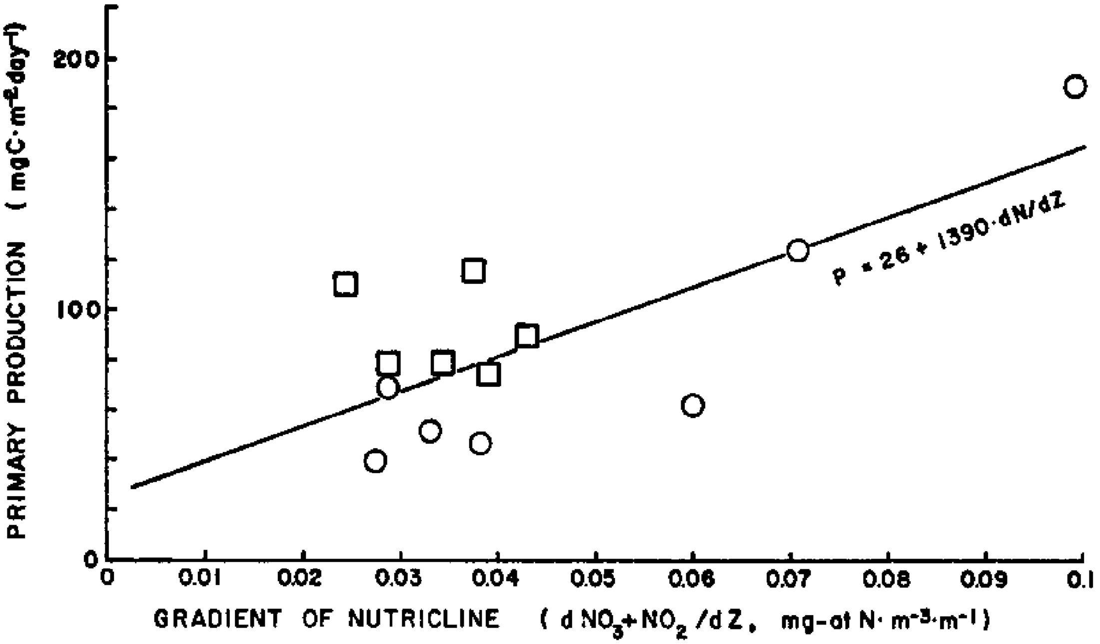
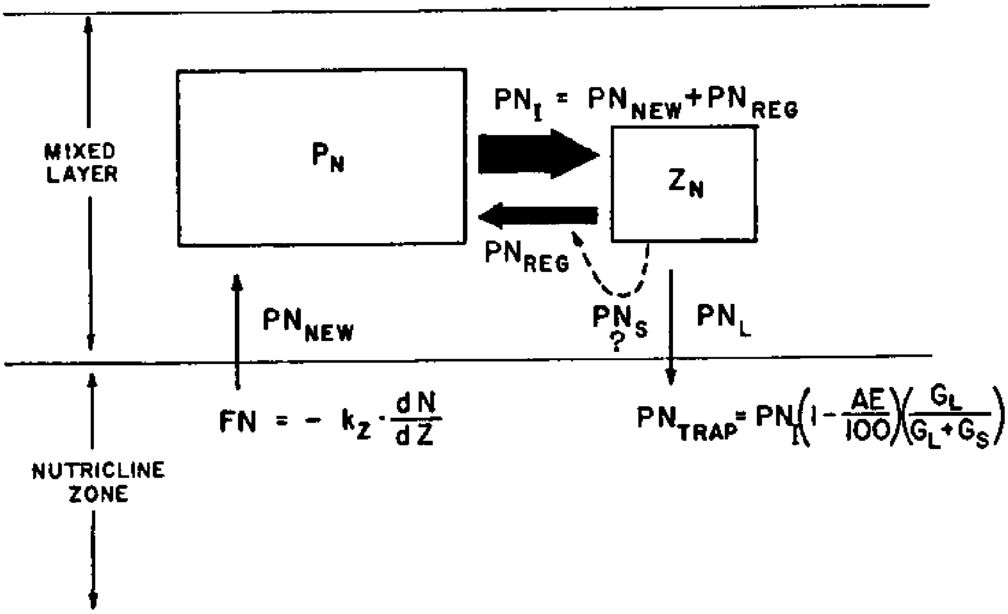


Figure 3. Relationship between daily primary productivity in the water column and gradient of the nutricline (nitrate + nitrite) at stations where the depth of 1% surface light was shallower than the depth at the top of the nutricline. Circles and squares represent data from winter and summer cruises, respectively.

Estimates of secondary production by macrozooplankton and the potential pelagic fish yield (from the fifth trophic level) in Hawaiian waters are made using our field data and the computational procedures and assumptions given by Allen (1971), Ryther (1969) and Sheldon et al. (1977). Because there was neither a significant difference in the macrozooplankton stock as median dry weight in the upper 200 m between subareas or in the median size of plankter weight (Table 2), the secondary production by macrozooplankters was calculated using the day and night overall mean stock (S) in the upper 200 m (5.5 mg dry wt. m^{-3}), an instantaneous growth rate (g) of 0.1 per day, and the mean PC/dry weight ratio (0.35). The calculated net production by the macrozooplankton ($P_{net} = g*S$) equals 38.5 mgC m^{-2} day^{-1}, 14 gC m^{-2} yr^{-1}, and 140 metric tons biomass km^{-2} yr^{-1} (using a biomass/PC ratio of 10). These values compare with average levels of primary production (Table 1) of about 90 mgC m^{-2} day^{-1}, 33 gC m^{-2} yr^{-1}, and 330 metric tons biomass km^{-2} yr^{-1}. For a 10% food chain efficiency and five trophic level food chain (plants to piscivorous fish), the calculated potential pelagic "tuna" fishery yield ranges from 33 to 140 kg km^{-2} yr^{-1} based on annualized rates of primary and secondary macrozooplankton production, respectively. It is expected that the estimate based on primary production could be too low by about 50% due to PC formed by bacteria and other microbial heterotrophs not considered in our study, while the estimate based on secondary macrozooplankton production



FN = Flux of Nutrient through nutricline
PN_{new} = Plant Nitrogen produced by nutrient supplied as $NO_3 + NO_2$
PN = Plant Nitrogen
ZN = Zooplankton Nitrogen
PN_I = Plant Nitrogen ingested by zooplankton
PN_{reg} = Plant Nitrogen produced from regenerated NH_4^+ and urea
PN_S = Plant Nitrogen formed into fecal pellets by small zooplankton
PN_L = Plant Nitrogen formed into fecal pellets by large zooplankton
PN_{trap} = Total PN trapped in a sediment trap
AE = Assimilation Efficiency of zooplankton
GL = Grazing by large zooplankton
GS = Grazing by small zooplankton

Figure 4. Vertical flux nitrogen mass balance model for a stratified, two-layered tropical oceanic environment

may be too high because we have ignored a more rigorous account of the trophic status of these animals (ca. 10% are carnivorous, Table 2). Thus, 50 to 100 kg biomass $km^{-2}yr^{-1}$ for the range of potential fishery yield values in Hawaiian waters seems the best estimate. This is 10 to 20 times lower than our initial estimate because of much lower primary productivity measured during the study (33 gC m^{-2} yr^{-1} versus 75 gC m^{-2} yr^{-1} estimated), a lower percentage of carnivorous taxa in the macrozooplankton catch, and using a 10% versus 15% food chain efficiency. The 50 to 100 kg km^{-2} yr^{-1} is two to four times greater than the average annual pelagic skipjack tuna landings in Hawaii per unit area of fishing ground from about 1950 to 1970 (Uchida 1970, 1975), for which the catch has averaged 25 kg km^{-2} yr^{-1} (ca. 4,500 metric tons per year in 181,000 km^2 fishing area). These data suggest that the pelagic tuna and other high-order piscivorous fish catch is close to the maximum sustainable catch per unit effort (discounting effects of migration) of one-half to one-fourth of the total potential yield (Sheldon et al., 1977). This finding is supported by those of Uchida (1968) who found higher catches per unit of effort in underfished areas outside the Hawaiian skipjack grounds. It would appear that whereas total landings can be increased within the Hawaiian area by increasing effort, the catch per unit of effort should decline unless a change in technology is made (viz., use of aggregating buoys or other school-locating techniques).

The study of ichthyoplankton in the Hawaiian Archipelago was carried out by grouping taxa as offshore pelagics versus reef and inshore fishes, with detailed emphasis being given to pelagic fishes of commercial and sport value (Table 3). The median abundance of total fish larvae is significantly higher in the NWHI than in the main Hawaiian Islands (Table 2), although apparently less so in summer than in winter (Figure 5). Further,

TABLE 3. LIST OF ICHTHYOPLANKTON TAXA IDENTIFIED FROM SAMPLES COLLECTED IN HAWAIIAN WATERS, WINTER AND SUMMER CRUISES IN 1979

A. OFFSHORE AND PELAGIC TAXA

1. Commercial and Sport Fish

   Nearshore
   - *Decapterus* sp.
   - *Selar crumenophthalmus*
   - *Seriola* spp.
   - Other Carangidae

   Oceanic
   - *Coryphaena equiselis*
   - *Coryphaena hippurus*
   - *Coryphaena* spp.
   - *Gempylus serpens*
   - *Nealotus tripes*
   - Other Gempylidae
   - Istiophoridae
   - *Auxis* sp.
   - *Euthynnus affinis*
   - *Katsuwonus pelamis*
   - *Thunnus alalunga*
   - *Thunnus albacares*
   - *Thunnus* spp.
   - Trichiuridae
   - *Xiphias gladius*
   - Unidentified Scombridae

2. Deep-living or Benthic
   - Amarsipidae
   - Belonidae
   - Brotulidae
   - Champsodontidae
   - Cheilodipteridae
   - Chlorophthalmidae
   - Evermannellidae
   - Gonostomatidae
   - Lophiiformes
   - Myctophidae
   - Notosudidae
   - Paralepididae
   - Pegasidae
   - Stomiatoidei
   - Stromateoidae
   - Tetragonuridae

3. Surface-living
   - Clupeidae
   - Engraulidae
   - Exocoetidae
   - Hemiramphidae
   - Molidae
   - Nomeidae
   - Scombersocidae

B. REEF AND INSHORE TAXA

1. Non-Pelagic Eggs
   - Ammodytidae
   - Apogonidae
   - Atherinidae
   - Blenniidae
   - Gobiidae
   - Pomacentridae
   - Syngnathidae
   - Tetraodontidae

2. Pelagic Eggs
   - Acanthuridae
   - Bothidae
   - Callionymidae
   - Carapidae
   - Chaetodontidae
   - Dactylopteridae
   - Diodontidae
   - Fistulariidae
   - Holocentridae
   - Kyphosidae
   - Labridae
   - Lutjanidae
   - Microdesmidae
   - Mugilidae
   - Mullidae
   - Ostraciontidae
   - Pleuronectidae
   - Pomacanthidae
   - Priacanthidae
   - Scorpaenidae
   - Serranidae
   - Sphyraenidae
   - Synodontidae
   - Tetraodontiformes
   - Others

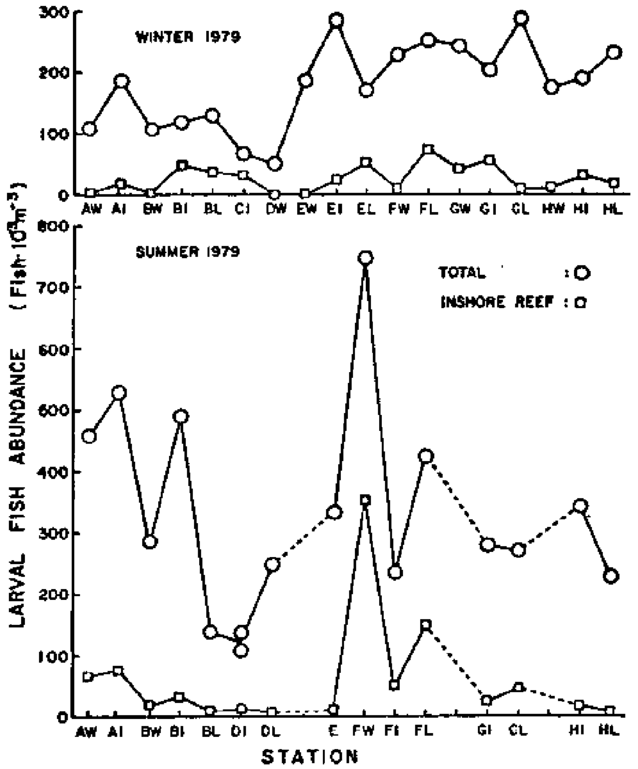


Figure 5. Variations in the abundance of total fish larvae (circles) and of fish larvae of inshore reef taxa (squares) between seasons and stations in Hawaiian waters in 1979

there is a significant positive correlation ($r = 0.62$, $p < 0.01$) between the percentage of larval fishes which are inshore taxa and the total concentration of fish larvae, suggesting an addition of reef and inshore ichthyoplankton to a "background" level of offshore, oceanic fish larvae at about 50 to 100 individuals per 1,000 m^3.

Among the significant findings in the ichthyoplankton study in spatial differences or gradients and seasonal changes are the following.

1. Larval Stolephorus buccaneeri were virtually absent from collections in 1979 at all stations in the present study (only two specimens caught in all neuston and oblique tows), whereas they were very abundant in the Northwestern Hawaiian Islands (Nihoa-Laysan) in 1977 (TC-77-02, oblique bongo net tows by National Marine Fisheries Service personnel).

2. In oblique nighttime tows to about 100 m total tuna species, primarily the skipjack and ahi, occurred at an average of less than 1/1,000 m^3 and 1% of total fish larvae in the winter cruise (83 tuna larvae total), whereas in the summer cruise these values increased to an average of 23/1,000 m^3 of total tuna larvae and over 7% of total fish larvae (1,569 tuna larvae total).

3. Tuna larvae tend to be captured at locations where the water temperature at 50 m depth exceeds 23° to 24°C, and in both 1977 (TC-77-02 bongo net series) and 1979 the catch of tuna larvae tends to tail off and decline from about French Frigate Shoals toward Midway.

4. The ichthyoplankton and taxa of daytime neuston collections are comprised mainly of larval and early juvenile flyingfishes (Exocoetidae), goatfishes (Mullidae), and larval lanternfishes (Myctophidae), which are probably forage for seabirds, while nighttime collections catch many adult myctophids. Also the sea moth, *Pegasus papilio*, was frequently caught in night neuston tows in the Northwestern Hawaiian Islands (103 specimens, both cruises), occurring there at 9/13 stations on cruise I and 7/10 stations on cruise II. By contract only two larvae of *Pegasus* were taken by oblique tows off Hawaii and Molokai (stations BW and CI) and none were taken by neuston net in the Hawaiian Islands.

5. Two species of pelagic sauris (Scombersocidae) were collected by neuston net in the present study, *Cololabis saira* (Pacific saury) at the northern end of the chain at Laysan, Lisianski, and Midway Islands on cruise I and *C. adocetus* (dwarf saury) from around Hawaii Island on both cruises. These occurrences of larval *Cololabis* at opposite ends of the Hawaiian Archipelago reflect cooler, subtropical fauna in the northwest and a warmer, tropical north equatorial fauna in the southeast.

6. Small numbers of larvae of billfishes (Istiophoridae and Xiphiidae) and mahimahi (*Coryphaena hippurus* and *C. equiselis*) were captured in neuston tows, the Istiophoridae in daytime tows and the other mainly at night. *C. hippurus* was much more common in winter (28 specimens) than in summer (1 specimen) 1979, whereas the little dolphin, *C. equiselis* was more nearly common in both seasons (in winter 6 fish, in summer 9 fish).

DISCUSSION AND CONCLUSIONS

We have presented above the major findings from our research in 1979 on the hydrography, plankton stocks and productivity, and estimated potential fishery yield from Hawaiian waters. We have given emphasis to seeking patterns in the differences for parameters between the Hawaiian and Northwestern Island subareas. A longer, more detailed analysis of our existing data will enable a search for statistically significant differences between seasons and between oceanic windward and leeward versus "inshore" stations. While there are statistically significant differences between subareas in a few parameters (e.g., level of primary productivity and PN concentration), they are not as great as one might expect *a priori* based on seasonal changes in hydrographic structure and weather across the Hawaiian chain. As a first approximation the oceanographic conditions in Hawaiian waters could be considered the same, with differences between areas less than a factor of two and related to random sampling variability and changes in the water column by the prevailing circulation. However, when evaluations of parameters are taken at a more specific level (e.g., some of the ichthyoplankton data), differences between subareas and time become more apparent (occurrences of *Stolephorus*, *Cololabis* spp., *Pegasus*, and tuna species).

The best estimate of 50 to 100 kg biomass km^{-2} yr^{-1} as the potential fishery yield in Hawaiian waters (to a distance of ± 30 km windward and leeward of the island masses) can vary from about 10 to 1,000 kg km^{-2} yr^{-1} depending on assumed values for the food chain efficiency (10%) and the number of transfers (4) through the trophic levels (5) to the final yield. We are unable to refine or make these estimates much more accurate, with the exception that we can obtain direct measurements of the instantaneous rates of growth (g) for representative macrozooplankters of about 10 micrograms dry weight to compare it with the 0.1 per day value we assumed. The effect of seasonal migrations by tunas on the landings is largely 50 to 100 kg km^{-2} yr^{-1} is accurate, it is possible to predict that the present catch of about 25 kg km^{-2} yr^{-1} is close to the maximum value of catch which can be sustained from Hawaiian waters unless greater harvest is offset by immigration. Thus, an increase in landings per effort would require exploitation of new fishing grounds offshore or in the Northwestern Hawaiian Islands or use of new technologies·in fishing.

FUTURE RESEARCH NEEDS

Future research needs which could ideally be addressed to supplement existing information include the factors and processes which control temporal fluctuations in hydrography, plankton stocks, and particulate carbon fixation from scales of days to between years. Such research might include an investigation of: (1) the short-term (days to weeks) nature of steady states between nutrient supply, plant production, and the consumption of particulate carbon by zooplankton, and (2) the control of these processes and the variations in abundances of biota due to the complex of currents and transport around our islands in the Hawaiian chain. How do larvae of inshore fish species get 30 km to windward of islands in summer if the prevailing surface current follows northeast tradewinds? What and how do seasonal changes in currents, hydrographic conditions, and food influence seasonal variations in fish larvae, recruitment and the catch of large pelagic fishes? Is the seasonal variation in catch of pelagic tunas due mainly to migration of fish stocks into Hawaiian waters in the second and third quarters of the year or are there some influences of changes in environmental conditions on fish schooling and availability?

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AN ANALYSIS OF THE HAWAIIAN OFFSHORE HANDLINE FISHERY: A PROGRESS REPORT

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ABSTRACT

Studies of Northwestern Hawaiian Islands bottomfish stocks provide urgently needed information concerning the response of these species to exploitation. Cluster analyses indicate the existence of three principal species groups in this fishery which are segregated on the basis of depth. No differences have been detected in species assemblages through time or between high island banks. Production estimates indicate that in rich areas a harvest of almost 600 pounds of bottomfish per nautical mile of 100-fathom contour could be sustained on an annual basis. Attempts at aging the opakapaka, *Pristipomoides filamentosus*, the dominant species in the fishery, are proceeding on schedule but parameter estimates are open to certain questions in interpretation. Opakapaka show a definite size stratification according to depth of capture and a description of this spatial pattern will allow bias to be reduced in the estimation of mortality rates. Studies concerning the selectivity of fish hooks indicate they provide relatively unbiased size samples and that gear restrictions would be ineffective in managing this fishery. Progress towards the completion of this project is on schedule although some problems remain to be overcome.

bottomfish
otoliths
depth distribution
gear selectivity
stock production
aging
mortality

INTRODUCTION

With the enactment of the Fishery Conservation and Management Act of 1976 and the subsequent establishment of the 200-mile fishery conservation zone, the fishery resources of the Northwestern Hawaiian Islands

(NWHI) have become increasingly important. It is now generally acknowledged that the magnitude of these largely untapped resources is substantial and that in the near future, catches from this region could significantly increase the total landings of fishery products in the state of Hawaii. The realization that these resources hold considerable economic promise has had several consequences.

One major effect has been a rapid increase in the funding and support of research programs, such as this one, aimed at both understanding the ecology of this pristine area and concomitantly, determining optimal strategies for the utilization of its resources. This in turn has led to several relatively detailed studies of populations or stocks in the NWHI which previously had attracted little or no attention, even around the main high islands. An excellent example of this is the Hawaiian handline fishery for deep-dwelling bottomfish, which prior to 1978 had never been studied, even though species taken in this fishery are some of the most highly valued in the state (Ralston, 1979). This observation only serves to underscore the importance of research programs currently being conducted in the NWHI in that they allow comparison of a disturbed ecosystem with an undisturbed one. Such comparisons are invaluable in assessing the effects of exploitation on community dynamics and aid not only in developing management strategies for the resources of the NWHI but, reciprocally, they allow an assessment of main island resources as well.

The initial specific objectives of this study were, and remain, fourfold. These are: (1) to attempt a more realistic multispecies stock-production analysis by using a multivariate clustering technique to provide estimates of sustainable yield of bottomfish per unit area; (2) to accurately determine the pattern of growth for the opakapaka, Pristipomoides filamentosus, the single most important component of this fishery; (3) to develop a statistical model for determining instantaneous mortality rates and to apply it to bottomfish length-frequency data; and (4) based upon these results to undertake an analysis of the problem of growth overfishing by utilizing the yield-per-recruit approach of Beverton and Holt (1957).

When all four phases of this study have been completed a synthesis of the information relating to selected bottomfish stocks will be possible. Alternate and independent application of both surplus production and dynamic pool models to the problems of overfishing will allow a realistic appraisal of the present condition of these stocks and their potential for future yields.

METHODS

All of the stock-production analyses reported upon herein were applied to the Hawaii Division of Fish and Game (HDFG) catch report data set. This computerized data file contains all of the monthly catch reports submitted to HDFG by the licensed commercial fishermen of the state, spanning the years 1959-78 inclusive. The Graham-Schaefer surplus production model (Ricker, 1975) was applied to those catches and effort statistics concerning species reported to have been commonly taken by deep-sea handline methods. No equilibrium approximation was attempted.

A multivariate clustering program (BMDP, P1M) grouped the 13 species in the fishery according to their various tendencies to appear with one another in the catch. Consequently, the groups that were formed include species which are more or less simultaneously subjected to fishing mortality; therefore, group members were treated as though they were exposed to identical values of annual fishing effort. The annual yield for group members was then pooled to provide estimates of group catch, whereas the accumulated annual number of vessel days during which group members were reported caught formed the corresponding value of fishing effort.

All research sampling was conducted aboard the RV Easy Rider while participating in cooperative vessel charters with other Sea Grant program participants. Four cruises have been made to date comprising some 60 to 70 days at sea. Every fish caught was identified to species and measured to the nearest millimeter fork length (FL). The depth of capture was noted. Otolith and gonad samples were taken from selected specimens for later analysis.

During examination in the laboratory the otoliths were mounted on glass slides after being sectioned and polished. Presumed daily increments are visible in such preparations when viewed through compound optics. The age of a specimen can therefore be estimated by relating the density of increments to size and then integrating the resultant function. Confidence intervals for these estimates have been calculated using the "Delta Method" in which the first several terms of the Taylor series are expanded about the mean value. Age and length data were fitted to the von Bertalanffy growth model (Ricker, 1975) with the help of the nonlinear regression routine obtainable through the Statistical Analysis System (SAS).

Gear selectivity experiments were performed by simultaneously fishing with four different sizes of hooks (Nos. 28, 30, 34, and 38). The presentation of hooks was planned to conform as closely as possible with a Latin Square design (Snedecor and Cochran, 1967). Each bottomfish gurdy on board the vessel was rigged with one hook of each size and each hook size was equally distributed according to line position between gurdies (i.e., top to bottom). The disposition of all four hooks on each gurdy was then monitored for all drops made while fishing.

RESULTS

Stock production

Cluster analyses were conducted on the catch records from each of the four major high island banks. This was done in order to determine whether biological heterogeneity in the deep-sea handline fishery can be attributed to geographical effects. These four banks are defined by the continuity of the 100-fathom contour and include the following islands: (1) Hawaii, (2) Maui, Lanai, Kahoolawe, and Molokai (MLKM), (3) Oahu, and (4) Kauai, Niihau, and Kaula Island (KNK). Subdivision of the MLKM bank was considered inadvisable in spite of its large size because the analysis treated each bank as a separate stock and movements within any given bank along the

100-fathom contour were thought to be likely. On the other hand, the 100-fathom contours around the islands of the KNK bank are not continuous and these three islands were pooled simply because of their close proximity to one another and their small sizes. The banks of the NWHI were not considered in this phase of the study because NWHI catches currently amount to only about 20% of total state landings (Ralston, 1979). Similarly, cluster analyses were employed on data from the years 1959, 1965, 1971, and 1977 to determine whether there have been temporal effects on bottomfish species composition. These various comparisons provided insight into any biological change which may have occurred in the fishery through time and also illuminated any differences which might exist between islands or banks with regard to their species composition.

The results from these two comparisons indicate that no discernible patterns of geographical or temporal difference exist in the bottomfish fishery. The intrinsic variation between clusters obtained from the same bank in three adjacent years (Hawaii in 1976, 1977, and 1978) was as great as comparisons of the variation in clusters formed between different banks and through longer periods of time. While there were a few suggestions of minor differences in the species composition of groups between banks, these were relatively insignificant and were ignored. Only one fairly consistent pattern of grouping was repeatedly exhibited across banks and through time. The clustering analysis shows that the bottomfish fishery is loosely composed of three species groups which are apparently segregated on the basis of the depth range of member species (Table 1). As previously stated, these groups behave in a manner for the most part independent of time and/or location.

TABLE 1. BOTTOMFISH SPECIES GROUPINGS DEFINED BY CLUSTER ANALYSIS

Group	Species	Approximate Depth Range (Fathoms)
I	Uku, ulua, taape, a'awa	30-70
II	Opakapaka, hapuupuu, kahala, gindai, nohu, lehi	40-120
III	Onaga, ehu, kalikali	100-160

Once these more realistic, biological groupings had been established, analysis of catch and effort statistics by bank and species group could proceed. Thus, the Graham-Schaefer model was applied to the HDFG data set 12 times, once for each bank and species group combination. Significant results ($p < 0.05$, one-tailed test) were obtained in 5 of the 12 applications of the model (Table 2). In general, the analyses from the MLKM bank described the effects of fishing adequately (all possible regressions significant) and the analyses of Group III were useful as well (three of four regressions significant). The fact that the results from the other applications of the model were statistically insignificant becomes more palatable when one realizes that approximately 50% of the statewide catch of bottomfish is harvested from the MLKM bank (Ralston, 1979). Furthermore, if one treats all the species of Groups I, II, and III, as one multispecies group and performs a similar production analysis, the regression for total bottomfish from the MLKM bank is significant as well (Table 2, lower portion and Figure 1). It is reassuring to note that the sum of the values of maximum sustainable yield (MSY) for the three species groups from the

TABLE 2. SUMMARY OF STOCK-PRODUCTION STATISTICS FOR ALL SIGNIFICANT REGRESSIONS

Species Group	Bank	Length of 100-Fathom Isobath	MSY (lb)	Optimum Effort (Boat-Days)	MSY/nmi	Catchability Coefficient
I	MLKM	390	50,600	480	130	0.00180
II	MLKM	390	107,600	662	276	0.00062
III	MLKM	390	70,400	396	181	0.00120
III	Oahu	150	4,100	119	27	0.00280
III	KNK	195	10,600	84	54	0.00600
		All Species Pooled as One Group				
	MLKM	390	233,800	901	599	0.00080
	Oahu	150	34,600	424	231	0.00168

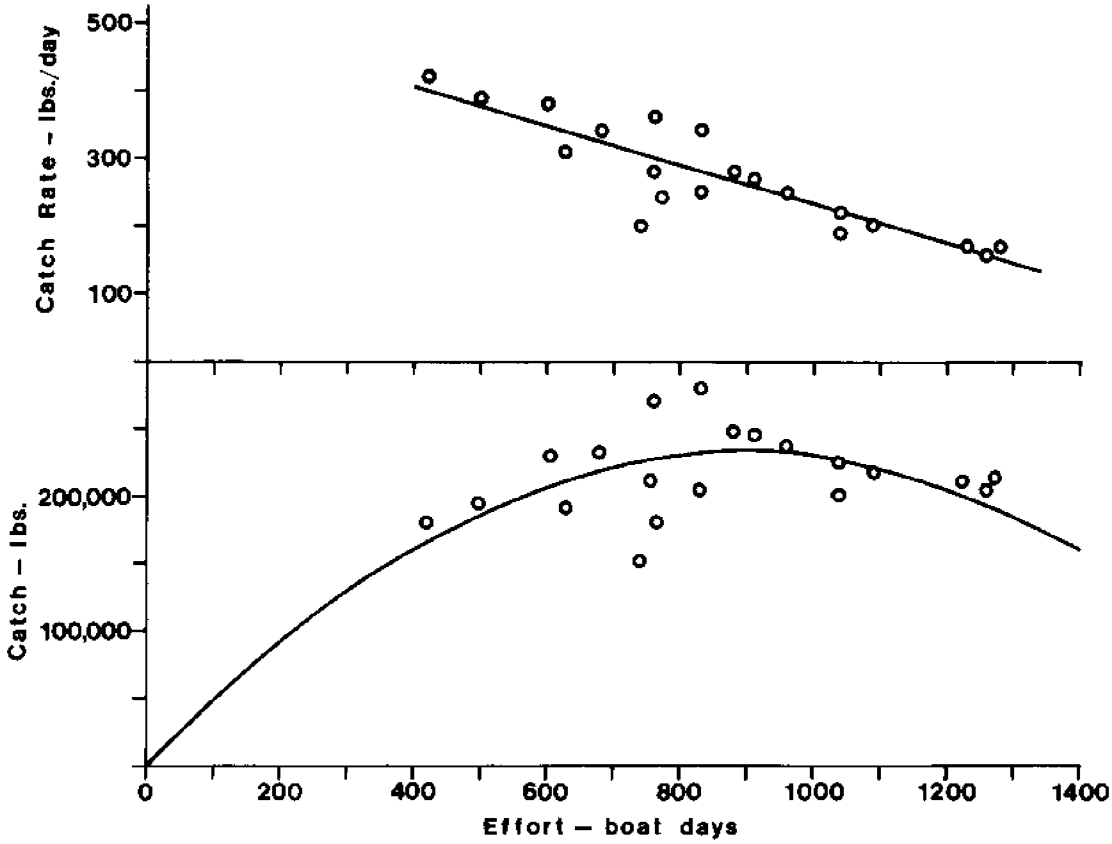

Figure 1. Graham-Schaefer stock-production analysis of the total bottomfish landed from the MLKM bank

MLKM bank in the upper portion of Table 2 accounts for 97.8% of the total MSY value for the pooled analysis in the lower portion of the table. This is excellent agreement considering the circumstances.

These results show that the production of bottomfish is greatest around the MLKM bank, not only in terms of total yield, but also when corrected for differences in fishable area between banks as well. For example, if all species are considered as one multispecies stock (lower portion of Table 2), a figure for MSY per nautical mile (nmi) of 100-fathom contour can be calculated. These results show that a yield of 599 lb of bottomfish/nmi can be sustained on an annual basis from the MLKM bank whereas a comparable figure for Oahu only amounts to 231 lb/nmi. These two figures provide convenient estimates of the upper and lower bounds of annual Hawaiian bottomfish production per nautical mile when all species are considered together.

There is some advantage to be gained however, by splitting the fishery into the groups listed in Table 1. Not only is the biological realism of the stock-production analysis enhanced but several interesting patterns emerge. Notice, for example, that while the estimate of MSY for Group I from the MLKM bank is less than that for Group III from the same bank, the fishing effort required to reach that figure is substantially greater, in spite of the fact that the catchability coefficient for Group I is greater. This apparent contradiction can be reconciled because the virgin biomass of Group I at this bank is much less than Group III, whereas the intrinsic rate of natural increase for this stock is nearly double that of Group III; hence, the disparity in catchability coefficients.

While these figures have no direct bearing on the NWHI, the subject of this workshop, this is only because of the historical lack of substantial fishing effort in this region. Without figures to work with it is impossible to estimate yields. In spite of this it is possible to extrapolate and apply the estimates of production for the high islands to the NWHI. It is known that the total perimeter of the 100-fathom contour in the NWHI is approximately 1,000 nmi. Employing the figures obtained earlier concerning the estimates of upper and lower bounds on bottomfish production, we may guess that MSY for bottomfish from all areas of the NWHI would amount to somewhere between 230,000 and 600,000 lb annually, a range comparable to that for the main high islands.

Age and growth

At this time complete readings and age estimations have been obtained from 43 separate otolith preparations. These were sampled from 35 different opakapaka specimens, ranging in size from 18.6 to 69.9 cm FL. Both left and right sagittal otoliths were examined in eight of these fish to calibrate the accuracy of the integration technique. The results of these calibration checks reveal that independent analyses of two otoliths taken from the same fish yield similar estimates of age. Thus, any variation in age estimates obtained from separate specimens of similar size is almost entirely attributable to true differences in age rather than sampling error stemming from methodology. Overall some 73% of the observed variation in ring density has been explained by the integration model and it has been possible, on the average, to estimate the age in years of individual fish with 95% confidence.

From these data it has been possible to formulate an estimate of the von Bertalanffy growth curve for opakapaka sampled at French Frigate Shoals and Necker Island in the NWHI (Figure 2). All of the plotted points in this figure correspond to separate individuals (N = 28).

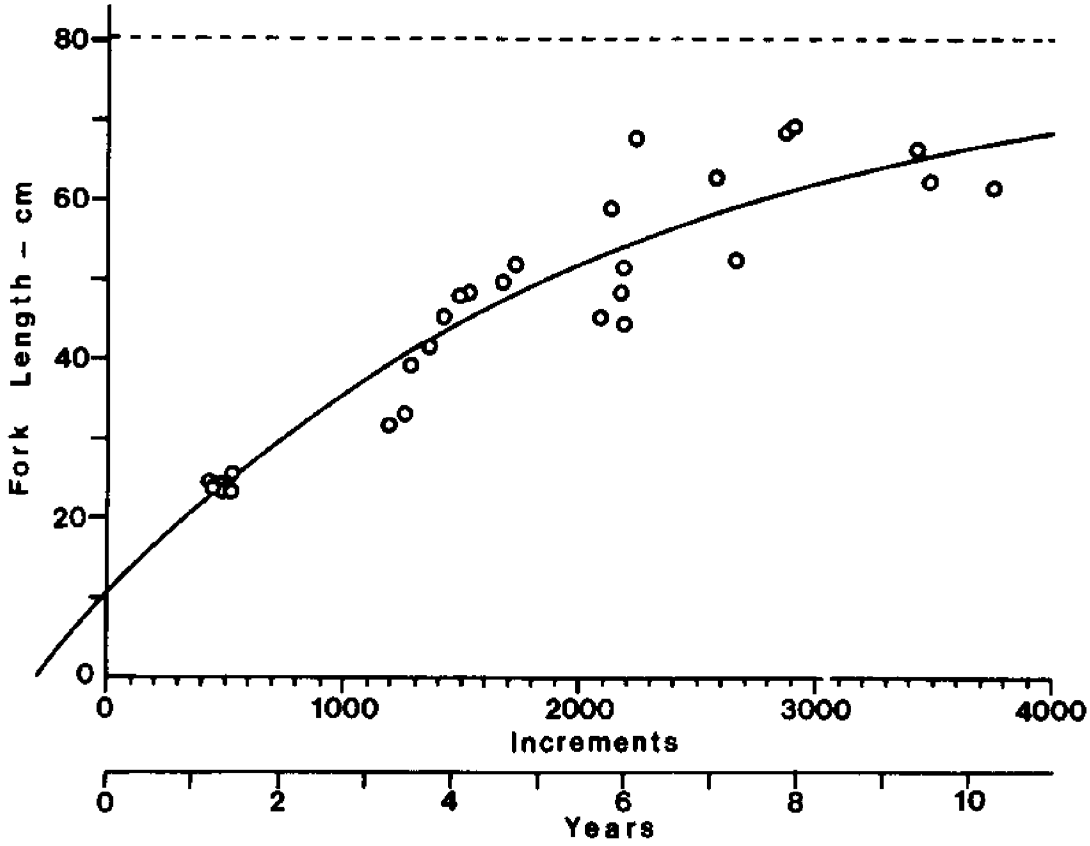

Figure 2. Growth of opakapaka at French Frigate Shoals and Necker Island

The growth equation describing this curve is:

$$\ell(t) = 80.5[1 - e^{-0.164(t + 0.841)}]$$

where t is age in years and ℓ is FL in centimeters. The estimate of asymptotic size (80.5 cm) appears to be very reasonable inasmuch as the largest opakapaka observed to date among over 1,000 measured specimens has been 78 cm FL. At present the estimate of the instantaneous growth rate (0.164/yr) and the scaling parameter (0.84 yr) are open to some question. Differences in the interpretation of increment periodicity between this program and National Marine Fisheries Service (NMFS) investigators have arisen and must be resolved (J. Uchiyama, Southwest Fisheries Center Honolulu Laboratory, NMFS, NOAA, Honolulu, Hawaii 96812, personal communication, May 1979). If increments are deposited more frequently than once a day, as suggested by these researchers, then the two parameter estimates provided here would underestimate the growth rate of this species. This topic will be further discussed under "Future Research Needs."

Estimation of mortality

Populations of animals frequently demonstrate a heterogeneous pattern of spatial distribution in the environment, according to such variables as age and size. If such a population were sampled within some subset of its total range, the results would present a biased representation of the species as a whole. Such considerations are important when attempting to estimate the mortality of certain bottomfish stocks.

The size, and therefore the age, of opakapaka is known to be nonrandomly distributed according to depth of capture and will serve to illustrate this point (Figure 3). If a sample of this species were obtained from a depth range of 40 to 70 fathoms, it is clear that many of the larger fish would be underrepresented. This should be evident in that the peak abundance of small fish (30 to 39 cm FL) occurs in 40 to 50 fathom depths and the abundance of this size group tapers off quite rapidly with increasing depth, whereas larger fish (60 to 69 cm FL) show a more even abundance distribution with varying depth. The effect of such a sampling bias (i.e., underrepresentation of large fish) would be to overestimate the mortality rate of the species. By similar reasoning, if the sample were obtained in deep water then the mortality rate would be underestimated. Only by knowing the form of the density distribution of the various sizes of fish at different depths can this sort of bias be corrected. The results presented in Figure 3 will help to provide an unbiased estimate of the mortality rate of Necker Island opakapaka. A similar description of the relationship among density, size, and depth is also available for French Frigate Shoals. Furthermore, there is evidence to suggest that no seasonal change in these patterns occurs although this species is known to undertake small-scale diel vertical migrations. Currently, it would appear that another important bottomfish species, the hapuupuu, *Epinephelus quernus*, shows no such spatial heterogeneity with regard to size.

Gear selectivity

It is important to study the selective nature of fishing gear for two reasons. Since fishing gear usually does not take a random sample of those fish present, it becomes necessary to evaluate the extent of statistical bias present in samples which are obtained by fishing. Additionally, gear selectivity studies frequently answer questions of direct import to management. For example, restrictions on gear can be used as a regulatory option. For these reasons the effects of variation in hook size on bottomfish catch have been examined.

First, it is reasonable to expect that larger hooks would catch larger fish. However, this does not appear to be the case according to the data already gathered (Figure 4). Over a broad range of hook sizes (Nos. 28 to 38) there is no significant difference in the average size of opakapaka

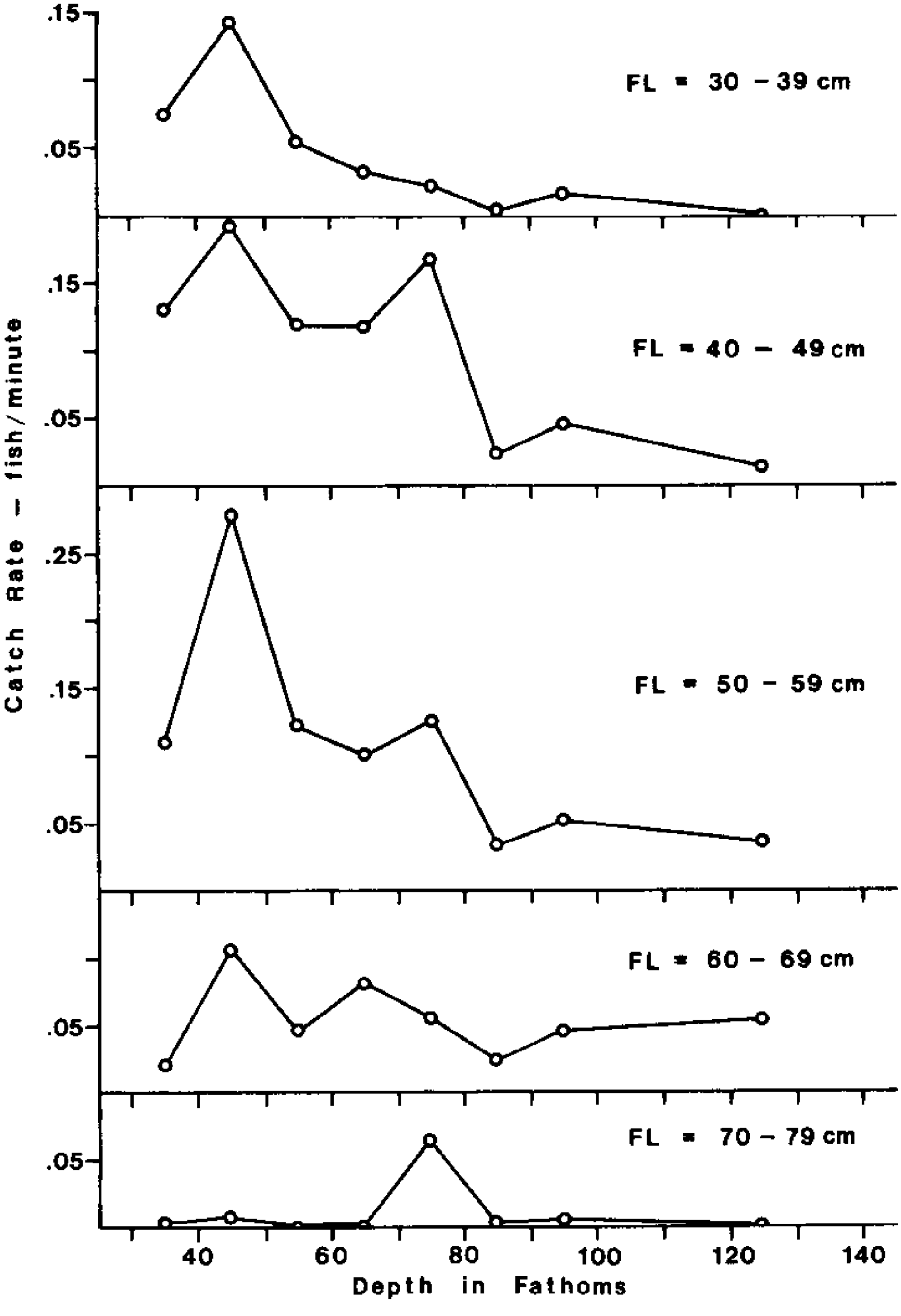

Figure 3. The relationship among size (cm FL), depth, and density (fish/min) of Necker Island opakapaka (based upon 645 captures in 35 hours of fishing)

caught on different sizes of hooks (F = 0.55, d.f. = 3, 99). During experiments conducted so far, the largest opakapaka caught was taken on the smallest size hook while fish as small as 26 cm FL have been captured on the largest size hook. Similar results were obtained for the hapuupuu (F = 0.70, d.f. = 3, 35) and appear to hold for ehu, *Etelis marshi*, pig ulua, *Caranx cheilio*, and kahala, *Seriola dumerili*, as well. Thus, size-frequency distributions of bottomfish caught by fishing with hooks of the indicated series are apparently representative over a broad size range. In addition, these results indicate that gear restrictions would be ineffectual in managing these stocks.

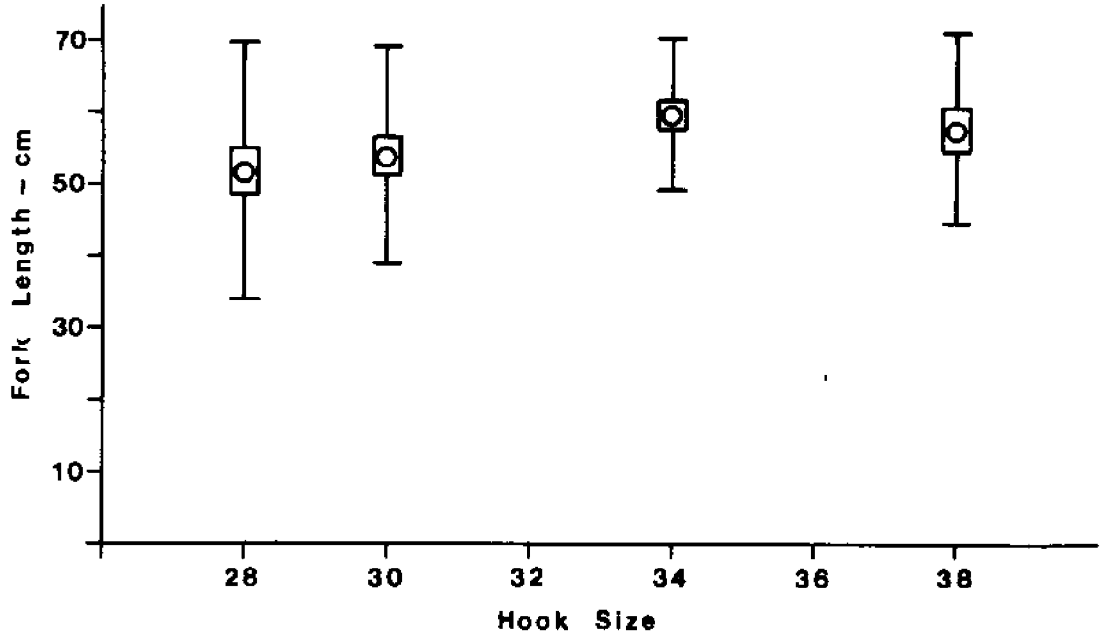

Figure 4. Effects of hook size on the size of opakapaka caught. Circles signify means which are boxed by the standard error and bracketed by the standard deviation.

Not only is the average size of the catch unaffected by hook size but the number of fish caught is similarly insensitive to such variation. Fishing experiments indicate that there is no difference in the mean number of opakapaka caught on each of the four different sizes of hooks on different days of fishing (F = 1.21, d.f. = 3, 19). Furthermore, bait loss was similar for all sizes of hooks (F = 1.66, d.f. = 3, 19). All of these results in conjunction with each other indicate that alterations in gear have very little effect on the outcome of fishing for bottomfish species. Differences among the particular days fished had a much greater impact on all of the variables measured than did differences in hook size.

FUTURE RESEARCH NEEDS

At this point, midway through the completion of this research program, real progress has been made. Attempts at treating the Hawaiian deep-sea handline fishery as a multispecies stock have proven successful with the help of cluster analysis techniques and other improvements in the analytic approach. Analysis of the spatial distribution of opakapaka has provided valuable information in assessing mortality rates. Furthermore, research into the selectivity of fish hooks as a sampling device has shown that length-frequency distributions obtained by this method are relatively unbiased and that gear restrictions are a poor choice for managing this fishery. While there is reason to be satisfied with the progress to date, several areas other than those listed will demand more attention during the ensuing year.

The most serious of these concerns the difference in interpretation relating to the periodicity of otolith increments in the opakapaka. At present there is no way of resolving this issue without obtaining definitive experimental evidence. This kind of evidence may be obtained by sequestering live fish which have had their otoliths marked *in vivo*. The difficulty in performing this experiment stems from maintaining opakapaka alive in captivity. Their deep-dwelling habit and physoclistous condition almost inevitably leads to a lethal embolism for those individuals brought to the surface. In spite of this hindrance, both this program and NMFS investigators have maintained opakapaka specimens in aquaria for moderate periods of time. The solution to this nagging problem is critical and constitutes the single most important aspect of this research program which remains unresolved.

The determination of opakapaka mortality rates should proceed smoothly once the previous problem is solved. Work is currently underway to generate a growth curve similar to Figure 2 concerning main high island opakapaka. Regression statistics from these curves will provide the basis for transforming length data into unbiased age estimates. Once corrections for age-depth stratification have been made (Figure 3) estimation of instantaneous mortality rates will be possible. If no differences exist in the growth of opakapaka from these two areas the data can be pooled resulting in improved estimates of regression parameters. At that point the application of the Beverton and Holt (1957) dynamic pool model would be very straightforward.

While this program has focused rather intensively on the biology of the opakapaka, it was initially hoped that similar analyses could be conducted on hapuupuu, uku, *Aprion virescens*, and onaga, *Etelis carbunculus*, as well. Several obstacles are hindering this goal at present. The first is the inordinate amount of work required in generating growth curves for these species. The analysis of daily otolith growth increments in these fishes is a very time-consuming process and initially it was planned that information gathered by NMFS researchers would be shared to optimize available resources. Progress at present is slow and it is not known whether the formulation of growth curves will be possible for any important species of bottomfish other than opakapaka. This problem is troubling but can be circumvented by other, though less desirable, means. It is possible to undertake a yield-per-recruit analysis without direct recourse to age data although potentially unrealistic assumptions must be made (Martin, 1978). A more serious problem, however, is the lack of extensive length-frequency samples from these three bottomfish species, especially for uku and onaga. Table 1 shows that opakapaka, uku, and onaga are segregated by depth and, as a result, catches of the latter two species have been negligible during field work. Adequate length-frequency samples for these two species are a necessity and could be obtained by a regular monitoring program at the United Fishing Agency fish auction. Interprogrammatic cooperation with NMFS should assist in this regard.

SUMMARY

A realistic stock-production analysis of HDFG catch reports has been completed and production estimates per unit area are available. Laboratory studies on the otoliths of opakapaka are progressing on schedule but further experiments are needed to provide additional clarification. In addition, most of the data collection and analysis necessary for the estimation of mortality rates of opakapaka stocks have already been accomplished. While problems have arisen which will require further work, a reasonable appraisal of Hawaii's deep-sea handline fisheries resource seems near at hand.

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A PRELIMINARY REPORT ON BOTTOMFISHING IN THE NORTHWESTERN HAWAIIAN ISLANDS

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ABSTRACT

Regional and day-night differences in the distribution and catchability of bottomfishes are shown through analysis of catch data collected by the National Marine Fisheries Service on cruises of the NOAA ship *Townsend Cromwell* in the Northwestern Hawaiian Islands. Large catches of opakapaka, *Pristipomoides filamentosus*, in the Nihoa to Gardner Pinnacles region are replaced by those of hapu'upu'u, *Epinephelus quernus*, further up the chain. Mean fish weight for several species increases going up the chain, possibly due to fishing pressure in the Nihoa to Gardner Pinnacles region. Day fishing results in a greater catch rate than night fishing. Preliminary growth estimates indicate that opakapaka takes 3.25 yr. and kahala, *Seriola dumerili*, takes 1.75 yr. to attain a 70-cm fork length.

bottomfish
age and growth
distribution and relative abundance

INTRODUCTION

With the creation of the 200-mile Fishery Conservation Zone in 1976 and the extensive fishing pressure around the main islands of Hawaii came the need for marine resource assessment of the Northwestern Hawaiian Islands (NWHI). Under the Tripartite Cooperative Agreement, the Southwest Fisheries Center Honolulu Laboratory, National Marine Fisheries Service (NMFS) assumed responsibility for the quantitative fishery assessment and survey of benthic slope and pelagic resources of the NWHI (Uchida et al., 1979). One major portion of our responsibility is the deepwater bottomfish resource.

At present, the NWHI bottomfish resource supports a small commercial fishery which has been in existence since at least 1948. Due to the long distance between the NWHI and marketing ports, most of the commercial fishing effort has been limited to the area between Nihoa and Gardner Pinnacles.

The Insular Resource Task of NMFS has examined various aspects of biological and fishery data on the NWHI demersal fishery. Studies on the feeding habits (see paper by Humphreys), spawning and fecundity (see paper by Kikkawa), occurrence of ciguatoxin (see paper by Ito and Uchida), and age and growth (J.H. Uchiyama, Southwest Fisheries Center Honolulu Laboratory, NMFS, NOAA, Honolulu, Hawaii 96812, personal communication, March 1980), are in various stages of completion. This report will discuss the distribution and relative abundance of the demersal fishes obtained from our survey cruises and the progress on age and growth studies on opakapaka, _Pristipomoides filamentosus_, and kahala, _Seriola dumerili_.

MATERIAL AND METHODS

The sole source of information used in this paper is the catch data obtained by NMFS on cruises of the _Townsend Cromwell_ from October 1975 to May 1979. During this period, the _Cromwell_ occupied 112 handline fishing stations on eight cruises in the NWHI. Except where otherwise stated, all references to catch refer to the catch of the eight most important commercial species caught by the _Cromwell_: opakapaka; ehu, _Etelis marshi_; onaga, _E. carbunculus_; kalekale, _P. sieboldii_; gindai, _P. zonatus_; butaguchi, _Caranx cheilio_; kahala; and hapu'upu'u, _Epinephelus quernus_.

Fishing operations were conducted while drifting near the edge of the banks at bottom depths varying from 30 to 200 fathoms. Our handline gear consisted of lines with from 2 to 15 hooks (Nos. 20 to 30) per line. We generally used hydraulic or electric gurdies to aid in line retrieval and occasionally fished manually retrieved lines as well. The most commonly used bait was stripped squid. In processing the catch, we recorded species, sex, weight, and both standard and fork or total length measurements. Where appropriate, we preserved gonads, stomachs, tissue samples, and otoliths for future analysis at the laboratory.

On the _Cromwell_ we usually retrieve lines as soon as one fish is on, regardless of the number of hooks we are using. For this reason, I chose line-hours rather than hook-hours as an estimate of fishing effort. In data analysis, I used catch per unit effort (CPUE) by station both for weight (kilogram) and numbers of each species as two measures of relative abundance and catchability.

I used analysis of variance (ANOVA) to test the null hypothesis that location in the chain, species, and day-night factors have no effect on CPUE. Since there were insufficient data to allow for a bank-by-bank analysis, I divided the project area into three regions. Region I, Nihoa through Gardner Pinnacles, represents the area fished by commercial vessels on a regular basis. Region II, Raita Bank through Lisianski Island, is separated from Region III, Pearl and Hermes Reef through Kure Atoll, by a natural break in the chain. In the test for day and night differences in catchability, the separations between day and night stations were not distinct, so I arbitrarily placed data into day or night categories depending on whether most of the fishing effort occurred before or after 0600 and 1930 hours.

We followed the methods of Struhsaker and Uchiyama (1976) in cleaning, mounting, and reading otoliths for age determinations.

RESULTS

The CPUE of the combined catch of all commercial species varied considerably among stations. Many stations had no catch at all whereas at one Midway Island station, the catch rate was 43.3 kg/line-hour (9.3 fish/line-hour). On a bank-to-bank basis, overall catch rates ranged from 0 at Salmon Bank and an unnamed bank northeast of Midway to 12.6 kg/line-hour (3.1 fish/line-hour) at Pearl and Hermes Reef. A portion of this variation may be due to the wide range in fishing effort at the various stations and banks (0.5 to 32.3 line-hours and 3.3 to 231.7 line-hours, respectively). Regional catch data for each species are presented in Table 1 for day, night, and overall catches. Table 2 compares day and night CPUE by weight for each species. Catch composition of the five major species in numbers by region is displayed in Figure 1 (onaga, gindai, and kalekale make up such a small portion of our catch that they are not included in this figure). Table 3 lists the incidental species caught with their overall catch rates.

In a three-way ANOVA of CPUE in terms of weight, significant differences in CPUE were found among regional ($P = 0.02$), species ($P = < 0.01$), and day-night ($P = 0.01$) classifications and with region to species ($P < 0.01$) and species to day-night ($P = 0.02$) interactions. In a three-way ANOVA with CPUE in terms of numbers, however, significant differences were found in only three cases: species, day-night, and region to species. In a one-way ANOVA of mean fish weight by region for each species, significant differences were found for ehu between Regions I and II, and I and III; hapu'upu'u between Regions I and II; kahala between Regions I and III; and gindai between Regions I and II. Results of a chi-square test of the number of fish caught by species by region show significant differences in species composition by region.

We have collected otoliths from fish of all of the commercially important species mentioned in this paper. Preliminary growth curves for opakapaka (Figure 2) and kahala (Figure 3) have been estimated from otolith examinations (Uchiyama, personal communication, March 1980). Laboratory, NMFS, NOAA, Honolulu, Hawaii 96812, personal communication, March 1980).

TABLE 1. COMMERCIAL CATCH DATA FOR BOTTOMFISH IN THE NORTHWESTERN HAWAIIAN ISLANDS

Species	Region I				Region II				Region III			
	Catch		CPUE		Catch		CPUE		Catch		CPUE	
	No.	Weight (kg)	No.	Weight (kg)	No.	Weight (kg)	No.	Weight (kg)	No.	Weight (kg)	No.	Weight (kg)
All species												
Day	589	2,028.6	1.815	6.251	321	1,506.2	1.785	8.377	178	769.2	1.841	7.954
Night	219	707.2	1.117	3.608	72	369.2	0.769	3.944	113	456.0	1.447	5.839
Total	808	2,735.8	1.552	5.256	393	1,875.4	1.437	6.860	291	1,225.2	1.665	7.009
Ehu												
Day	99	132.2	0.305	0.407	90	195.8	0.501	1.089	67	136.8	0.693	1.415
Night	62	105.7	0.316	0.539	21	42.8	0.224	0.457	30	46.1	0.384	0.590
Total	161	237.9	0.309	0.457	111	238.6	0.406	0.873	97	182.9	0.555	1.041
Opakapaka												
Day	245	817.3	0.755	2.519	40	163.4	0.222	0.909	0	0	0	0
Night	89	255.0	0.454	1.301	4	15.8	0.043	0.169	7	34.3	0.090	0.439
Total	334	1,072.3	0.642	2.060	44	179.2	0.161	0.655	7	34.3	0.040	0.196
Hapu'upu'u												
Day	75	424.9	0.231	1.309	79	562.2	0.439	3.127	57	338.4	0.589	3.499
Night	17	114.1	0.087	0.582	22	147.0	0.235	1.571	47	203.2	0.602	2.602
Total	92	539.0	0.177	1.036	101	709.2	0.369	2.594	104	541.6	0.595	3.098
Butaguchi												
Day	66	409.1	0.203	1.261	55	297.4	0.306	1.654	32	162.7	0.331	1.683
Night	7	24.5	0.036	0.125	8	37.1	0.085	0.396	7	35.8	0.090	0.458
Total	73	433.6	0.140	0.833	63	334.5	0.230	1.223	39	198.5	0.223	1.136
Kahala												
Day	36	173.6	0.111	0.535	30	232.3	0.167	1.292	8	96.8	0.083	1.001
Night	22	183.0	0.112	0.934	11	114.4	0.118	1.222	15	117.2	0.192	1.501
Total	58	356.6	0.111	0.685	41	346.7	0.150	1.268	23	214.0	0.132	1.224
Gindai												
Day	25	35.3	0.077	0.109	22	36.3	0.122	0.202	0	0	0	0
Night	5	8.6	0.026	0.044	5	11.0	0.053	0.117	0	0	0	0
Total	30	43.9	0.058	0.084	27	47.3	0.099	0.173	0	0	0	0
Kalekale												
Day	42	28.5	0.129	0.088	2	1.2	0.011	0.007	8	3.8	0.083	0.039
Night	16	9.8	0.082	0.050	1	1.1	0.011	0.012	5	3.7	0.064	0.047
Total	58	38.3	0.111	0.074	3	2.3	0.011	0.008	13	7.5	0.074	0.043
Onaga												
Day	0	0	0	0	3	15.8	0.017	0.088	6	30.7	0.062	0.317
Night	1	6.6	0.005	0.034	0	0	0	0	2	15.6	0.026	0.200
Total	1	6.6	0.002	0.013	3	15.8	0.011	0.058	8	46.3	0.046	0.265

TABLE 2. OVERALL CATCH PER UNIT EFFORT FOR DAY AND NIGHT FISHING STATIONS

Species	CPUE (weight)		Ratio
	Day	Night	
Ehu	0.77	0.53	1.45
Opakapaka	1.63	0.53	1.96
Hapu'upu'u	2.21	1.26	1.75
Butaguchi	1.45	0.26	5.58
Kahala	0.84	1.13	0.74
Gindai	0.12	0.05	2.40
Kalekale	0.06	0.04	1.50
Onaga	0.08	0.06	1.33
All species together	7.16	4.17	1.72

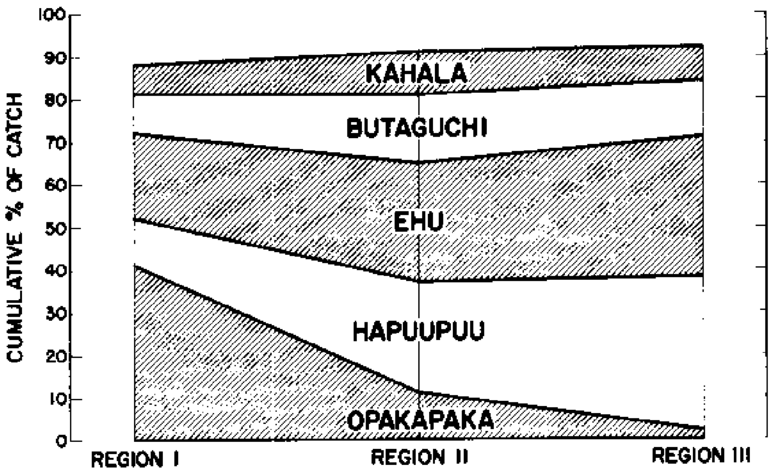

Figure 1. Catch composition by region in terms of numbers

TABLE 3. CATCH OF INCIDENTAL SPECIES IN THE NORTHWESTERN HAWAIIAN ISLANDS

Species	Catch		CPUE	
	Number	Weight (kg)	Number	Weight (kg)
Gempylidae				
Promethichthys prometheus	47	20.6	0.049	0.021
Carangidae				
Caranx lugubris	13	41.0	0.013	0.042
C. ignobilis	38	349.7	0.039	0.361
C. speciosus	1	0.9	0.001	0.001
C. sexfasciatus	1	0.7	0.001	0.001
C. melampygus	3	11.6	0.003	0.012
Carangoides ferdau	3	18.1	0.003	0.019
Elagatis bipinnulatus	2	20.2	0.002	0.021
Priacanthidae				
Priacanthus sp.	5	2.7	0.005	0.003
Holocentridae				
Myripristis sp.	6	2.0	0.006	0.002
Tetraodontidae				
(*Sphoeroides cutaneus* and *Lagocephalus* sp. included)	17	9.1	0.018	0.009
Scorpaenidae				
Pontius macrocephalus	9	10.7	0.009	0.011
Scorpaenopsis cacopsis	1	1.5	0.001	0.002
Scorpaena colorata	1	0.7	0.001	0.001
Labridae				
Bodianus bilunulatus	5	5.7	0.005	0.006
B. oxycephalus	7	14.1	0.007	0.015
Lutjanidae				
Aprion virescens	1	7.5	0.001	0.008
Pristipomoides auricilla	2	1.6	0.002	0.002
Scombridae				
Scomber japonicus	3	5.2	0.003	0.005
Sarda orientalis	3	13.3	0.003	0.014
Mullidae				
Mulloidichthys pflugeri	1	1.4	0.001	0.001
Parupeneus porphyreus	1	1.4	0.001	0.001
Sphyraenidae				
Sphyraena sp.	4	4.0	0.004	0.004
Synodontidae				
Trachinocephalus myops	1	0.6	0.001	0.001
Muraenidae				
Gymnothorax berndti	1	0.9	0.001	0.001
Squalidae	2	7.3	0.002	0.008
Carcharhinidae	8	--	0.008	--

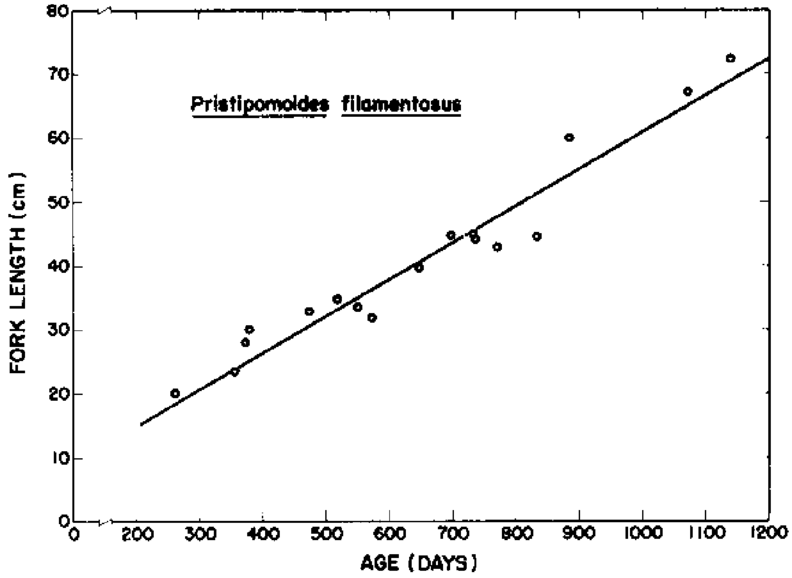

Figure 2. Preliminary growth curve for opakapaka, *Pristipomoides filamentosus*

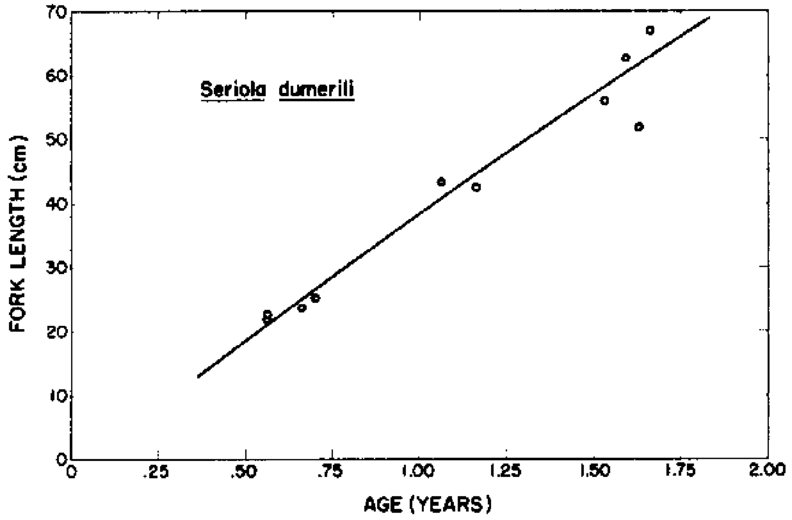

Figure 3. Preliminary growth curve for kahala, *Seriola dumerili*

DISCUSSION AND CONCLUSIONS

The three-way ANOVA tests showed that the regional increase in overall CPUE in terms of weight for the combination of all commercial species presented in Table 1 is significant ($P = 0.02$) whereas the change in CPUE in terms of number is not ($P = 0.12$). This results in an increase, by region, in the mean weight of the hypothetical composite commercial bottomfish. There are two possible explanations for this increase. Either the mean weight of individuals within a species is increasing or a generally larger species comprises a greater percentage of the catch on a regional basis from Regions I to III. To check on the first possibility, I ran a one-way analysis of variance of mean fish weight by region for each species. As mentioned in the results section, ehu, kahala, gindai, and hapu'upu'u showed significant regional differences in mean weight. Also, in all significant cases, mean weight increased between Regions I and II or I and III. Thus, increase in mean weight of fish by species does contribute to the overall increase in CPUE by region. This may be an indication of fishing pressure in Region I where mean weights were significantly lower for these species, or it may be due to other factors such as temperature or habitat differences between regions.

The significant difference in CPUE in terms of numbers by species by region shown in the three-way ANOVA indicates that there is a change in species composition by region, as well. Cell values for variance in the chi-square test showed that opakapaka and hapu'upu'u are major contributors in this difference. These changes in relative abundance for opakapaka and hapu'upu'u are shown graphically in the species composition by region (Figure 1). The difference in overall mean weights for opakapaka (4.0 kg) and hapu'upu'u (6.8 kg) indicates that the regional change in the species composition is also a factor in the regional increase in CPUE in terms of weight.

Day and night differences in catchability are also significant. Results of the three-way ANOVA show that day and night CPUE in terms of weight is significantly different on both an overall and by-species basis. Differences in day and night CPUE are presented in Table 2 as the ratio of day CPUE to night CPUE. As can be seen, the day CPUE is, in general, higher than the night CPUE. In fact, the only commercial species with a higher CPUE at night is kahala. The day-night difference is particularly noticeable for butaguchi where the day CPUE is over five times greater than the night CPUE. These differences in catchability may be due to changes in feeding activity between day and night or a nightly migration away from the areas that we normally fish. Similar trends were found for CPUE in terms of number, but they were not found to be significant on a species basis.

Commercially, fishing for opakapaka is usually conducted at night with night catches reported to be far better than day catches (C. Yamamoto, captain, FV *Koko*, Honolulu, Hawaii 96814, personal communication, May 1980 and W. Shinsato, captain, FV *Taihei Maru*, Honolulu, Hawaii 96814, personal communication, May 1980). That our results differ from the experiences of commercial fishermen is probably due to the differences in fishing techniques employed. On the *Townsend Cromwell* we fish close to the bottom while drifting for both day and night fishing operations. Commercial fishermen on the other hand, may drift fish during the day, but at night they usually anchor over opakapaka grounds, chum to aggregate the fish, and fish well off the bottom (up to 15 fathoms).

Our studies of age and growth of bottomfishes are still in the preliminary stages. We have made age estimates on a few specimens of each of the commercial species discussed in this paper. We still have many otoliths to read, but we do have enough data to establish tentative growth curves for opakapaka (Figure 2) and kahala (Figure 3). Because we have no data for fish outside of the size ranges of those used to generate the curves, estimates of age using these curves should be limited to fish falling within these ranges. For greater confidence in our growth estimates, we must verify the temporal nature of the suspected daily growth increments on otoliths. We are currently conducting experiments to mark otoliths by tetracycline injections in captive fish (e.g., opakapaka; akule, Trachurops crumenophthalmus; papio, Caranx sp.; and malu, Parupeneus pleurostigma) to verify the temporal periodicity of otolith growth increments.

FUTURE RESEARCH NEEDS

Much work remains to be done in this project. At the conclusion of the field work, we should have enough catch information to make a bank-by-bank analysis of distribution and relative abundance of bottomfishes in the NWHI. We should also have enough otoliths read to determine reliable growth curves for all the commercial species. Reliability of these curves, of course, will be largely dependent upon verification of the daily nature of the otolith growth increments. This, combined with future progress in other areas under current investigation (fecundity, spawning season, foraging habits, and ciguatoxin), will give us a fair understanding of the biology and catchability of bottomfishes in the NWHI.

There are other areas of investigation that would also be helpful. Recording the time of day that each fish is caught, rather than just the duration of the station as we presently do, would give a much better picture of the catchability of each species throughout the day. It is possible that there are some interesting relationships, such as increased catchability at dawn and dusk, that are obscured by present methods of data collection.

Fishing operations should be conducted while at anchor using chum to aggregate fish. This technique should produce high catches. Catch results using this technique could then be compared with those obtained while drift fishing.

A study of recruitment has been proposed by NMFS which is designed to exert heavy fishing pressure on a small bank followed by monitoring the recovery of fish stocks. Results from this study would produce a better estimate of bottomfish stocks in the NWHI than is now available.

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PRELIMINARY STUDY ON THE SPAWNING SEASON OF THE OPAKAPAKA, <u>PRISTIPOMOIDES FILAMENTOSUS</u>

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ABSTRACT

As part of the survey and assessment program of the Northwestern Hawaiian Islands, the National Marine Fisheries Service has been studying the distribution, apparent abundance, and biology of commercially valuable bottomfish. This study deals with the reproductive cycle of the opakapaka, *Pristipomoides filamentosus*, one of the most important snappers in the Hawaiian fishery. The results showed that the development of ova within the paired ovaries is heterogeneous. Stages of maturation, determined from the development of ova in the most advanced mode in the distribution of random ova diameters, showed a positive relationship with the gonadal somatic indices. The gonadal somatic index peaked in August with spawning possibly taking place in September.

opakapaka
reproduction
Northwestern Hawaiian Islands

INTRODUCTION

The opakapaka or pink snapper, *Pristipomoides filamentosus* Cuvier and Valenciennes, which has been fished intensively around the Hawaiian Archipelago for decades, is the most important bottomfish in terms of landed weight and cash value. This snapper is prized for its good taste and pleasing appearance (Brooks Takenaka, Assistant Manager, United Fishing Agency, Honolulu, Hawaii, personal communication, January 1980).

There is a limited amount of literature on the life history and biology of the opakapaka. Most papers written about the opakapaka deal with the fishery.

In 1976, the National Marine Fisheries Service (NMFS), Honolulu Laboratory initiated a resource assessment program for the Northwestern Hawaiian Islands (NWHI). Part of the program deals with the bottomfish resource and its interaction with the ecosystem. This study examines the spawning behavior of the opakapaka.

METHODS

For a major part of the resource assessment program, the NOAA ship Townsend Cromwell was used to survey the bottomfish resource in the NWHI. The opakapaka with other bottomfishes were caught on handline gear using four hooks (No. 26) per line. The lines were retrieved by four powered gurdies on the starboard rail. Opakapaka were usually caught between 40 and 120 fathoms.

The fish landed were measured for fork length (FL) and standard length (SL) in millimeters and weighed to the nearest 10 g. Otoliths, gonads, and stomach content samples were removed and retained for further studies. Samples were preserved in 4% formaldehyde and seawater. No quantitative observations were taken on the preserved ovarian material until 6 or more months had passed and shrinkage had been stabilized.

Homogeneity

A pair of ovaries was examined for homogeneous development of the ova. A No. 5 cork borer with an inside diameter of 10.026 mm was used to extract core samples from the anterior, middle, and posterior regions of both ovaries. Each of the core extended from the outer surface of the ovary to the centrally located lumen and was divided into an outer layer, central layer located adjacent to the lumen, and a middle layer, thus providing a total of 18 subsamples. Developing ova were teased from each of the 18 subsamples and 200 randomly selected ova were measured.

Spawning seasonality

For the spawning season of the opakapaka, 21 ovaries collected between February 1978 and June 1979 were examined. Maturity of the ovary was determined by examining the middle core sample. Four hundred randomly selected ova were classified according to stage of maturity from the three layers of the cored sample. The mean of the last two advanced modes were taken to determine ovarian maturation state.

Developmental stages of the ova

The developmental stages, determined on the basis of physical appearance (Uchiyama and Shomura, 1974), are described as follows:

1) Primordial

Primordial ova are found in all the ovaries, usually ovoid in structure and transparent. No ova diameters were measured.

2) Early developing ova

Ova are transparent to translucent with the beginning of opaque yolklike matter in the ovum. The shape of the ova is usually ovoid or wedgelike. Size range: 0.15 to 0.39 mm in diameter.

3) Developing ova

Ova are completely opaque and ovoid. Size range: 0.16 to 0.67 mm in diameter.

4) Advanced developing

Ova are ovoid and have a translucent margin. The fertilization membrane has formed. Size range: 0.39 to 0.60 mm in diameter.

5) Early ripe

Ova are usually round or spherical. The yolk material is translucent and the oil globules have formed. Size range: 0.47 to 0.58 mm in diameter.

6) Ripe ova

Ova are transparent and contain oil globules. No ovary in the ripe condition was collected.

7) Residual ova

Ova are degenerating and show signs of shrinking.

RESULTS

Homogeneity of development

In the test of homogeneity, ovary No. 14 was selected and the ova diameters in the developing stage from each of the 18 sites were compared. The frequency distributions of the diameters were skewed to the right of the mean. A Kruskal-Wallis non-parametric test (Sokal and Rohlf, 1969) was used to test the homogeneity of locations for the distributions of ova diameters for the 18 sites. The results showed that the locations of the 18 distributions differed significantly ($X^2 = 191.45$, df = 17, $P = 0.05$). The development of the ovary in the opakapaka is therefore heterogeneous. Heterogeneous development of large ovaries were also demonstrated in the bigeye tuna, *Thunnus obesus*, by Yuen (1955), in the albacore, *T. alalunga* by Otsu and Uchida (1959), and in the swordfish, *Xiphias gladius*, by Uchiyama and Shomura (1974).

Spawning season

The gonadal somatic index (GSI), because it can be easily calculated, can be used to reduce time-consuming and tedious examination and measurement of the ova, provided it can be shown to have a positive relationship with stages of maturity (Table 1). To explore this possibility, a test was conducted initially to determine whether fish size was related to the GSI; however, no significant correlation was obtained ($r = 0.025$; $df = 20$; $P > 0.05$), indicating that fish size was not associated in any way to the GSI. A test between fish size and stages of maturity also showed no significant correlation ($r = 0.212$; $df = 20$; $P > 0.05$). When GSI was plotted against stages of maturity, however, there was an indication of a positive trend. A test of the relationship between GSI and stages of maturity showed a significant positive correlation ($r = 0.540$; $df = 20$; $P < 0.01$), but because only two samples past the early developing stage were available, the relationship cannot be accepted as conclusive (Figure 1). It would appear, however, that as females mature, the weight of the ovary not only increases faster than the total body weight, but also rises and falls in relation to development, spawning, and redevelopment.

To determine the spawning cycle of the opakapaka, GSI was plotted against the month of capture. The results show that it reached its lowest level in March and peaked in August (Figure 2). The opakapaka, therefore, appears to have one spawning period each year in early fall, probably in September (Table 1).

DISCUSSION

By examining conditions and occurrence of the early ripe and advanced developing ova throughout the 18 sites, it was possible to determine visually that development of the ovary in the opakapaka was heterogeneous. Of the total 18 subsamples from one fish, only six subsamples had ova in the advance developing stage and two subsamples had ova in the early ripe stage.

In the test for homogeneity of location, developing ova were used because of their consistency throughout the 19 subsamples.

TABLE 1. FORK LENGTHS, GONAD WEIGHTS, GONADAL SOMATIC INDICES, AND STAGES OF MATURATION OF 28 OPAKAPAKA SAMPLED BETWEEN FEBRUARY 1978 AND JUNE 1979

Sample No.	Date of Catch	Fork Length (cm)	Fish Weight (kg)	Preserved Gonad Weight (g)	Gonadal Somatic Index[1]	Maturity[2]
1	10/25/78	70.1	5.28	58.61	1.11	Dev.
2	8/09/78	60.4	3.72	--	--	Dev.
3	8/11/78	71.4	5.58	58.84	1.05	Dev.
4	10/25/78	72.7	5.05	37.16	0.74	Imma.
5	--	58.7	3.69	64.00	1.73	Adv. Dev.
6	8/09/78	66.2	4.66	--	--	Dev.
7	8/09/78	63.1	4.00	54.68	1.37	Dev.
8	9/13/78	62.1	4.00	96.22	2.41	Imma.
9	8/11/78	72.22	5.88			
10	9/13/78	52.0	2.52	89.44	3.55	Resid.
11	9/17/78	76.3	6.49	136.16	2.10	Adv. Dev.
12	9/17/78	48.7	2.02	33.61	1.66	Dev.
13	9/19/78	--	--	20.81	--	Dev.
14	8/24/78	67.1	5.45	223.42	4.10	Early Ripe
15	10/ /78	54.0	2.18	35.81	1.64	Adv. Dev.
16	10/ /78	52.0	2.49	36.38	1.46	Adv. Dev.
17	10/ /78	59.0	2.81	14.09	0.50	Adv. Dev.
18	10/ /78	58.0	2.36	--	--	Adv. Dev.
19	3/05/78	57.3	3.00	11.12	0.37	Imma.
20	3/05/78	55.4	2.90	10.99	0.38	Imma.
21	10/ /78	71.0	5.53	152.8	2.76	Adv. Dev.
22	3/06/78	73.5	6.30	40.85	0.65	Imma.
23	2/26/78	52.6	2.17	10.34	0.48	Imma.
24	3/06/78	64.0	5.40	25.57	0.47	Imma.
25	2/26/78	68.3	5.30	28.78	0.54	Imma.
26	6/02/79	45.6	2.10	38.01	2.10	Dev.
27	5/18/79	94.7	6.90	74.70	1.37	Dev.
28	5/23/79	74.9	--	--	--	Dev.

[1] Gonadal somatic index = $\frac{\text{gonad weight}}{\text{fish weight}} \times 100$

[2] Dev. = developing ova; Imma. = immature ova; Adv. Dev. = advanced developing ova; and Resid. = residual ova.

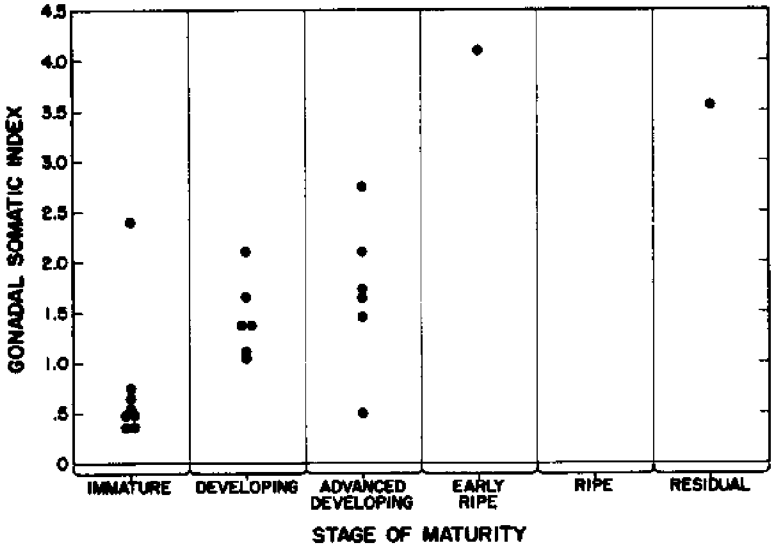

Figure 1. Relationship between stages of maturity and gonadal somatic index in the opakapaka, Pristipomoides filamentosus

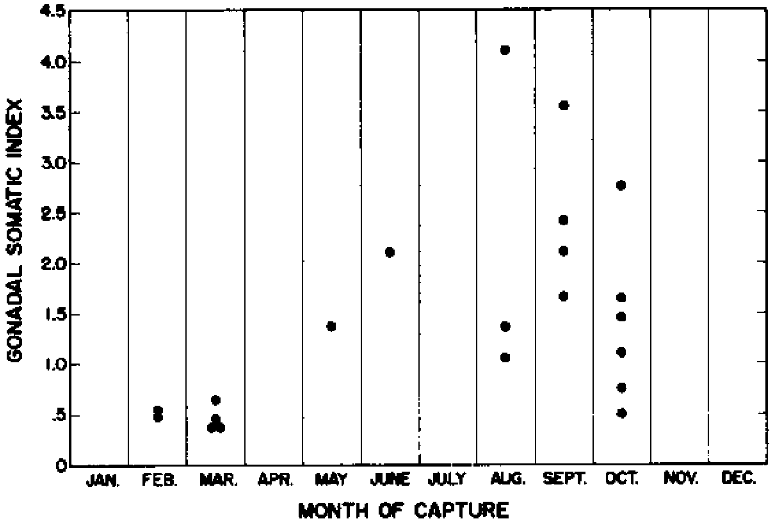

Figure 2. Relationship between month of capture and gonadal somatic index in the opakapaka, Pristipomoides filamentosus

FUTURE RESEARCH NEEDS

More opakapaka need to be sampled between November and July, including a wide range of gonads to determine minimum size of spawning and sexual maturity. It is important that ripe ovaries be obtained to better understand ovary development, fecundity, and spawning cycles.

SUMMARY

Preliminary results show that the opakapaka ovaries develop heterogeneously.

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FEEDING HABITS OF THE KAHALA, SERIOLA DUMERILI, IN THE HAWAIIAN ARCHIPELAGO

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ABSTRACT

Stomach contents of kahala, Seriola dumerili, were examined for a determination of possible relationships between the feeding habit and incidence of ciguatoxicity in this species and also as part of a study on its overall life history. Preliminary results indicated a change from cephalopods to fish as the principal dietary constituent with increase in weight of kahala. Also, the diet of fish caught in the Northwestern Hawaiian Islands appeared more varied in terms of a larger combined cephalopod and crustacean volume than those caught in two other areas within the main islands. Fish dominated the diet of kahala, with Carangidae the largest contributor among forage items. High incidences of parasitic nematodes and trematodes were observed with nematodes the most predominant in occurrence. Further examination of stomach contents is needed to ascertain the dietary trends indicated thus far.

Northwestern Hawaiian Islands
Seriola dumerili
ciguatera
stomach analysis

INTRODUCTION

The kahala, Seriola dumerili (Risso), is found worldwide and its Indo-Pacific distribution reaches Hawaii, Australia, Japan, China, and eastern Africa (Mather and Bartlett, 1966). Within the Hawaiian Archipelago, kahala is found primarily in 40 to 100-fathom depths within coastal waters and it appears to be primarily associated with the bottom (Gosline and Brock, 1960).

Food habit studies on members of *Seriola* are few. The feeding habits of pelagic larval and juvenile stages of *Seriola quinqueradiata* were studied in waters off Kyushu, Japan. The diet consisted primarily of planktonic crustaceans and the larvae and juvenile stages of Engraulidae, Scomberesocidae, and Mullidae (Anraku and Azeta, 1965). Studies on the yellowtail, *Seriola dorsalis*, in California indicated that this species was an "opportunistic feeder," its diet consisting mainly of pelagic red crabs, squid, sardines, anchovies, jack mackerel, *Trachurus symmetricus*, and Pacific mackerel, *Scomber japonicus* (Baxter, 1960). No published food habit studies are available for kahala found in Hawaiian waters or elsewhere.

The objectives of the current food habit study on kahala are twofold: (1) to determine whether differences in forage items exist in the diets of ciguatoxic and non-ciguatoxic fish in conjunction with the current ciguatoxin study of kahala and, (2) to investigate the food habits as part of an overall life history study of this species.

METHODS

Stomachs are collected along with gonads and flesh samples as part of an ongoing ciguatoxin study of kahala. A cooperative program was established by which fishermen and fish dealers send all kahala to the fish auction house located at the United Fishing Agency (UFA). Sampling is conducted by National Marine Fisheries Service employees six days a week on all kahala sent to UFA. Data are collected on weight, fork length, sex, depth, and location of capture for each fish.

The samples are processed at the University of Hawaii John A. Burns School of Medicine, Pathology Department, with a practical and relatively specific radioimmunoassay (RIA) for the detection of ciguatoxin (Hokama et al., 1977). The toxicity levels of the fish tissues are determined from radioactive counts per minute per gram tissue (c/min/g) as follows: <350,000 c/min/g tissue - negative; 350,000 to 399,999 c/min/g tissue - borderline: and ≥400,000 c/min/g tissue - positive.

Because stomachs are not preserved at time of capture, there is a lag time of one to ten days before stomachs are collected and preserved. Collected stomachs are placed in a cloth bag and preserved in 10% formaldehyde until time of examination.

For detailed examination, stomach contents are emptied and sorted into identifiable groups. The volume of each food item is measured (by water displacement) and coded as to its state of digestion. Invertebrates were usually identifiable to suborder whereas most fish were identifiable to family and occasionally to species. Unidentified fish were cleaned of flesh and stained in alizarin for identification via vertebrae count and morphology.

Bait is usually identifiable by its appearance (sliced fish sections) and its minimal state of digestion. Food items suspected as bait are recorded but not considered actual food items. Additionally, all nematodes and trematodes collected from stomachs are recorded and preserved but are considered to be parasites and not food items.

RESULTS

The percentage of frequency of occurrence and total volume of each food item indicated that the major categories of food consumed by kahala consisted of Crustacea, Cephalopoda, and other Mollusca, fish, and unidentified remains. Diet was analyzed in relation to ciguatoxicity, sex, location of capture, and weight.

Ciguatoxicity versus diet

No apparent differences in the major food categories appear between ciguatoxic and non-ciguatoxic kahala examined. Fish appeared frequently and predominated in volume for both groups. Among ciguatoxic individuals, fish contributing the most by volume were Carangidae, Tetraodontidae, and unidentified fish remains; whereas, for non-ciguatoxic fish Carangidae, Scombridae, and unidentified fish remains were the major contributors (Tables 1 and 2).

TABLE 1. NUMBER, FREQUENCY OF OCCURRENCE, AND VOLUME OF FORAGE ITEMS FOUND IN STOMACHS OF 29 CIGUATOXIC KAHALA

Food Items	No. of Items	Stomachs in Which Occurred		Aggregate Total Volume	
		Number	Percent	Milliliter	Percent
Crustacea					
Unidentified shrimp	2	1	3.4	--	--
Fish					
Carangidae					
Decapterus sp.	1	1	3.4	18	5.5
Trachurops crumenophthalmus	1	1	3.4	66	20.3
Mullidae	1	1	3.4	2.0	0.6
Balistidae	1	1	3.4	13	4.0
Tetraodontidae	35	3	10.3	60.0	18.4
Unidentified fish larva	1	1	3.4	--	--
Unidentified fish	5	4	13.8	10.6	3.3
Unidentified fish remains	--	6	20.7	59.5	18.3
Unidentified remains	--	22	75.9	96.2	29.6
Parasites					
Trematodes	40	11	37.9	--	--
Nematodes	152	10	34.5	--	--

TABLE 2. NUMBER, FREQUENCY OF OCCURRENCE, AND VOLUME OF FORAGE ITEMS FOUND IN STOMACHS OF 125 NON-CIGUATOXIC KAHALA

Food Items	No. of Items	Stomachs in Which Occurred		Aggregate Total Volume	
		Number	Percent	Milliliter	Percent
Annelida					
Unidentified	12	4	3.2	--	--
Crustacea					
Isopoda	2	2	1.6	0.3	--
Decapoda					
Heterocarpus ensifer	21	1	0.8	8.3	0.1
Unidentified penaeid shrimp	5	2	1.6	6.6	0.1
Unidentified caridid shrimp	1	1	0.8	0.5	--
Unidentified shrimp	148	2	1.6	59.9	0.9
Unidentified shrimp remains	--	1	0.8	52	0.8
Crab megalops	1	1	0.8	0.1	--
Unidentified Crustacea	5	3	2.4	0.3	--
Unidentified Crustacea remains	--	1	0.8	0.1	--
Mollusca					
Unidentified gastropod	2	1	0.8	--	--
Unidentified Bivalvia remains	--	2	1.6	1.8	--
Squid	17	7	5.6	51.3	0.8
Octopus	7	6	4.8	135.5	2.1
Unidentified Cephalopoda	6	4	3.2	10.7	0.2
Unidentified Cephalopoda remains	--	1	0.8	11.4	0.2
Fish					
Congridae	3	3	2.4	74.3	1.2
Antigoniidae	3	2	1.6	19	0.3
Fistulariidae	2	1	0.8	6.1	0.1
Carangidae					
Decapterus pinnulatus	4	4	3.2	449	7.0
Decapterus sp.	20	14	11.2	1,107.8	17.3

TABLE 2. NUMBER, FREQUENCY OF OCCURRENCE, AND VOLUME OF FORAGE ITEMS FOUND IN STOMACHS OF 125 NON-CIGUATOXIC KAHALA (Continued)

Food Items	No. of Items	Stomachs in Which Occurred		Aggregate Total Volume	
		Number	Percent	Milliliter	Percent
Trachurops crumenophthalmus	4	2	1.6	133	2.1
Unidentified	3	3	2.4	115	1.8
Unidentified remains	--	4	3.2	177	2.8
Lutjanidae					
Pristipomoides sieboldii	2	2	1.6	406	6.3
Unidentified	2	2	1.6	50	0.8
Mullidae	1	1	0.8	4.0	0.1
Labridae	2	2	1.6	22	0.3
Scombridae					
Auxis sp.	4	3	2.4	843	13.1
Auxis thazard	1	1	0.8	547	8.5
Monacanthidae					
Pseudomonacanthus garretti	5	1	0.8	218	3.4
Unidentified	8	3	2.4	116.8	1.8
Unidentified remains	--	1	0.8	1.3	--
Ostraciontidae					
Unidentified remains	--	1	0.8	6.8	0.1
Tetraodontidae	6	6	4.8	116.6	1.8
Unidentified flatfish	1	1	0.8	4.7	0.1
Unidentified fish	46	20	16.0	83.3	1.3
Unidentified fish remains	--	43	34.4	799.6	12.5
Unidentified squid and fish remains	--	1	0.8	5.6	0.1
Unidentified remains	--	65	52.0	772.6	12.0
Parasites					
Trematodes	183	33	26.4	--	--
Nematodes	2,757	92	73.6	--	--

Among ciguatoxic fish, nematodes and trematodes occurred in approximately 35% of the stomachs; whereas, among non-ciguatoxic fish, nematodes and trematodes occurred in approximately 75% and 25% of the stomachs, respectively.

Sex versus diet

Both sexes appear identical in their diet of major food categories; fish predominated followed by small amounts of cephalopods and crustaceans. Among both sexes, most of fish by volume were Carangidae and Scombridae.

The incidence of nematodes and trematodes between the sexes were very similar. Nematodes occurred in the stomachs two to three times more often than trematodes.

Location versus diet

Diet comparisons were made for fish from three areas: the island of Hawaii and the Molokai-Lanai-Maui-Kahoolawe area among the main islands, and Gardner Pinnacles in the Northwestern Hawaiian Islands. The frequency of occurrence of major food items among the three areas appear very similar. Kahala from both the island of Hawaii and the Molokai-Lanai-Maui-Kahoolawe area had a high content of fish and rather low content of crustaceans or cephalopods. For kahala from Gardner Pinnacles, fish were still predominant in volume although to a lesser extent than for kahala from the other two areas. The former had a larger volume of cephalopods and crustaceans and the volume of unidentified remains also was larger.

For kahala from the island of Hawaii the major fish contributors by volume were the Scombridae and Carangidae. In kahala from the Molokai-Lanai-Maui-Kahoolawe area the Carangidae and Lutjanidae predominated in volume and from those in the Gardner Pinnacles area, Monacanthidae, unidentified fish remains, and Carangidae predominated. Octopus was the only cephalopod.

Occurrence of nematodes and trematodes was very similar among fish in the three areas; nematodes occurred in approximately 75% of the stomachs and trematodes in about 25%.

Weight versus diet

The kahala were divided into three groups according to weight: <5.4 kg (12 lb), 5.4 to 10.0 kg (12 to 22 lb), and >10.0 kg (22 lb).

The volumetric data showed that the lighter weight group had a smaller percentage of fish compared to the two heavier groups. The lighter group showed a larger proportion of cephalopod compared to the other two groups which showed a predominance of fish. Octopus comprised practically all the cephalopods and Tetraodontidae contributed most of the fish for the first group. In the 5.4 to 10.0 kg group Carangidae and unidentified fish remains contributed the bulk of the fish whereas in kahala >10.0 kg the fish species consisted chiefly of Scombridae and Carangidae.

In the two groups >5.4 kg, nematodes and trematodes occurred in approximately 75% and 25% of the stomachs, respectively. Among fish in the lighter weight group, nematodes and trematodes occurred in 17% and 39% of the stomachs, respectively.

CONCLUSION

Preliminary results show no relation between toxicity, diet, and sex among kahala examined thus far. There appears to be some relationship though between diet and location of capture; fish from Gardner Pinnacles apparently have a more varied diet (a greater proportion of combined cephalopod and crustacean volume) than those from the island of Hawaii and the Molokai-Lanai-Maui-Kahoolawe area. Dietary differences are also indicated in comparisons of weight versus diet which show a greater volume of cephalopods for fish <5.4 kg and a changeover to fish as the major dietary component in larger kahala. Hence, except for the younger kahala, fish is the principal diet of kahala. Carangidae was the most frequently occurring family in terms of percentage of occurrence and total volume. Results to date reflect only trends in the data and should be considered only preliminary because of the small sample sizes.

The incidence of parasitic nematodes and trematodes were high in the stomachs of kahala; nematodes and trematodes were present in approximately 75% and 25%, respectively, of stomachs examined, regardless of sex and location of capture. In the ciguatoxic group and the group comprising fish <5.4 kg, trematodes were more abundant than nematodes. With the exception of the two above-mentioned groups, nematodes were the predominant parasite.

FUTURE RESEARCH NEEDS

Further analysis of stomach contents is needed to confirm the trends in dietary composition and incidence of parasites. Because only 15% of the kahala stomachs collected have so far been examined it should be emphasized that the results are preliminary. As more stomachs are examined other relationships will be investigated such as the consistency of diet over time, prey size in relation to fish weight, and various combinations of factors such as weight and location versus diet. Also, as more samples are processed, it may be possible to identify other food items, especially fish, that presently remain unidentified.

SUMMARY

One hundred and fifty-four stomachs collected from kahala, *Seriola dumerili*, representing 15% of the stomachs collected to date, were examined to determine a possible relationship between feeding habits and incidence to ciguatoxicity and as part of an overall study of the life history aspects of commercially valuable fishes in the Hawaiian Archipelago. Preliminary results indicate a change from cephalopods to fish as the principal food item with increase in size. In general, members of the family

Carangidae were the most important contributors among forage items for kahala. The results also indicated no apparent differences in the major food categories between ciguatoxic and non-ciguatoxic fishes and between sexes. Among sampling sites, however, differences were noted in volumes of cephalopods and crustaceans consumed.

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EXPLORATORY FISHING ON THE HANCOCK SEAMOUNTS BY THE *TOWNSEND CROMWELL*, 1976-79

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ABSTRACT

Under authority of the U.S. Fishery Conservation and Management Act (FCMA) of 1976, which extended jurisdiction over fishery resources within 200 miles of the nation's coastline, the National Marine Fisheries Service initiated a program to collect catch and effort data and biological information on the pelagic armorhead, *Pentaceros richardsoni*, and alfonsin, *Beryx splendens*, at Hancock Seamounts which fall within the Fishery Conservation Zone. Data were collected from three sources--research cruises of the NOAA ship *Townsend Cromwell*, fishing trips of Japanese commercial vessels carrying U.S. observers, and fishing trips of Japanese commercial vessels fishing in 1969-76 prior to the enactment of the FCMA. The preliminary results of this study showed that 77% of the *Cromwell*'s catch in 1979 consisted of armorheads, that night trawling was significantly more productive than day trawling, and that 95% of the armorhead were the so-called "lean" type. Experimental handline fishing over the seamounts revealed that in addition to armorheads and alfonsins, the Japanese mackerel, *Scomber japonicus*, also appeared to be in relatively good numbers.

Hancock Seamounts
Pentaceros richardsoni
Beryx splendons
bottom trawling
handline fishing

INTRODUCTION

The central North Pacific seamounts extend to the northwest from the northern end of the Hawaiian ridge towards the Emperor Seamount chain. Southeast Hancock and Northwest Hancock are the most southeasterly of this group (Figure 1), respectively located 300 and 367 km (162 and 198 nmi) to the northwest of Kure.

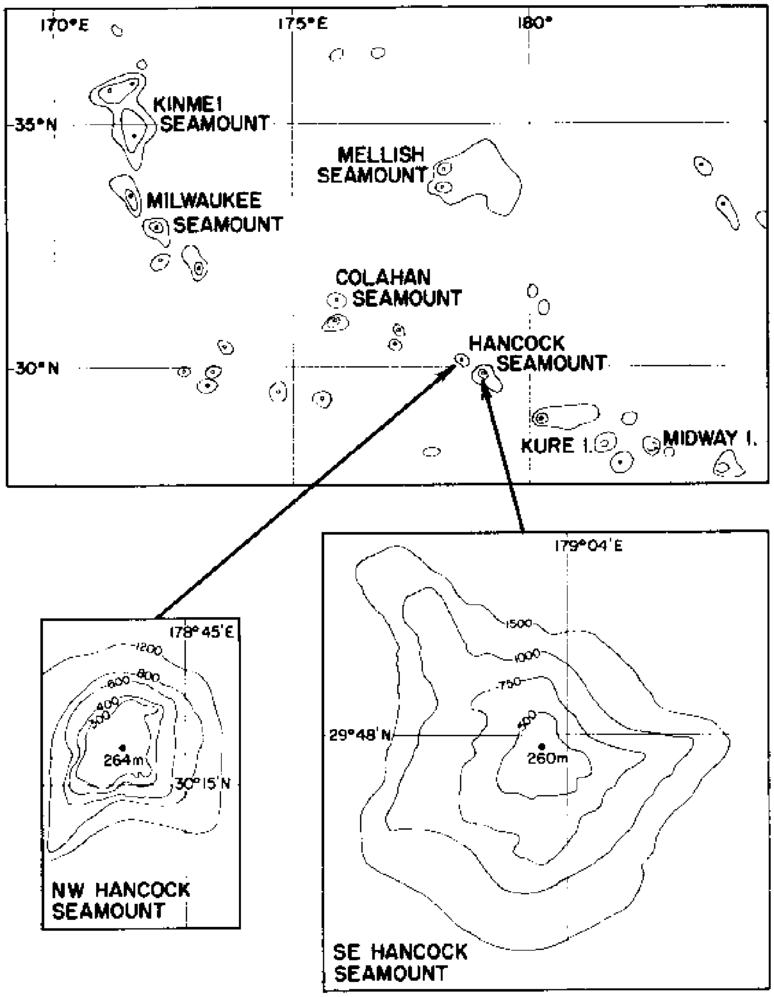

Figure 1. The location of Hancock Seamounts in relation to Midway and Kure and other North Pacific seamounts, and their depth configurations

Until quite recently interest in this group of seamounts, as in others, has primarily been geological, and almost nothing was known about their biological resources. However in 1967 a Russian trawler discovered the occurrence of pelagic armorhead, Pentaceros richardsoni, and alfonsin, Beryx splendens, on the seamounts northwest of the Hawaiian chain (Sakiura, 1972) and a fishery was born. In 1969 Japanese trawlers, which had been diverted from the Bering Sea fishing grounds, joined the Soviets in exploiting the new fishery.

Sakiura (1972) in his translation of a Russian paper, reported that commercial trawlers of the U.S.S.R. harvested approximately 133,400 metric tons (MT) of pelagic armorhead during 1969-70. Except for this remarkably high estimate of early catches on the then virgin grounds, no information on subsequent Soviet fishing is available.

Pelagic armorhead make up approximately 90% of the Japanese trawl catches from the seamounts with alfonsin and rockfish, Sebastes matsubari, constituting most of the remainder of the commercially valuable part of the catch.

In the Japanese bottom longline fishery the prime target species is alfonsin, followed by Sebastes sp. and Epinephelus sp.

For the Japanese, during the early years (1969 to 1971) of the seamount trawl fishery, there was considerable variation in both catch and effort. From 1972 to 1976 the catch of pelagic armorhead stabilized at 20,000 to 30,000 MT/yr. However, as fishing effort increased, catch per unit effort (CPUE) decreased each year, with CPUEs in metric tons per hour of trawling of approximately 60 in 1972, 34 in 1973, 22 in 1974, 14 in 1975, and 10 in 1976 (Sasaki, 1978). These figures include all Japanese commercial trawling in the central North Pacific seamount fishery. Available information indicate that the Hancocks were very productive grounds for pelagic armorhead, with catch rates reaching 83 MT/h in 1972, 40 MT/h in 1973, and 23 MT/h in 1974, 16 MT/h in 1975, and 11 MT/h in 1976 (Japan Marine Fishery Resource Research Center, 1973; Takahashi and Sasaki, 1977).

Since the Japanese bottom longline fishery for alfonsin, which began on the Milwaukee Banks around 1972, is a so-called "open fishery," requiring no permits or licenses in Japan, virtually nothing is known about the activity of the Japanese longline vessels. However, fragmentary reports indicate that the CPUE for longline-caught alfonsin was also declining through 1975 (Suisan Sekai, 1976; Sasaki, 1978).

On March 1, 1977, the United States, under authority of the Fishery Conservation and Management Act (FCMA) of 1976, extended its jurisdiction over fishery resources to all the area within 200 miles of the nation's coastline. The 200-mile Fishery Conservation Zone (FCZ) around the Hawaiian Archipelago included all of Southeast Hancock. The 200-mile line actually crosses Northwest Hancock, but apparently all of the relatively shallow trawlable ground on this seamount also falls within the FCZ.

In January 1977 the National Marine Fisheries Service (NMFS) Southwest Region published an environmental impact statement and Preliminary Fishery Management Plan which in essence limited fishing for pelagic armorheads and alfonsins within the FCZ by foreign vessels to 50 vessel-days per year each of trawling and bottom longlining. The annual quota by foreign vessels of pelagic armorheads and alfonsins was set not to exceed 2,000 MT/yr of either species or of the combined species.

Under the FCMA, Japan and the U.S.S.R. were each allocated 1,000 MT of seamount groundfish for 1977. No Japanese vessels fished on the Hancock Seamounts in 1977. In May 1977 a Soviet trawler, the Ekvator, was apprehended and cited by the U.S. Coast Guard for trawling in the Hancock area contrary to regulations defined in the FCMA. This vessel had taken 22 MT of pelagic armorhead within the FCZ.

In 1978 the Ryuyo Maru No. 2 was the only foreign vessel to fish the Hancock Seamounts. It was chartered by the Japan Marine Fishery Resource Research Center (JAMARC), and was accompanied by a NMFS observer (Kazama, 1978). In 1979 the sole foreign vessel to fish on the Hancocks was the commercial Japanese trawler, Aso Maru, also accompanied by a NMFS observer (Evering, 1979).

No U.S. commercial fishing vessels presently fish or have ever fished on the north central Pacific seamounts.

The National Marine Fisheries Service, Southwest Fisheries Center Honolulu Laboratory, conducted only intermittent resource surveys of the Hancock Seamounts. The data presented in this report are based on five exploratory fishing surveys during Townsend Cromwell cruises 76-06, October 1976; 77-02, May 1977; 78-01, February 1978; 78-03, September 1978; and 79-02, May 1979.

METHODS

Bottom fishing was conducted by stern trawling and hook-and-line fishing.

During the first cruise in 1976 the net used was a high opening Norwegian fish trawl with a 20-m headrope and a 25-m footrope. On the subsequent cruises, a larger "Noreastern" fish trawl with a 27-m headrope and a 32-m footrope was used with a pair of 1.8 x 2.7 steel V-type doors.

On the first two cruises (76-06 and 77-02) only blind tows, without the aid of a net sonde, were conducted. On the last three cruises, a "Noreastern" trawl was used with a Furuno 400 Mark II[1] net recorder (net sonde).

Handline fishing on the seamounts was conducted with 20-hook gear using cut squid as bait. During the first two cruises lines were manually handled. On subsequent cruises hydraulic gurdies were employed.

RESULTS

Trawling

During the five cruises, nine successful trawl tows (net was on the bottom), totaling 137 minutes of fishing time, were made on Northwest Hancock and three successful tows, totaling 77 minutes, were made on Southeast Hancock (Table 1). On cruise 78-01, the net sonde was used for the first time, however, it was malfunctioning and none of the four trawls made on Southeast Hancock were on the bottom, resulting in zero catch. Table 1 lists weight and the total catch of fish species taken in the 12 successful trawls. Table 2 gives pertinent information for each trawl and lists the dominant species taken on each station.

As noted earlier, during the first two cruises trawling was conducted without a net sonde. Although a net sonde was used on cruise 78-03, it was not until the last cruise that the vessel personnel had acquired a reasonable degree of expertise in the use of the equipment. This may be one of the factors responsible for the remarkably larger catches of armorhead on cruise 79-02 compared to earlier cruises. Another is that cruise

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

TABLE 1. FISHES CAUGHT TRAWLING ON HANCOCK SEAMOUNTS BY THE *TOWNSEND CROMWELL* IN ORDER OF THEIR ABUNDANCE IN THE HAULS BY WEIGHT

Fish	Number	Weight (kg)
Pentaceros richardsoni	2,579	975
Promethichthys prometheus	282	172
Zenopsis nebulosus	188	61
Squalus fernandinus	53	60
Beryx splendens	304	49
Ariomma lurida	134	31
Conger sp.	11	21
Antigonia steindachneri	137	7
Physiculus edelmanni	40	5
Polymixia nobilis	14	4
Emmelichthys sp.	17	2.7
Priacanthus boops	13	2.6
Diaphus trachops	145	2.6
Brotulidae	36	2.5
Polymixia japonica	29	2.4
Mytophum nitidulum	138	1.7
Hyperoglyphe japonica	2	1.3
Isistius brasiliensis	4	1.0
Sternoptychidae	2	<1
Antigonia eos	26	<1
Macrorhamphosus scolopax	8	<1
Chascanopsetta prorigera	3	<1
Parabothus coarctatus	10	<1
Argentia sp.	32	<1
Lophiomus miacanthus	4	<1
Tosanoides filamentosus	1	<1
Bothidae	6	<1
Centroscyllium nigrum	3	<1
Beryx decadactalys	1	<1
Hoplichthys sp.	1	<1
Pseudanthias kelloggi	2	<1
Rhynchocymba nystromi nystromi	4	<1
Astronesthus lucifer	1	<1
Argyropelecus aculeatus	2	<1
Etmopterus villosus	3	<1
Physiculus grinnelli	1	<1
Argyripnus atlanticus	1	<1
Parapercis roseoviridis	2	<1
Peristedion engyceros	1	<1

TABLE 2. DOMINANT SPECIES (BY WEIGHT) TAKEN IN 12 TRAWLS ON THE HANCOCK SEAMOUNTS ON TOWNSEND CROMWELL CRUISES

Dominant Species in Haul (Weight)	No. Fish	Weight (kg)	Area SE - NW Hancock	Date	Local Time	Bottom Depth (fm)	Surface Temp. °C	Bottom Temp. °c	Fishing Time (min)	Cruise No.	Station No.	Total Catch (kg)	Percentage of P. richardsoni in catch
P. richardsoni	34	21.9	SE	10/24/76	2133	145-160	25.2	13.5	19	76-06	49	29.7	74
B. splendens	3	3.6											
M. nitidulum	125	1.6											
P. richardsoni	64	21.0	SE	5/2/77	0835	144-170	21.5	12.6	20	77-02	52	68.0	31
A. lurida	134	30.5											
S. fernandinus	6	5.0											
Z. nebulosa	14	4.0											
Emmelichthys sp.	16	2.7											
Z. nebulosa	11	3.0	NW	9/9/78	1324	155-165	26.6	12.0	10	78-03	31	3.2	0
B. splendens	1	0.1											
A. eos	5	0.1											
P. richardsoni	118	59.5	NW	9/10/78	2150	150-165	26.6	12.0	15	78-03	33	95.0	28
P. prometheus	22	25.1											
Z. nebulosa	61	23.8											
S. fernandinus	4	3.6											
A. eos	37	2.7											
B. splendens	44	2.3											
P. richardsoni	32	71.2	NW	9/10/78	0925	155-165	26.6	12.0	23	78-03	34(1)	18.7	60
Z. nebulosa	24	6.9											
H. japonica	5	0.3											
A. eos	10	0.3											
B. splendens	99	18.1	NW	9/10/78	1115	155-165	26.6	12.0	20	78-03	34(2)	37.2	25
Z. nebulosa	36	9.9											
P. richardsoni	26	9.2											
A. eos	9	0.3											
P. richardsoni	31	10.5	NW	5/4/79	1405	147-149	19.9	15.0	14	79-02	26	14.7	71
Z. nebulosa	7	2.0											
A. steindachneri	17	0.5											
P. richardsoni	10	3.5	NW	5/5/79	1000	144-150	20.9	14.9	17	79-02	31	6.9	51
Z. nebulosa	12	2.8											
A. steindachneri	11	0.3											
P. richardsoni	270	93.6	NW	5/5/79	2116	144	20.4	14.2	14	79-02	33	113.8	82
P. prometheus	28	10.5											
B. splendens	32	4.7											
D. trachops	145	2.6											
P. richardsoni	553	208.0	NW	5/5/79	2320	141	20.5	14.2	13	79-02	34	228.7	91
S. fernandinus	4	8.5											
P. prometheus	15	7.0											
B. splendens	14	1.4											
P. prometheus	225	132.9	NW	5/6/79	0155	144	20.5	14.4	11	79-02	35	165.8	15
P. richardsoni	70	25.1											
B. splendens	50	7.8											
P. richardsoni	1,373	546.0	SE	5/6/79	2100	140	19.9	14.8	38	79-02	37	614.9	89
S. fernandinus	39	43.5											
B. splendens	60	7.4											
Z. nebulosa	31	6.9											

78-03 followed the fishing trip of the Japanese trawler Ryuyo Maru No. 2 at Hancock whereas on cruise 79-02 the Cromwell preceded the Japanese trawler Aso Maru. On cruise 79-02 the mean catch per hour was 642 kg total and 497 kg for armorhead, whereas for the three other cruises combined the mean catch per hour was 108 kg total and 62 kg for armorhead. This heterogeneity in such limited data precludes any extensive analysis. From Table 2 it is clear that, in general, the same species dominated the catches, and that our catch results, in agreement with those of the Japanese and Soviets, indicate that evening and night trawls are far more productive than day trawls. The mean night catch per hour was 680 kg total and 520 kg armorhead compared to mean day catch rates of 86 kg total and 38 kg for armorhead.

For cruise 79-02 the mean length of armorhead was 25.5 cm for both males and females, and 95% of the fish were the so-called "lean" type. This is the same proportion of lean fish reported for the Aso Maru. It is of some interest to note that only on the best hauls, during cruise 79-02 (stations 33, 34, and 37), did the percentage of armorhead in the catch approach that reported for Japanese trawlers (Sasaki, 1978).

Handlining

Table 3 summarizes the handlining conducted on the seamounts. Line hours fished totaled 24 at seven stations on Southeast Hancock and 28 at six stations on Northwest Hancock. Armorhead were most abundant with a mean catch for all fishing stations of 1.7 kg/line-hour. Although alfonsins were taken in small numbers on four stations, the overall mean catch of 0.2 kg/line-hour was very low. The largest catch, 37.4 kg/line-hour of Japanese mackerel, Scomber japonicus, was made on Southeast Hancock, during Townsend Cromwell's first visit to the seamounts.

DISCUSSION AND CONCLUSIONS

The Townsend Cromwell's fishing activity on the Hancock Seamounts has provided much needed experience for NMFS scientific and vessel personnel. However, the data we have collected are certainly insufficient to allow even general speculation on the condition of the armorhead and alfonsin fishery on the Hancock Seamounts.

Subsequent to cessation of intensive foreign commercial fishing on the Hancocks, since the 1976 season, the only other data available on the fishing conditions in the area are from trawling operations of the Ryuro Maru No. 2 in 1978 and the Aso Maru in 1979. The impression of the NMFS observers assigned to those vessels was that the Japanese considered fishing to be poor when compared to the conditions which prevailed during earlier years of the fishery.

Townsend Cromwell cruise 80-02 during April of 1980 will conduct the most intensive survey of the Hancock Seamounts and others in the vicinity of Kure and Midway Islands thus far attempted by NMFS. In addition to bottom fishing with trawl and handlines, we will utilize 100-hook bottom longline gear similar to that used in the Japanese alfonsin fisheries.

A U.S. domestic seamount fishery would seem unlikely in the near future. However, foreign interest in the Hancock Seamount grounds will probably continue.

To develop an acceptable fishery management plan, NMFS will require an adequate data base. Future plans at the Southwest Fisheries Center Honolulu Laboratory call for a comprehensive study of the Hancock Seamounts and other seamounts located within the Hawaiian Island FCZ.

SUMMARY

A study of fishery resources over Hancock Seamounts, which are located within the FCZ of the Hawaiian Archipelago, was initiated in October 1976. Data collected aboard the Townsend Cromwell were in general agreement with Japanese fishing results which indicated that catch rates were significantly higher at night rather than during daytime and that a large proportion of the catch at Hancock Seamounts consisted of pelagic armorhead, Pentaceros richardsoni, most of which were the so-called "lean" type. The balance of the catch consisted of alfonsin, Beryx splendens. Handline fishing also produced relatively good numbers of Japanese mackerel, Scomber japonicus. Future research needs include

TABLE 3. HANDLINE CATCHES ON THE HANCOCK SEAMOUNTS ON *TOWNSEND CROMWELL* CRUISES

Species	No. Fish	Weight (kg)	Area SE - NW Hancock	Date	Fishing Time (Local)	Cruise No.	Station No.	Catch Per Line-Hour (kg)
Scomber japonicus	28	43.6	SE	10/29/76	1740-1815	76-06	47	37.4
Hyperoglyphe japonica	1	6.4						5.5
Pentaceros richardsoni	2	1.4						1.2
Decapterus russellii	1	1.2						1.0
Squalus fernandinus	1	0.7						0.6
Beryx splendens	1	0.9	SE	10/29/76	1822-1930	76-06	48	1.0
Hyperoglyphe japonica	2	4.2	SE	5/25/77	1815-2145	77-02	50	0.6
Squalus fernandinus	3	3.3						0.5
Pentaceros richardsoni	6	2.9						0.4
Beryx splendens	1	0.8						0.1
Squalus fernandinus	12	14.1	SE	2/10/78	0950-1135	78-01	60	4.0
Scomber japonicus	11	13.6						3.9
Decapterus russellii	4	4.5						1.2
Pentaceros richardsoni	7	3.2						1.0
Squalus fernandinus	4	7.1	SE	2/11/78	0820-0905	78-01	67	4.7
Pentaceros richardsoni	8	2.6						1.7
Decapterus russellii	1	0.9						0.6
Pentaceros richardsoni	60	21.2	SE	2/11/78	1115-1435	78-01	68	3.2
Squalus fernandinus	13	17.4						2.6
Hyperoglyphe japonica	1	2.0						0.1
Scomber japonicus	1	0.5						0.03
Hyperoglyphe japonica	1	2.2	NW	9/7/78	1736-2107	78-03	26	0.3
Beryx splendens	1	0.9						0.15
Pentaceros richardsoni	2	0.7						0.14

TABLE 3. HANDLINE CATCHES ON THE HANCOCK SEAMOUNTS ON *TOWNSEND CROMWELL* CRUISES (Continued)

Species	No. Fish	Weight (kg)	Area SE - NW Hancock	Date	Fishing Time (Local)	Cruise No.	Station No.	Catch Per Line-Hour (kg)
Pentaceros richardsoni	9	3.8	NW	9/8/78	0900-1133	78-03	28	1.2
Scomber japonicus	1	1.2						0.4
Hyperoglyphe japonica	1	1.2						0.4
Decapterus russellii	1	1.2						0.4
Pseudanthias	1	0.2						0.1
Hyperoglyphe japonica	7	12.4	NW	9/9/78	1746-2011	78-03	32	2.6
Pentaceros richardsoni	5	1.9						0.4
Scomber japonicus	1	1.4						0.3
Squalus fernandinus	1	1.2						0.2
Pentaceros richardsoni	34	13.2	NW	10/2/79	1647-2012	79-02	28	4.7
Beryx splendens	1	0.8						0.3
Pentaceros richardsoni	23	10.0	NW	10/2/79	0519-1842	79-02	30	1.5
Beryx splendens	9	7.8						1.2
Hyperoglyphe japonica	2	3.8						0.6
Pentaceros richardsoni	51	25.37	NW	10/2/79	1818-1957	79-02	32	7.7
Hyperoglyphe japonica	2	3.9						0.6
Pentaceros richardsoni	10	3.8	SE	10/3/79	1910-2005	79-02	36	1.3

monitoring of the stock at Hancock Seamounts and additional surveys of other seamounts in the vicinity of Kure and Midway. Collection of biological and morphometric data will be continued.

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SURVEY OF THE PELAGIC FISHES OF THE NORTHWESTERN HAWAIIAN ISLANDS

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ABSTRACT

Longline fishery catch statistics were used to estimate relative abundance of true pelagic species within the Fishery Conservation Zone of the Northwestern Hawaiian Islands. Relative apparent abundance of coastal pelagic species was determined by trolling surveys. Growth curves for *Euthynnus affinis* and *Thunnus alalunga* were estimated from otolith age determinations. A study of the fecundity of *Acanthocybium solandri* has begun.

fecundity
relative apparent abundance
Northwestern Hawaiian Islands
age and growth
pelagic fishes

INTRODUCTION

The survey area in the Northwestern Hawaiian Islands (NWHI) included in this study extends from Nihoa to Kure Atoll and is about 1,700 km long and 640 km wide. Much of this area is in the pelagic realm. The pelagic resources considered in this report consist of the true pelagic and the coastal pelagic fishes.

The foreign longline fishery in the Pacific has been harvesting the true pelagic fishes from an area northwest of the inhabited high islands. This fishing ground extends into the U.S. 200-mile Fishery Conservation Zone (FCZ) around the NWHI. The true pelagic species include the bigeye tuna, *Thunnus obesus*; yellowfin tuna, *T. albacares*; albacore, *T. alalunga*; northern bluefin tuna, *T. thynnus*; skipjack tuna, *Katsuwonus pelamis*; swordfish, *Xiphias gladius*; striped marlin, *Tetrapturus audax*; shortbill spearfish, *T. angustirostris*; blue marlin, *Makaira nigricans*; black marlin, *M. indica*; sailfish, *Istiophorus platypterus*; mahimahi, *Coryphaena hippurus*; and sharks, *Carcharhinus maou* (*C. longimanus*), *C. falciformis*, Isurus oxyrinchus, and Prionace glauca. Yong and Wetherall (1980) have estimated the foreign longline monthly effort and catch within the 200-mile FCZ for 1965 through 1977.

The Japanese baitboat fishery has also harvested skipjack, bigeye, and yellowfin tunas in the FCZ. In 1972, the eastward expansion of the albacore baitboat fishery reached the NWHI (Fisheries Agency of Japan, 1977a). Albacore was caught only in 1972, 1975, and 1977 in the vicinity of Hancock Seamounts. Yellowfin and bigeye tunas were caught primarily on or near the banks of the NWHI; skipjack tuna was also caught on or near the banks but was also caught in abundance on the open sea southwest of the FCZ (Fisheries Agency of Japan, 1977b; Yong and Wetherall, 1980). Catches of skipjack tuna, the target species, peaked for about a period of a month between May and August. Whereas the catch rates of skipjack tuna have averaged between 6 and 11 metric tons (MT)/vessel/day, single-day catches up to 50 MT a day have been reported (Tanaka, n.d.). Yong and Wetherall (1980) also estimated the monthly fishing effort and skipjack tuna catch within the 200-mile FCZ for 1972 through 1977.

Besides skipjack and yellowfin tunas, which are also considered as true pelagic species, the coastal pelagic species include the ono, Acanthocybium solandri; kawakawa, Euthynnus affinis; rainbow runner, Elagatis bipinnulatus; bigeye scad, Trachurops crumenophthalmus; Japanese mackerel, Scomber japonicus; and four species of mackerel scad, Decapterus macarellus (= D. pinnulatus), D. maruadsi, D. muroadsi (= D. russellii), and D. macrosoma. At present, a commercial fishery for the coastal pelagic resources does not exist in the NWHI. On a few occasions, lobster fishing vessels have trolled for kawakawa and yellowfin tuna to use as bait in lobster traps. Mahimahi and ono caught on trolling lines by lobster fishermen are sold at the Honolulu fish auction.

Research cruises to the NWHI were made on 30 occasions during the 1950s and 1960s and data on trolling and fish school and bird flock sightings from these cruises have been published by Murphy and Ikehara (1955), Graham (1957), and Waldron (1964). And prior to the current series of NWHI survey cruises, the NOAA ship Townsend Cromwell made a search-survey cruise for skipjack tuna in 1975 which included parts of the NWHI.

Except for these fish school surveys and some baitfish surveys in the NWHI, the pelagic resources have not been studied. Records of the foreign longline fishery and baitboat fishery provide us with estimates of relative apparent abundance of tunas and billfishes. This study includes the distribution, catch rates, age and growth, fecundity and spawning, and foraging habits of the coastal pelagic species.

MATERIAL AND METHODS

Trolling and tagging operations

The seven survey cruises of the Townsend Cromwell since the summer of 1977 included a standard trolling procedure. Nine lines were trolled at 7 knots during various times of the day at the edge of banks between the

73 and 274-m depth contours. When a fish was landed, it was measured for fork length, sexed, and sometimes weighed. Time of landing, position, and depth were also recorded on the Standardized Surface Trolling Data Sheet (SSTDS). Ovaries and stomach contents were preserved in a solution of 4% formaldehyde and seawater. Otoliths were extracted and frozen in water for examination at the laboratory.

Kawakawa, yellowfin tuna, and ono were tagged in 1977. Troll-caught fishes were measured, tagged with a dart tag (Yamashita and Waldron, 1958), and released.

Distribution and relative apparent abundance

Yong and Wetherall (1980) tabulated the catch and effort by 1° squares from Japanese and unpublished Taiwan longline fishery data for 1971 through 1975 and from Japanese baitboat data for 1972 through 1977. Catch and effort data were estimated by 5° squares for 1965 through 1970, 1976, and 1977. They estimated the catch of major tuna and billfish species and effort within the FCZ around the NWHI using these tabulations.

The distribution of troll-caught pelagic fishes was analyzed by comparing the number of fishes caught per line-hour of fishing in each 6-min cell around the NWHI. The position of capture on the SSTDS was used to place the fish into cells. When the position of capture was missing, the position was estimated using the ship's track chart and the time of capture.

Age and growth studies

In the laboratory, sagittae, the largest of the otoliths, were cleaned, etched, mounted, and read as described by Uchiyama and Struhsaker (in press). Age-length determinations were used to calculate the von Bertalanffy growth parameters.

Experiments were also conducted to verify that growth rings were deposited daily. At the Kewalo Research Facility, pelagic fishes maintained in aquaria were either injected or orally fed oxytetracycline at a rate of about 33 mg oxytetracycline/kg of fish to mark a spot on the sagittae. The daily deposition of growth rings was verified by matching the number of daily growth rings counted between the mark, which was visible under ultraviolet excitation, and the edge of the rostrum or postrostrum with the number of days the fish was kept alive and feeding after marking.

Fecundity and spawning season

Since 1978, all developing and ripe ovaries of pelagic fishes were collected to determine the length of the spawning period. Immature ovaries were noted in the remarks column of the SSTDS. The maturity of the ovary was determined on the basis of the most advanced ova present as described by Uchiyama and Shomura (1974). Then the monthly percentage distribution of sampled ovaries in each developmental stage, i.e., immature, developing, advanced developing, early ripe, and ripe, was calculated.

Fecundity estimates were made only on ovaries in the advanced developing, early ripe, and ripe stages. The ova development within an ovary was tested for homogeneity and fecundity estimates were made as described by Otsu and Uchida (1959).

Study on foraging habits

The volume and individual counts of forage items were determined for each stomach. Each item was identified to species when possible and measured for volume and length.

Night-light stations

A 1,500-W bulb night light was used to attract bigeye scad, mackerel scad, and other organisms. Dip nets and jig lines were used to capture organisms attracted to the light. Hourly data on organisms caught and estimates of the quantity of organisms attracted to the light were kept.

RESULTS

Distribution and relative apparent abundance

Annual catch rates of tunas and billfishes were estimated using catch and effort data obtained from foreign longline vessels operating within the FCZ around the NWHI (Table 1). The catch rate of the whole mixed species fishery remained stable during the 5 years of study, but fluctuations in the catch rates of individual species such as bigeye tuna, albacore, and striped marlin occurred. Although the longline fishery was a winter fishery in the 1970s (Figure 1), there was also a summer fishery in the 1960s. The estimated annual catch of major tuna species was obtained by combining the catch by longliners with the catch by the baitboats (Table 2).

Kawakawa was the species most frequently caught by trolling gear (Figure 2). Areas where large numbers of kawakawa were caught have remained productive for this species throughout the survey period. Yellowfin tuna was plentiful at Pearl and Hermes Reef. Trolling at Kure was very poor.

Trolling catch rates for coastal pelagic fishes decreased toward the northwest end of the chain (Table 3). This decrease could be due to environmental conditions, or to the pole-and-line fishing by the Japanese, or other factors. The catch rates of coastal pelagic fishes appeared to decline with time (Figure 3). A regression of catch rate on time produced a significant negative slope for both Nihoa ($P = 0.024$) and Laysan ($P = 0.006$) indicating a decline in apparent abundance over time.

TABLE 1. ESTIMATED ANNUAL CATCH, EFFORT, AND CATCH PER UNIT EFFORT BY FOREIGN LONGLINERS WITHIN 200 MILES OF THE NORTHWESTERN HAWAIIAN ISLANDS, 1971-75 (Yong and Wetherall, 1980)

Year	Species[1]	Effort		Catch		CPUE
		Days	Hooks	(kg)	(No.)	No./1,000 Hooks
1971	YF	1,592	3,184,000	467,437	9,872	3.10
	BE	—	—	820,988	19,155	6.02
	AL	—	—	397,875	15,658	4.92
	BF	—	—	1,121	6	0.00
	SJ	—	—	1,604	353	0.11
	All tunas	—	—	1,689,025	45,044	14.15
	BLM	—	—	81,496	838	0.26
	BM	—	—	2,700	56	0.02
	SM	—	—	261,192	8,583	2.70
	SWF	—	—	58,233	747	0.23
	SBSF, SF	—	—	8,271	512	0.16
	All billfishes	—	—	411,894	10,736	3.37
1972	YF	1,747	3,494,000	260,452	5,391	1.54
	BE	—	—	1,284,487	28,250	8.08
	AL	—	—	478,494	18,713	5.36
	BF	—	—	1,534	8	0.00
	SJ	—	—	1,982	273	0.08
	All tunas	—	—	2,026,949	52,635	15.06
	BLM	—	—	53,382	690	0.20
	BM	—	—	2,281	38	0.01
	SM	—	—	172,714	5,394	1.54
	SWF	—	—	178,456	2,289	0.66
	SBSF, SF	—	—	8,195	477	0.14
	All billfishes	—	—	415,028	8,888	2.54
1973	YF	985	1,970,000	132,825	2,706	1.37
	BE	—	—	496,445	10,244	5.20
	AL	—	—	348,159	15,150	7.69
	BF	—	—	1,661	8	0.00
	SJ	—	—	625	102	0.05
	All tunas	—	—	979,716	28,210	14.32
	BLM	—	—	17,695	251	0.13
	BM	—	—	1,087	14	0.01
	SM	—	—	78,215	2,966	1.50
	SWF	—	—	82,431	1,057	0.54
	SMSF, SF	—	—	9,951	559	0.28
	All billfishes	—	—	189,379	4,847	2.46
1974	YF	444	888,000	118,991	2,411	2.72
	BE	—	—	95,463	2,457	2.77
	AL	—	—	280,710	11,755	13.24
	BF	—	—	1,631	8	0.01
	SJ	—	—	547	108	0.12
	All tunas	—	—	497,345	16,739	18.85
	BLM	—	—	24,429	371	0.42
	BM	—	—	1,172	18	0.02
	SM	—	—	20,191	725	0.82
	SWF	—	—	41,981	538	0.61
	SBSF, SF	—	—	7,014	439	0.49
	All billfishes	—	—	94,787	2,091	2.35
1975	YF	832	1,664,000	170,677	3,798	2.28
	BE	—	—	512,260	11,792	7.09
	AL	—	—	169,695	7,446	4.47
	BF	—	—	1,652	8	0.00
	SJ	—	—	695	169	0.10
	All tunas	—	—	854,979	23,213	13.95
	BLM	—	—	13,766	178	0.11
	BM	—	—	649	11	0.01
	SM	—	—	69,622	2,447	1.47
	SWF	—	—	24,798	318	0.19
	SBSF, SF	—	—	6,775	408	0.24
	All billfishes	—	—	115,610	3,362	2.02

[1] YF = yellowfin tuna, *Thunnus albacares*; BE = bigeye tuna, *T. obesus*; AL = albacore, *T. obesus*; AL = albacore, *T. alalunga*; BF = bluefin tuna, *T. orientalis*; SJ = skipjack tuna, *Katsuwonus pelamis*; BLM = blue marlin, *Makaira nigricans*; BM = black marlin, *M. indica*; SM = striped marlin, *Tetrapturus audax*; SWF = swordfish, *Xiphias gladius*; SBSF = shortbill spearfish, *T. angustirostris*; and SF = sailfish, *Istiophorus platypterus*.

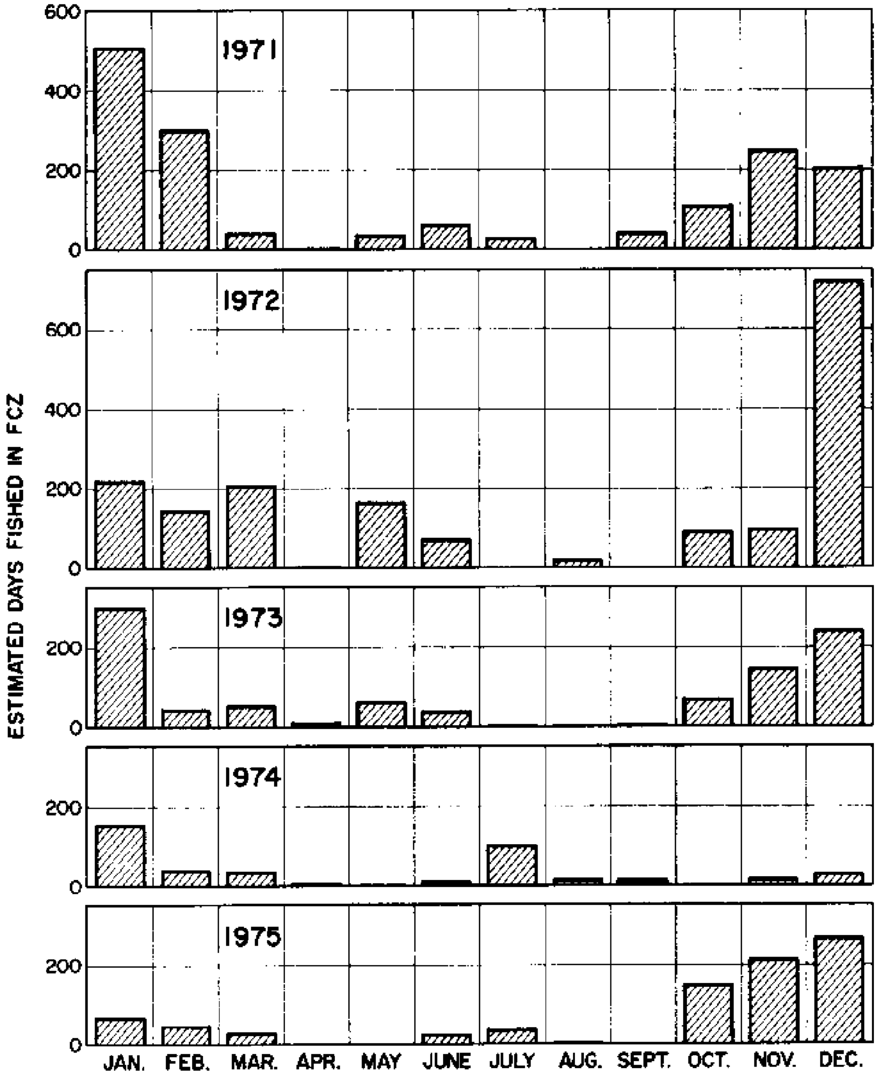

Figure 1. Estimated monthly effort by Japanese longliners within the 200-mile Fishery Conservation Zone of the Northwestern Hawaiian Islands, 1971-75 (Yong and Wetherall, 1980).

TABLE 2. ESTIMATED ANNUAL CATCH (METRIC TONS) OF TUNAS IN THE NORTHWESTERN HAWAIIAN ISLANDS, 1972-77[1]

Year	Albacore	Yellowfin tuna	Bigeye tuna	Bluefin tuna	Skipjack tuna
1972	577	277	1,287	2	2
	26	19	105	26	1,282
	603	296	1,392	28	1,284
1973	348	133	496	2	1
	0	20	109	0	823
	348	153	605	2	824
1974	281	119	95	2	1
	0	50	147	0	1,971
	281	169	242	2	1,972
1975	170	171	512	2	1
	89	167	71	25	1,906
	279	338	583	27	1,907
1976	912	330	1,155	1	1
	0	124	92	0	4,294
	912	454	1,247	1	4,295
1977	480	308	1,514	1	1
	49	337	734	0	4,375
	529	645	2,248	1	4,376

[1] First line is annual catch by foreign longliners.
Second line is annual catch by baitboats.
Third line is total annual catch (line 1 + line 2).

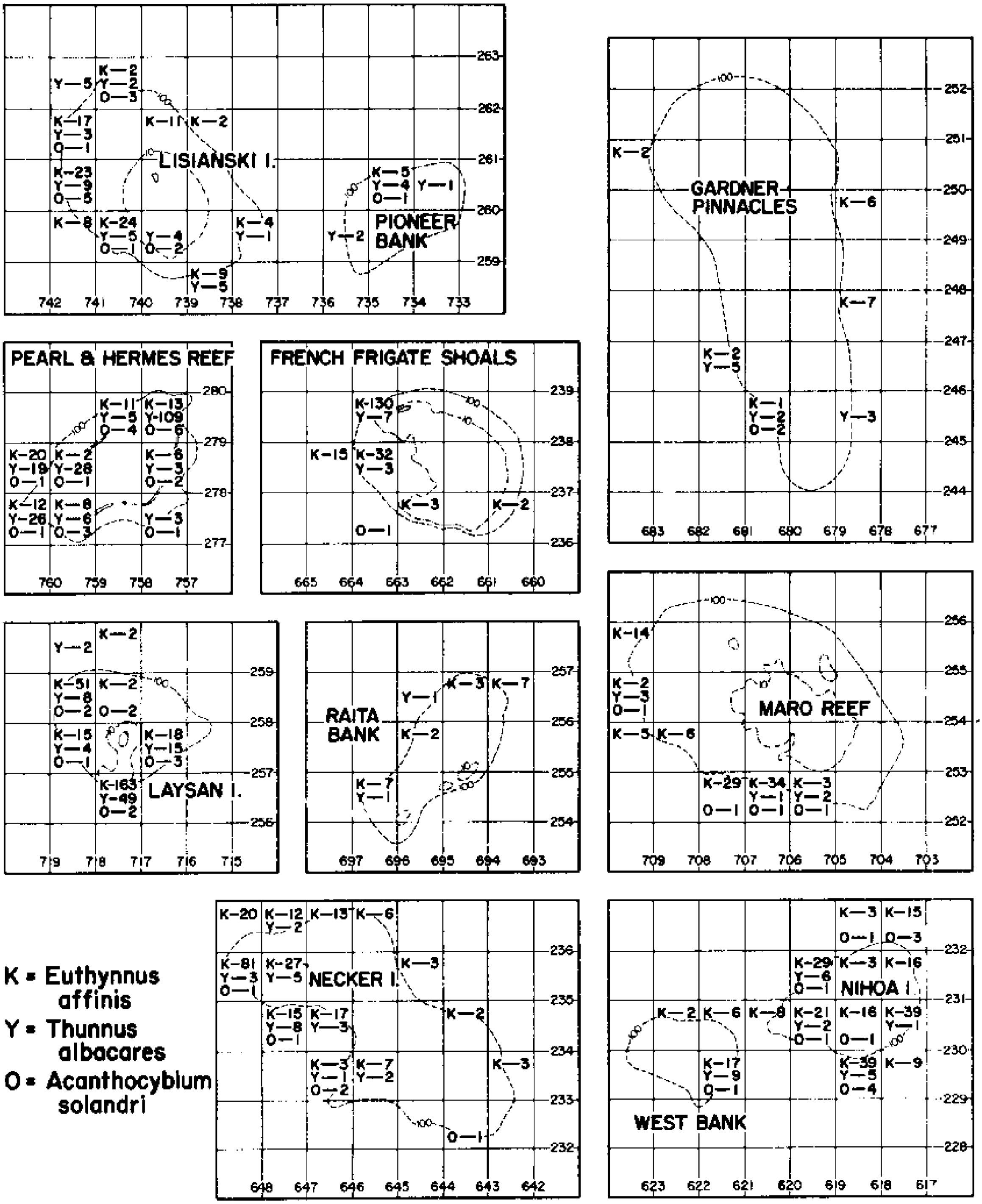

Figure 2. Distribution of coastal pelagic fishes in the Northwestern Hawaiian Islands as depicted by the number of fishes caught per cell by trolling, 1976-79

TABLE 3. RELATIVE APPARENT ABUNDANCE OF TROLL-CAUGHT COASTAL PELAGIC FISHES IN THE NORTHWESTERN HAWAIIAN ISLANDS

Island/Bank	Effort (Hook/h)	Total Catch (No.)	Catch Rate (No./Hook/h)	No. of Each Species Caught:[1]										
				KK	YF	SJ	WA	DO	RN	BA	C1	C2	C3	BLM
Nihoa	375.2	363	0.97	319	29	4	11	--	--	--	--	--	--	--
Necker	413.4	285	0.69	227	30	10	6	6	2	3	--	1	1	--
French Frigate Shoals	303.1	224	0.74	183	13	19	2	3	1	--	--	3	--	--
Brooks	13.8	7	0.51	7	--	--	--	--	--	--	--	--	--	--
Gardner Pinnacles	200.3	59	0.29	43	10	--	4	1	1	--	--	--	--	--
Raita	12.8	21	1.64	19	2	--	--	--	--	--	--	--	--	--
Maro	241.4	175	0.72	129	3	6	4	7	1	--	10	2	13	--
Laysan	457.1	389	0.85	252	78	18	11	--	2	15	5	5	4	--
Northampton Seamount	99.0	42	0.42	15	15	1	10	--	--	--	--	--	--	1
Pioneer	32.5	24	0.74	6	7	--	3	--	--	--	8	--	--	--
Lisianski	404.7	206	0.51	121	33	6	13	1	--	--	32	--	--	--
Salmon	10.1	6	0.60	1	4	1	--	--	--	--	--	--	--	--
Pearl and Hermes Reef	889.3	379	0.43	77	248	7	18	1	6	--	22	--	--	--
Midway	29.8	2	0.07	--	2	--	--	--	--	--	--	--	--	--
Kure	58.2	1	0.02	--	1	--	--	--	--	--	--	--	--	--

[1] KK = kawakawa; YF = yellowfin tuna; SJ = skipjack tuna; WA = ono; DO = mahimahi; RN = rainbow runner; BA = barracuda, *Sphyraena helleri*; C1 = white ulua, *Caranx ignobilis*; C2 = omilu, *C. melampygus*; C3 = kahala, *Seriola dumerili*; and BLM = blue marlin.

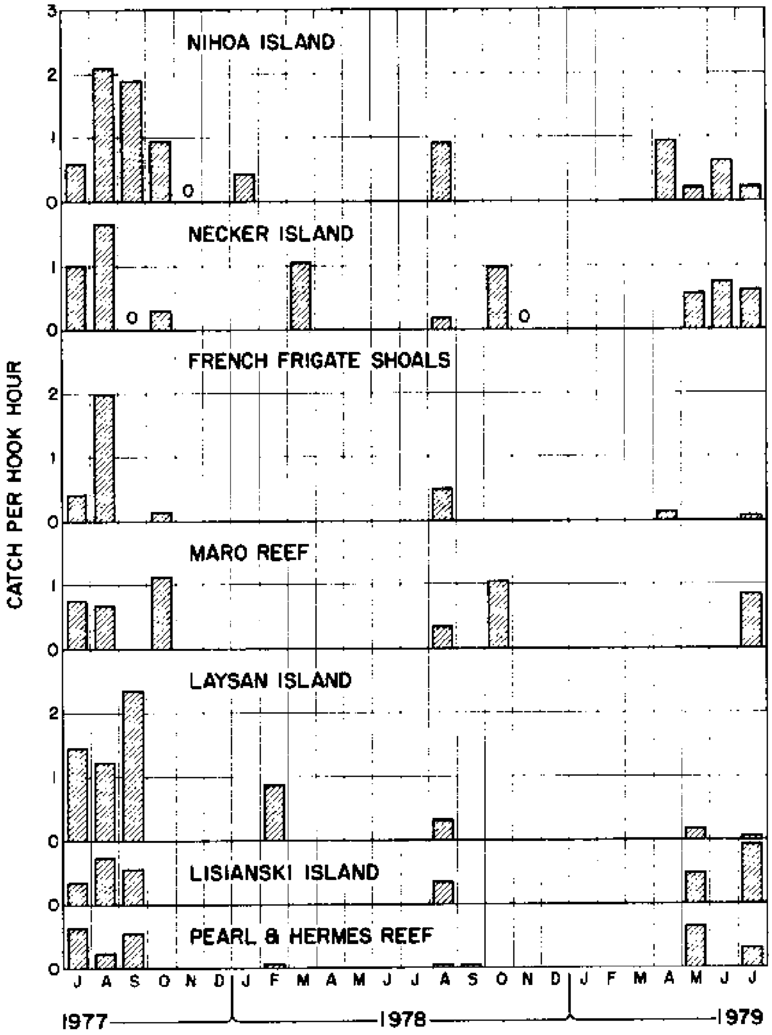

Figure 3. Changes in the catch rate of coastal pelagic fishes with time.

Age and growth

Preliminary von Bertalanffy growth curves were calculated for kawakawa and albacore (Figures 4 and 5).

Fecundity and spawning season

Yellowfin tuna caught on the banks were undeveloped throughout the year. Work to obtain fecundity estimates of ono are presently in progress. Ova development does not appear to be homogeneous within the ono's ovary.

Foraging habits

Over 285 stomach content samples have been collected from troll-caught kawakawa, yellowfin tuna, skipjack tuna, ono, mahimahi, and rainbow runner.

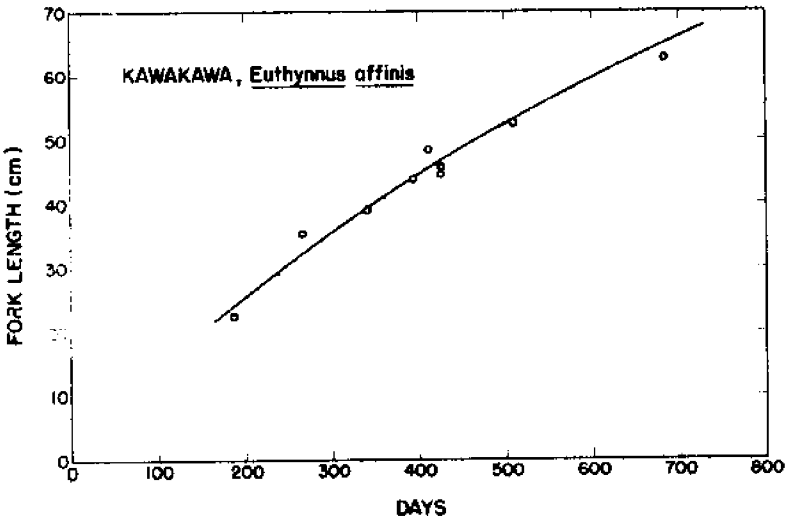

Figure 4. Growth curve of kawakawa from the Northwestern Hawaiian Islands. Von Bertalanffy growth parameters: L_∞ = 117.8 cm, K = 0.42 cm, and T_O = -0.03.

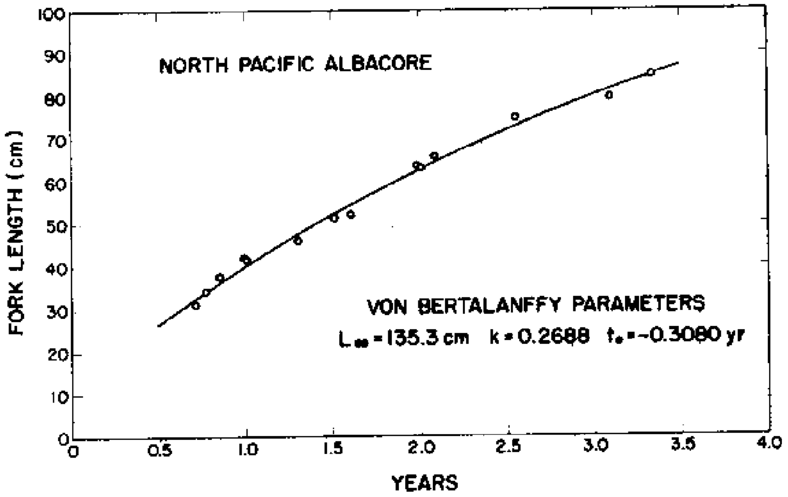

Figure 5. Growth curve of North Pacific albacore

Tagging

Nine-hundred ninety-nine kawakawa, yellowfin tuna, and ono were tagged in 1977. Only a single recovery has been reported, thus far. A yellowfin tuna tagged at Pearl and Hermes Reef was recovered by a Japanese pole-and-line fishing vessel northwest of Pearl and Hermes Reef (lat. 27°40'N, long. 170°30'W). The fish had traveled at least 31 nmi in 37 days.

Night-light stations

Twenty-four night-light stations, mostly during the summer months, have been occupied since 1978. Mackerel scad were attracted to the light at French Frigate Shoals and Kure.

DISCUSSION AND CONCLUSIONS

The catch statistics of foreign longline operations probably provides the best measure of apparent abundance. Estimates of catch and effort by Korean longline vessels operating in the FCZ will also be analyzed in the future.

Because the results are only preliminary no conclusions are made at this time.

FUTURE RESEARCH NEEDS

More fishing effort is needed to observe a change in the relative abundance of the coastal pelagic fishes and to be able to estimate stock size. To determine seasonal availability, more fishing effort is required during the fall, winter, and early spring. Experiments to validate daily growth rings on otoliths have begun for kawakawa and the bigeye scad. Other pelagic species should also be aged. A study of the pelagic squid resource is also needed.

SUMMARY

The relative apparent abundance of longline and troll-caught pelagic species were estimated. Growth curves of *Euthynnus affinis* and *Thunnus alalunga* were estimated from daily growth rings on otoliths. Maturation of ovarian ova in ono was nonhomogeneous at the preripe stage.

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GENETIC ASPECTS OF POPULATION STRUCTURE OF FOUR SPECIES IN THE NORTHWESTERN HAWAIIAN ISLANDS

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ABSTRACT

A population genetic study of four marine species was initiated to provide insight into patterns of stock structure characteristics of organisms in the Hawaiian Archipelago. The four exemplar species, spiny lobster (Panulirus marginatus), limpet (Cellana exarata), snapper (Pristipomoides filamentosus), and damselfish (Stegastes fasciolatus), were chosen because they represent a diversity of ecological and life history types as well as several taxonomic groups. Initial screening indicated low levels of genetic variability in both the lobster and the opakapaka with moderate to high levels of polymorphism in the damselfish and limpet.

Seven-hundred sixty lobsters from Kure Atoll, Maro Reef, Necker Island, and Oahu were analyzed for electrophoretic variation at six genetically variable loci. Distributions of allele frequencies at each locus were extremely similar among sites providing no evidence for stock heterogeneity of lobsters within the archipelago. Electrophoretic analysis of a total of 461 limpets from French Frigate Shoals, Necker Island, Molokai, and Hawaii, on the other hand, revealed marked heterogeneity among the four locations at five of the six polymorphic loci studied. This observed heterogeneity is strong evidence for the existence of at least three discrete breeding units of limpets within the Hawaiian Islands. Although somewhat preliminary in nature, the results observed to date for the lobster and limpet indicate substantially different patterns of stock structure among taxa within the Hawaiian Archipelago and emphasize the need for continued detailed analyses of these and other species in order to define stock boundaries.

stock structure
population genetics
electrophoresis
polymorphism

INTRODUCTION

The rational and non-destructive exploitation of any biological resource depends, in part, on knowing the magnitude and properties of that resource. Such characteristics as: standing crop, productivity, trophic interactions, and population dynamics of the species must all be determined. Furthermore, since exploitation of any biological resource on a sustained yield basis is dependent upon the continued successful reproduction of the species in the face of harvest-induced mortality, nearly all management schemes in fisheries biology are based on the unit stock concept. This approach involves the individual management of independent reproductive units or populations. An understanding of the genetic structure of the species is thus of critical importance in formulating policy decisions regarding protection, conservation, and/or exploitation of any fishery resource.

The general question of stock structure can be subdivided into a series of interrelated questions, the most fundamental of which is whether or not a given fisheries resource is composed of a single large stock or multiple smaller stocks. If the resource is composed of a single stock, then it can be effectively managed as a single unit. If, on the other hand, multiple stocks or breeding units contribute to the resource, separate management schemes for each stock could well be required to efficiently manage the resource. When multiple stocks or populations occur, it is necessary to determine their distribution in time and space and to estimate the relative contribution of each unit to the total resource.

There are many factors, both biological and physical, which contribute to the stock structure of a species. These can be grouped according to their effect into factors which promote population subdivision and factors which promote population homogeneity. The former group includes physical barriers to gene flow such as: discontinuous habitat, heterogeneous environmental factors (temperature, salinity, etc.), and oceanographic features such as water depth and current patterns which reduce or prevent mixing between areas. Biological properties of a species which contribute to population heterogeneity include: the occurrence of sessile, territorial, and/or non-migratory adults; benthic embryonic and/or larval stages; and, when present, planktonic stages of short duration. Factors promoting movement of adults and/or mixing and dispersal of offspring contribute to population homogeneity.

Various approaches have been utilized to examine the stock structure of commercially important marine organisms. Investigations designed to detect heterogeneity in life history characteristics (fecundity, age and size class distributions, time of spawning), parasite burdens, and patterns of adult migration have, for certain species, clearly indicated the existence of multiple stocks. Each of these approaches requires the existence of an established fishery to provide the large number of individual specimens required for analysis. Because of our rudimentary knowledge of the biology of species in the Northwestern Hawaiian Islands and the modest nature of the developing fishery in this region we did not feel that these approaches held much immediate promise for understanding stock structure. The measurement of morphological differentiation using meristic and morphometric characteristics of individuals from different geographic regions is a procedure commonly used in looking for different stocks. This approach, although frequently employed to investigate population differentiation, suffers because of the major influence certain environmental variables such as temperature have on meristic characters and because of the complex, multigenic bases for nearly all morphological characters.

The electrophoretic survey of protein similarities and differences among individuals within a species provides an alternative approach to the problem and has recently been applied to stock identification in a number of vertebrates and invertebrates (de Ligny, 1969; Morgan et al., 1973; Jamieson, 1975; Tracey et al., 1975; Menzies and Kerrigan, 1978; Allendorf and Utter, 1979; Buroker et al., 1979). The strength of this approach lies in the fact that, in nearly all cases: (a) the biochemical phenotype of the organism is unaffected by environmental variables; (b) the biochemical phenotype of each individual is stable through time; and (c) the genetic variation observed in proteins is almost always due to single Mendelian factors which are codominantly expressed (Ayala, 1975). For these reasons, the genotype of an individual can be inferred directly from the protein phenotype because the protein products of different alleles are present and clearly visible after electrophoresis and enzyme staining. Since the existence of discrete stocks implies both reproductive isolation (partial or complete) and genetic divergence, direct measures of genetic similarity and difference such as those provided by electrophoresis should be an efficient means for detecting and defining the limits of such stocks.

The present research program is focused on four species: a spiny lobster (Panulirus marginatus), a limpet or opihi (Cellana exarata), a snapper (Pristipomoides filamentosus), and a damselfish (Stegastes fasciolatus = Eupomacentrus fasciolatus). These species have been selected on the basis of their commercial importance and their reproductive habits and ecology. Furthermore, because each of these species is being studied by one or more of the agencies involved in the present Northwestern Hawaiian Islands investigation, information on stock structure for these organisms will be of immediate value to the other studies.

The opakapaka (P. filamentosus) was chosen because it is the dominant snapper in the Hawaiian fishery, abundant around many of the Northwestern Hawaiian Islands, and representative of several commercially important snappers and groupers which are offshore, deepwater, benthically oriented forms. The small, shallow-water damselfish (S. fasciolatus) was chosen because it is representative of many inshore reef species, it occurs throughout the archipelago, and it has somewhat restricted dispersal potential. The species lays demersal eggs and apparently has a benthically oriented larval stage lasting for only about 20 days. The adults have a home range of less than 5 m^2. The spiny lobster (P. marginatus) was chosen because it is abundant (especially in the Northwestern Hawaiian Islands) and of major commercial importance, and because it probably has a pelagic larval life of at least six months (based on studies of other, related species). The limpet (C. exarata) was chosen because it has some commercial value in Hawaii, because it is relatively immobile and restricted to the intertidal shoreline as an adult, and because the pelagic larval period presumably is less than two weeks in duration. Together, these four exemplar species represent diverse taxonomic, ecological, and life history groups. For these reasons, insights gained into the genetic aspects of population structure of these four species should contribute significantly to our understanding of the population structure of other similar species.

OBJECTIVES

This study is designed to provide insight into genetic aspects of population structure of marine organisms in the Hawaiian Archipelago. Four species (two invertebrates and two vertebrates) representing different ecological and life history groups were chosen for detailed study. The major goal is to determine whether or not each of these species is composed of a single, large interbreeding stock or multiple, reproductively independent stocks. The specific questions to be answered in this investigation are:

1. What genetic variation is exhibited by these four species?
2. What are the patterns of genetic variation through space and time?
3. Do multiple stocks exist for any of these species?
4. If multiple stocks exist, what are their geographical boundaries?
5. If multiple stocks exist, what is the contribution of each stock to the total species abundance?

MATERIALS AND METHODS

Population sampling

Samples of adult individuals from several geographic localities in the Hawaiian Archipelago were collected for each of the four species. Spiny lobsters were captured in standard lobster traps in conjunction with commercial fishing operations and scientific research cruises. During the research cruises, collections were augmented via hand capture of lobsters by divers using SCUBA. In the present analysis, a total of 760 animals from four locations is considered: Kure Atoll (June 1979 to January 1980; N = 202), Maro Reef (November 1979; N = 151), Necker Island (April 1979; N = 358), and Oahu (August 1979 through February 1980; N = 49). Captive lobsters were either frozen immediately on shipboard or placed in holding tanks and returned alive to Honolulu. The former animals were kept frozen (-15°C) until dissection. Whenever possible, the live lobsters were delivered to our laboratory and frozen intact. Live lobsters destined for commercial use were sampled by removal of the fifth walking leg which was frozen for future use.

Sampling of limpet populations inhabiting the rocky intertidal zone was performed in a number of localities. In the present study, samples from four sites--La Perouse Pinnacle, French Frigate Shoals (October 19, 1979; N = 62); Necker Island (November 4, 1979; N = 93); Halawa Bay, Molokai (November 28, 1979; N = 163); and Kahuku Ranch (west side of South Point Peninsula), Hawaii (December 31, 1979; N = 143)--were gathered by hand, with care exercised to sample all size classes (above 1 cm).

The limpets were placed on ice and returned alive to the laboratory where they were individually frozen in seawater and stored at -76°C until prepared for electrophoresis.

Damselfish and snapper populations were also sampled. The damselfish were taken in shallow reef habitat by hand spear. Snapper samples were obtained through arrangements with commercial fishing operations and on research cruises by means of power-assisted handline equipment.

Tissue preparation

Tissues dissected from lobsters (walking leg red muscle, tail white muscle, eye, heart, hepatopancreas, gill, and green gland) and limpets (gonad, viscera, and foot) were homogenized in approximately equal volumes of either 0.1 M potassium phosphate buffer, pH 7.0 (for lobsters) or 0.1 M Tris, 0.001 M EDTA, 5×10^{-5} M NADP buffer adjusted to pH 7.0 with HCl (for limpets) and centrifuged at 15,000 to 20,000 g for a minimum of 20 minutes (at 5°C). Supernatants were transferred to individually labelled glass vials, capped, and stored at -76°C until used for electrophoresis.

Electrophoresis

Tissue extracts were subjected to a variety of electrophoretic methods and buffer combinations modified from a number of sources. Two methods of starch gel electrophoresis, horizontal (modified from Selander et al., 1971) and vertical (Buchler Instruments, Fort Lee, New Jersey) and vertical polyacrylamide gel electrophoresis (modified from Reid and Bieleski, 1968) were carried out using over 20 different buffer combinations, providing a broad spectrum of electrophoretic conditions designed to maximize resolution and differentiation of electrophoretic patterns.

Starch gels were run using 11.8% (W/V) Electrostarch (Lot 307, Electrostarch Co., Madison, Wisconsin) for horizontal gels or 12.2% (W/V) Electrostarch for vertical gels. Polyacrylamide gels consisted of 7.5% Cyanogum (Fisher Chemical Co., St. Louis, Mo.). After electrophoretic separations, enzyme patterns were visualized as zymograms by application of enzyme-specific histochemical stains to the gels. An average of 37 such staining techniques (modified from Shaw and Prasad, 1970; Selander et al., 1971; Siciliano and Shaw, 1976) were employed for each species.

Patterns of variation on gels which were consistent with simple models of Mendelian inheritance of biochemical phenotypes were scored and recorded according to such models: the data were recorded as genotypes.

Statistical analyses

The putative genotype data for each population sample were summarized as genotype and allele frequency distributions. These distributions were examined for internal consistency with the Mendelian inheritance model by Chi-square testing of goodness-of-fit of observed genotype ratios to those expected under random mating in the absence of selection. The expected ratios were computed from observed allele frequencies using Levene's (1949) unbiased method for small samples.

Interlocality (intersample) heterogeneity of allele frequency distributions which might be indicative of population subdivision were examined via contingency Chi-square procedures.

Evidence of heterozygote deficiency, which could indicate nonpanmictic breeding structure (Li, 1976) was sought by computing the index

$$d = \frac{h_o - h_e}{h_e}$$

where h_o and h_e are the observed and expected number of heterozygotes in a sample, respectively (Selander, 1970). An unusual abundance of negative d values might indicate population subdivision even if, individually, the absolute value of d is small. Finally, if for a given genetic locus, interlocality allele frequency distributions were statistically homogeneous, samples were pooled among locations. These pooled samples were then examined with respect to the d index which is expected to be negative if the populations were actually heterogeneous. A lack of negative d values over several loci in the pooled samples would be inconsistent with the idea of population subdivision.

RESULTS AND DISCUSSION

Species screening

The initial screening of enzyme loci, electrophoretic media, and buffer conditions has yielded between 35 and 50 genetic loci that can be reliably analyzed by electrophoresis in each of the four species under study (Table 1). Although the actual values in Table 1 are preliminary, they indicate a wide range in genetic polymorphism among the four species with the lobster and snapper exhibiting low levels of genetic variation and the damselfish and limpet exhibiting moderate to high levels of polymorphism compared to other species (Ayala, 1975). The apparent low levels of genetic variation exhibited by the lobster and snapper make a rigorous test of the null hypothesis (that all individuals of each species in the Hawaiian Archipelago are members of one large interbreeding population) difficult and require that large sample sizes from each locality be used. Such large sample sizes can be obtained for the lobster (see below) but

TABLE 1. SUMMARY OF OBSERVED GENETIC VARIATION

	Lobster	Snapper	Damselfish	Limpet
Number of loci scorable	36	50	47	40
Proportion of loci exhibiting genetic variation	0.22	0.12	0.21	0.45
Proportion of loci polymorphic (at .05 level)	0.06	0.06	0.11	0.37

will be difficult to acquire for the snapper due to restricted species occurrence, limited fishing, and difficulty of obtaining tissue samples. These problems should not apply to the damselfish and limpet which have considerably more genetic variation and are more readily collected. Because most of our efforts to date have been concentrated on the two invertebrate species (lobster and limpet) the following discussion will be limited to these organisms.

Lobster--population analysis

Genetic variation in the lobster was observed at approximately 20% of the loci screened. Six of these loci have been analyzed in detail from four different sites and the data summarized in Table 2. The most striking

TABLE 2. ALLELE FREQUENCIES FOR SPINY LOBSTER (*PANULIRUS MARGINATUS*)

Locus[1]	Allele[2] (sample size[3])	Locality			
		Kure	Maro	Necker	Oahu
Est-3	common	.982	.973	.997	1.000
	rare	.018	.027	.003	.000
	(2N)	(388)	(302)	(716)	(98)
Gpi	common	.965	.963	.968	.969
	rare	.035	.037	.032	.031
	(2N)	(394)	(294)	(714)	(96)
Pep-3	common	.988	.989	.984	1.000
	rare	.012	.011	.016	.000
	(2N)	(332)	(266)	(698)	(88)
Pgm	a	.008	.011	.020	.011
	b	.981	.985	.973	.989
	c	.011	.004	.007	.000
	(2N)	(366)	(278)	(712)	(92)
Umb	common	.989	.996	.985	.969
	rare	.011	.004	.015	.031
	(2N)	(376)	(282)	(664)	(96)
Mpi	common	.995	.987	.993	.990
	rare	.005	.013	.007	.010
	(2N)	(404)	(300)	(714)	(98)

[1] Est = esterase, Gpi = glucosephosphate isomerase, Pep = peptidase (leu-gly-gly), Pgm = phosphoglucomutase, Umb = umbelliferyl esterase, Mpi = mannosephosphate isomerase

[2] Common = the single most common allele, rare = pooled class containing all other alleles

[3] Sample size = number of alleles scored

results of this analysis are the low levels of genetic variation observed at all six loci (with the most common allele always present in a frequency of at least 0.96) and the uniformity of allele frequencies for each locus among localities. Indeed, χ^2 tests for overall heterogeneity among localities were not significant for any of the six loci examined. Furthermore, χ^2 tests for heterogeneity among all possible pairwise combinations (36) yielded only one statistically significant deviation ($p < .05$) (Umb: Maro vs. Oahu). Since one would expect such an outcome once in 20 tests (on the average) due to random sampling error, this result does not provide any support for the idea of stock heterogeneity.

If two or more reproductively independent stocks were contributing individuals to the samples, one would expect a deficiency in heterozygous genotypes (Wahlund Effect) in samples pooled from all locations. In fact, none of the five pooled samples showed a deficiency of heterozygotes. Thus, by two measures--χ^2 tests of gene frequency distributions and examination for heterozygote deficiency--we have failed to detect any evidence of stock heterogeneity in *Panulirus marginatus*. These results are consistent with, but do not prove, the hypothesis that all of the *Panulirus marginatus* in the Hawaiian Archipelago are part of a single large panmictic population.

The above outcome is coincident with predictions based on knowledge of the long pelagic larval stage (6 to 9 months) of other panulirid lobsters. However, because of the low levels of genetic variation at the six gene loci studied to date, the hypothesis of stock homogeneity has not been rigorously tested by these data. For this reason it is imperative that other, more polymorphic loci (one esterase and two peptidase loci), be analyzed in detail before firm conclusions are drawn.

Lobster--puerulus larvae identification

One of the secondary goals in our original proposal was to attempt to use biochemical traits to identify puerulus larvae to species. The major justification for this effort is to allow the identification of *P. marginatus* larvae collected by MacDonald (see paper by MacDonald and Stimson) in his investigation of patterns of larval recruitment at Kure. By using tissue extracts of adult *P. marginatus* and *P. penicillatus* from Hawaii and extracts of *P. penicillatus* post-larvae and pueruli from Enewetak Atoll (Marshall Islands) as controls, we have found at least three enzyme systems (isocitrate) dehydrogenase, glucosephosphate isomerase, and malate dehydrogenase) which serve as distinguishing features for the two species. Using this technique (in conjunction with morphological analyses of the larvae) it is now possible to look specifically at larval recruitment patterns of *P. marginatus*.

Lobster--sex ratio analysis

During the enzyme screening of the spiny lobster outlined above, it became obvious that the pattern of genetic variation observed for one system--mannosephosphate isomerase (MPI)--was unusual both with regard to the frequency of certain enzyme phenotypes and with regard to the relationship between enzyme phenotype and sex. Three different MPI alleles (slow = s, medium = m, and fast = f) have been detected. The fast allele is rare (6/690) but has been observed in both males (as "f/s") and females (as "f/m"). In our initial screening of 357 adults, we found that virtually all females express the "m/m" phenotype (153/159) while most males (194/197) expressed the "m/s" phenotype. Because chromosomal mechanisms of sex-determination, like the X-Y system in mammals, have been reported for other species of invertebrates including decapod crustaceans (Niiyama, 1950), it appears that in the spiny lobster the "m" allele is fixed on the X-like chromosome and the "s" allele is fixed on the Y-like chromosome. Furthermore, if we assume that the fast allele (f) is restricted to the X-like chromosome, all but three of the phenotypes observed in the initial screening of 357 adults can be explained by this simple sex-limited allele model. The three unexplained observations include two "female" lobsters with the "m/s" phenotype and one "male" lobster with an apparent "s/s" phenotype. If errors were made in sexing or recording the two "m/s" females, then these exceptions would disappear and the only unexplained observation is the "s/s" male. Since it was not possible to recheck the sex identification (because we had only one fifth walking leg from each animal) we decided to examine new, intact specimens for both external sex characters and MPI phenotype. We have analyzed 47 additional male and 104 additional female lobsters and have observed no exceptional phenotypes (i.e., all males were "m/s" of "f/s" and all females were "m/m" of "f/m"). We conclude from these data that the "s" allele of MPI is sex-limited and occurs only in male lobsters. Because we have been able to demonstrate the expression of MPI in both puerulus larvae and late stage pre-hatch embryos, we now have a biochemical probe (MPI phenotype) for sexing individuals and determining the sex ratio at each stage in the life history of the species. We have analyzed 20 puerulus larvae, of which 11 were males ("m/s") and 9 were females ("m/m"). We have also examined 2,060 pre-hatch embryos taken from 13 different berried females. The sex ratio among these embryos was 1,086 males to 974 females for a sex ratio of 52:48 (males:females). This sex ratio among pre-hatch embryos is significantly different from 50:50 ($\chi^2_{df=1} = 6.09$; $p < 0.02$). These data indicate an excess of males among pre-hatch embryos and, assuming little or no sex-related mortality from fertilization to this later stage of development, suggest that the sex ratio at fertilization is greater than 50:50. The excess of males seen at the embryonic stage is consistent with the excess of males in the adult population as reported by Uchida et al. (see paper by Uchida et al., part II).

Limpet--population analysis

Genetic variation in the limpet was observed at about 45% of the loci screened. Six of these loci have been analyzed in detail for animals from four sites and the data are summarized in Table 3. In contrast to the results for the lobsters, the limpets exhibit much higher levels of genetic variation; for five of the six loci in Table 3, the most common allele has a frequency of less than 0.95 in most populations. Gene frequency distributions among all four sites are significantly heterogeneous at five of the six loci examined. These results are inconsistent with the null hypothesis that the limpets throughout the Hawaiian Islands are all members of one large panmictic population. Rather, they provide strong evidence for stock heterogeneity within the archipelago.

TABLE 3. ALLELE FREQUENCIES FOR LIMPET (<u>CELLANA EXARATA</u>)

Locus[1]	Allele (sample size[2])	Locality				Results of χ^2 test for heterogeneity among all sites
		Hawaii	Molokai	Necker	French Frigate Shoals	
Acp-1	a	.164	.174	.060	.139	
	b	.336	.339	.783	.861	
	c	.479	.469	.098	.000	$p \ll .005$
	d[3]	.021	.019	.060	.000	
	(2N)	(280)	(322)	(184)	(122)	
Acp-2	a	.926	.978	.591	.443	
	b[3]	.074	.022	.409	.557	$p \ll .005$
	(2N)	(282)	(324)	(186)	(124)	
Est-1	a[3]	.031	.006	.000	.008	
	b	.041	.068	.000	.000	
	c	.195	.174	.810	.820	$p \ll .005$
	d	.733	.752	.190	.172	
	(2N)	(266)	(322)	(184)	(122)	
Est-2	a	.112	.104	.017	.008	
	b	.004	.000	.035	.000	$p < .01$
	c[3]	.884	.896	.947	.992	
	(2N)	(276)	(318)	(172)	(124)	
Idh-2	a	.010	.000	.000	.000	
	b	.986	.994	1.000	1.000	N.S.[4]
	c	.004	.006	.000	.000	
	(2N)	(286)	(326)	(184)	(124)	
Nap-2	a	.008	.000	.000	.000	
	b	.443	.391	.466	.475	
	c	.519	.587	.157	.025	
	d	.027	.022	.039	.383	$p \ll .005$
	e	.004	.000	.326	.117	
	f	.000	.000	.011	.000	
	(2N)	(262)	(322)	(178)	(120)	

[1] Acp = acid phosphatase, Est - esterase, Idh = isocitrate dehydrogenase, Nap = naphthylamidase

[2] Sample size = number of alleles scored

[3] Allelic class containing two or more alleles

[4] N.S. = not significant, $p \geq .05$

The pattern of heterogeneity within the archipelago was investigated by pair-wise χ^2 tests of allele frequency distributions at geographically adjacent island groups (Table 4). This analysis reveals significant heterogeneity between the two "high" island samples (Hawaii vs. Molokai) and even greater heterogeneity between Molokai (a "high" island) and Necker (a "low" island) and between Necker and French Frigate Shoals (both low islands). We interpret these findings as evidence for the existence of several populations or stocks of limpets within the archipelago. Substantial reproductive isolation appears to characterize the two "low" island samples compared to those of the "high" islands. In the future, we plan to see whether or not these allele frequency differences are stable through time by studying samples collected one year later and to attempt to determine the geographical limits of each stock by analyzing specimens from intermediate localities.

TABLE 4. RESULTS OF χ^2 TESTS FOR HETEROGENEITY AMONG SAMPLES OF CELLANA EXARATA

Locus	Localities compared		
	Hawaii vs. Molokai	Molokai vs. Necker	Necker vs. French Frigate Shoals
Acp-1	N.S.	$p << .005$	$p < .005$
Acp-2	$p < .005$	$p << .005$	$p < .005$
Est-1	N.S.	$p << .005$	N.S.
Est-2	N.S.	N.S.	N.S.
Nap-2	N.S.	$p << .005$	$p < .005$

FUTURE RESEARCH NEEDS

Although substantial progress has been made both in establishing conditions for the electrophoretic analysis of all four species under study and in conducting preliminary analyses of stock structure for the lobster and limpet, there are two major areas of concern regarding future research on this project and the successful completion of the study. The first of these involves the extremely low levels of genetic variation observed in the lobster and the snapper. Such low levels of polymorphism make it extremely difficult to rigorously test the hypothesis of stock homogeneity and necessitate the use of very large sample sizes. An alternative approach, which we have used throughout the past year and will continue to employ, is to continue the search for other genetic loci which may exhibit higher levels of genetic variation. Although this approach offers some promise, it is quite time consuming and does not guarantee success.

The second major problem concerns the procurement of adequate samples of the four species under study. So far we have collected the limpet and damselfish samples largely on our own and have been reasonably successful in obtaining adequate samples from most of the desired localities. Sampling of both the lobster and the snapper have, for reasons of practicability, largely depended upon the cooperation of other individuals and agencies. This cooperative sampling, together with restrictions on ship availability, competition for specimens, and the high commercial value of these two species, has made it difficult to obtain the necessary samples from all designated localities.

SUMMARY

Levels of genetic variation in the lobster and snapper are very low compared to other organisms which have been studied. For the lobster, the preliminary analysis of allele frequency distributions at six loci failed to detect any significant heterogeneity among animals from Kure, Maro, Necker, and Oahu. This observation is consistent with the existence of a single unit stock of P. marginatus within the Hawaiian Archipelago. However, due to the low levels of genetic variation, this is not a robust test of the hypothesis. The test could be strengthened by the discovery and analysis of more polymorphic loci and/or increased sample sizes of individuals from certain localities.

Electrophoretic analysis of P. marginatus and P. penicillatus is shown to be useful for distinguishing puerulus larvae of the two species.

A polymorphism of mannosephosphate isomerase is present in the spiny lobster and one allele--"s"--is limited to males. This sex-limited allele is expressed in late embryos and puerulus larvae and therefore allows the determination of sex ratio in all life history stages. Preliminary analyses of sex ratio in larvae and late embryos indicate a significant excess of males.

Moderate to high levels of genetic variation characterize the damselfish and limpet. This result, when contrasted with the data for the lobster and snapper, emphasizes the substantial variation in levels of genetic polymorphism that occurs among taxa. Analyses of gene frequency distributions for six loci in the limpet provide strong evidence of stock heterogeneity within the Hawaiian Islands. A major discontinuity in gene frequencies between Molokai and Necker suggests that limpet populations in the Northwestern Hawaiian Islands are very distinct from those of the major Hawaiian Islands. Overall, the low levels of genetic variation exhibited by the lobster and the snapper emphasize the need for large sample sizes (a need which will be difficult to meet with the snapper).

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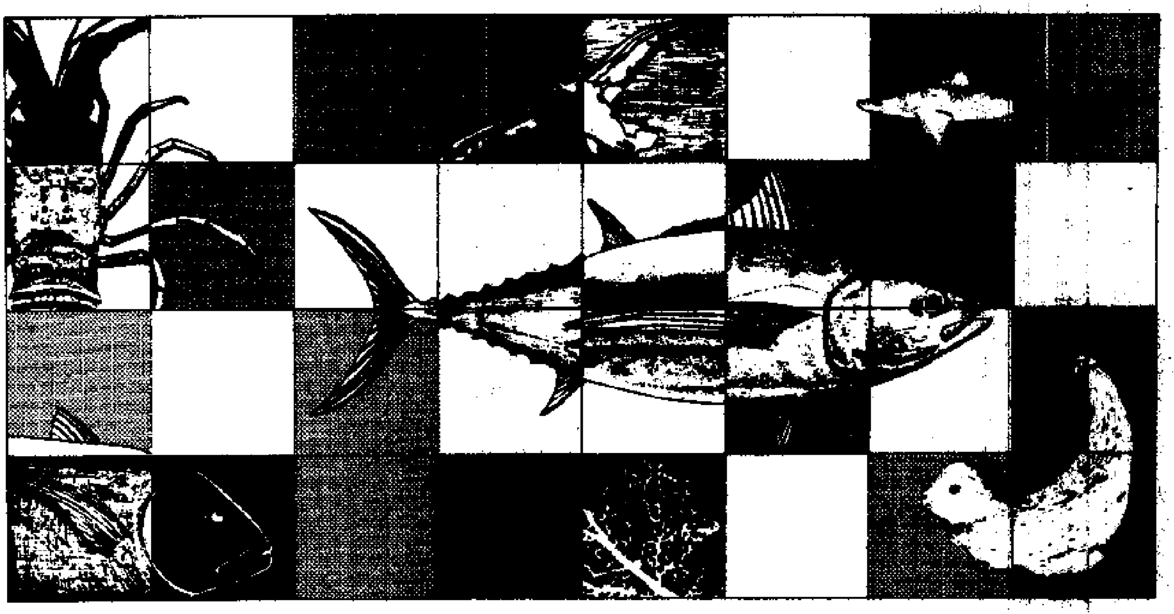
Management



STATUS OF THE HAWAIIAN ISLANDS NATIONAL WILDLIFE REFUGE

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ABSTRACT

After more than 70 years of refuge operations, conservation of migratory bird resources and protection of endangered species still rank as primary resource management goals of the U.S. Fish and Wildlife Service in the Northwestern Hawaiian Islands. Both accumulated research data and the evolution of pertinent legislation have influenced refuge operations over the years. Results of ongoing tripartite and Sea Grant research will greatly improve our joint capability for wise management of fish and wildlife resources. However, the well-documented history of human abuse and the demonstrated vulnerability of the Northwestern Hawaiian Islands to irreversible ecological change will continue to dictate a conservative stance restricting human use to activities of clearly demonstrated compatibility with management goals.

migratory birds
endangered species
resource management
National Wildlife Refuge
Northwestern Hawaiian Islands

In the interest of putting my discussion into perspective, let it be said clearly at the outset that the U.S. Fish and Wildlife Service (FWS) takes its resource management role in the Hawaiian Islands National Wildlife Refuge very seriously. FWS is more than a participating agency in a cooperative study of fish and wildlife resources. When all is said and done, the area will still be a national wildlife refuge. FWS will still manage the wildlife resources and habitat within the constraints of pertinent laws, regulations, and treaties. Many important questions have been and will continue to be answered in the tripartite and Sea Grant studies. Whether or not the data will justify a change in refuge management policies relating to consumptive use of fishery resources, or any other human activity in the refuge, remains to be seen.

It would be constructive at this point to relate the FWS' current management stance in the Hawaiian Islands National Wildlife Refuge to a brief historical perspective. The federal refuge system had its beginning in 1903 with designation by President Theodore Roosevelt of Pelican Island in Florida to protect nesting pelicans, herons, and egrets from plume hunters. Shortly thereafter, in 1909, similar commercial exploitation of wildlife prompted President Roosevelt to take similar action in designation of the Hawaiian Islands Bird Reservation. Slaughter of hundreds of thousands of seabirds for feathers, the unrestricted taking of eggs, and the indirect destruction of habitat through guano harvest prompted the President to take this action. Other unrestricted commercial exploitation of seals and turtles also preceded this action. By Presidential Proclamation in 1940, the unique land and nearshore waters of the Northwestern Hawaiian Islands became the Hawaiian Islands National Wildlife Refuge. Unfortunately, refuge designation in itself came too late for at least three native bird species unique to Laysan Island that became extinct early in this century as a result of habitat destruction by rabbits. Other species, notably the Laysan duck, Laysan finch, and the Hawaiian monk seal, perched precariously on the brink of extinction early in this century, yet all experienced a reversal of this trend under the refuge umbrella. In the absence of effective resource management and enforcement, exploitation of some forms of refuge wildlife occurred intermittently past the midpoint of this century. As recently as 1959 green turtles were commercially harvested at French Frigate Shoals. Now identified as a threatened species by federal law, turtles derive important protection on nesting islands and nearshore waters of the refuge.

Although intermittent early trips were made to survey refuge resources, permanent FWS presence in the islands did not begin until 1964, with the arrival of Eugene Kridler in Honolulu. Since that time, the FWS staff in the islands has grown to accommodate increasing responsibilities in refuge management, endangered species management, ecological services, research, and law enforcement. Until recent establishment of a field station on Tern Island, actual FWS presence in the Northwestern Hawaiian Islands has been intermittent, due to the extreme logistical problems of access. Despite this, many lessons have been learned that have helped form the basis of the FWS' management stance in this unique area.

A visitor to many refuge islands can easily be lulled into a feeling of complacency by the sheer apparent magnitude of the seabird populations and the numbers of seals and turtles that share some isolated beaches. Yet, the historic record clearly illustrates that these unique wildlife resources, and the nearshore waters that sustain them, are vulnerable to very real, but often subtle, threats. The lesson learned through the impact of rabbits on Laysan Island is legend. The threat of inadvertently introduced rats or other predators on this or other islands can hardly be overstated. Rats on Midway destroyed populations of Laysan rails placed there in a vain attempt to save a species whose habitat had been devastated. This year unchecked populations of rats on Midway and Kure are preventing successful reproduction in major portions of Bonin petrel colonies and threaten reproduction of other species as well. The history of shipwrecks that mark the beaches and reefs of the Northwestern Hawaiian Islands, including a Japanese fishing boat aground on Laysan in 1970 and the very recent grounding of a fishing boat at French Frigate Shoals, makes it very clear that the threat of rat introductions on other islands is very real. The question is not if it will occur, but when, where, and whether it can be controlled.

The risk of accidental species introductions is not confined to predators, as a review of the historic impact of exotic flora on the Northwestern Hawaiian Islands will illustrate. Not surprisingly, the highest percentage of aggressive weedy species is found on islands frequented by man. Military activities are responsible for many of the inadvertent plant introductions. Researchers and other well-intended visitors have also contributed to the problem in the absence of proper precautions. Many weedy plants have irreversibly altered the terrestrial ecosystems of some islands, including the availability of nest sites for seabirds and landbirds. Regrettably, the movement of birds between islands also helps disperse exotic seeds. Pest insect species may also be inadvertently introduced, as has occurred at Pearl and Hermes Reef. Consequences to island flora and fauna can be very serious.

The intimate ecological relationship between the terrestrial wildlife of the refuge and the integrity of the marine environment played a determining role in the original designation of boundaries. Awareness of this relationship is still influential in the FWS' current management program. Turtles and seals inhabit refuge waters for a significant portion of their life, and, together with seabirds, are totally dependent upon marine resources for their food. The nearshore reef ecosystems are also unique in themselves, supporting corals and other marine species less common or absent in the high islands. For these and other reasons, FWS places great importance on the wise use of the marine environment in the Hawaiian Islands National Wildlife Refuge.

The threat of serious oil spills in the refuge area was highlighted in 1977 by the spill of more than 5 million gallons of crude oil from the Irenes Challenge, when it broke apart 50 miles north of Lisianski. It was a matter of chance that this spill missed the refuge. Yet, bilge oil and other boat-related pollutants, such as trash and discarded fishing gear, often litters the beaches of the Northwestern Hawaiian Islands. Repeated sightings of birds, seals, and turtles covered with oil or entangled with debris make it clear that the threats associated with intensified boat traffic in refuge waters are not hypothetical.

Over 400 national wildlife refuges make up a nationwide system that is as diverse as the wildlife it was designed to protect. Yet, the Hawaiian Islands National Wildlife Refuge is atypical in many respects. The refuge supports a wide variety of both marine and terrestrial species, including rare species, and a varied seabird resource that is virtually unrepresented elsewhere in the system. Atoll and volcanic island ecosystems, such as are broadly represented in the Hawaiian Islands National Wildlife Refuge, are found only in the Pacific Islands refuge complex. The well-documented vulnerability of the islands in the Hawaiian Islands National Wildlife Refuge to irreversible ecological change also makes the site unique from a management perspective. Although commercial exploitation, research, recreation, and educational uses are long-range potential human uses of the area, it is clear that such uses cannot be permitted without substantial restrictions to prevent irreversible change.

The Fish and Wildlife Service's basic management policies for national wildlife refuges are formulated nationally, within constraints imposed by many pertinent laws, regulations, statutes, and treaties. Over time, these national policies have evolved as relevant legislation and new biological data have been dictated. Policies are further defined by regional offices and fine-tuned to specific refuges. In recent years, national laws and international treaties have been more constraining than ever and have reduced the inherent management flexibility of the system. This is particularly true in the Hawaiian Islands National Wildlife Refuge, where migratory bird treaties with Pacific rim nations, the Endangered Species Act, the Marine Mammal Protection Act, and the National Environmental Policy Act have all made it necessary for FWS to more rigorously evaluate its own actions and what it permits to occur on refuge lands and waters.

To insure compliance with pertinent legal concerns, FWS has taken steps to update management policies on a national, regional, and area office level. The results of a recent task force study of refuge management policies are now being reviewed. As recently as March 1980, Region One policy on marine birds has been updated to reflect evolving responsibilities dictated by international treaties. This policy statement is particularly relevant to the Hawaiian Islands National Wildlife Refuge because it stresses the need to "maintain all marine birds occurring on National Wildlife Refuge lands and waters at not less than current population levels, in their natural diversity and on native habitat throughout their range."

On a local basis, FWS has also taken steps in recent years that reflect both concern for the wildlife resources we are obligated to manage and recognition of the economic potential of lands and waters within and adjacent to the Hawaiian Islands National Wildlife Refuge. Participation in this cooperative effort to evaluate fishery potential and associated ecological impacts of that fishery is indicative of that recognition. FWS has also initiated a serious evaluation of management alternatives for the Tern Island facility, including various fishery options, through an open interchange of ideas with interested agencies, industry, legislators, and the general public. At considerable expense, FWS is currently maintaining the Tern Island field station with a rotational staff of refuge personnel, so that no future options for the site will be precluded by a failure on our part to keep the facility functional. This station is also now providing important logistical support for several tripartite and Sea Grant researchers.

At this point in the tripartite study, it is critical that we evaluate which important questions are not likely to be answered by our present line of inquiry and to determine how efforts can be redirected or better coordinated towards that objective. A readily apparent data gap involves our limited understanding of ecological relationships between terrestrial and marine resources. Greater emphasis in future research must be directed at both the documented and potential impacts of human activity on all trophic levels. This effort should encompass both consumptive and nonconsumptive uses. It is safe to say from a management standpoint that all proposed future human activity in the refuge will be carefully scrutinized. Any permitted activity is likely to be subject to restrictions. In the case of commercial exploitation, time would be well spent in a thorough evaluation of means to minimize anticipated ecological impacts rather than simply documenting resource abundance and distribution. The recent grounding of a fishing vessel at French Frigate Shoals highlights the need for more stringent regulations to reduce risk to human safety and threats to insular ecosystems.

Educational use of national wildlife refuges is a national objective of the Fish and Wildlife Service, but only where this activity is compatible with primary conservation goals. In view of the extreme sensitivity of the Hawaiian Islands National Wildlife Refuge, FWS has placed severe restrictions on public access in the past. Steps have also been taken to compensate, in part for this reduced opportunity, by providing alternatives such as pamphlets and exhibits. Recreational use has also been problematic due to difficulties in enforcement. While it may be argued that additional use could occur with minimal disturbance, inability to enforce limited access regulations will preclude expanded recreational opportunity in most areas of the refuge.

Research activities in the refuge have also been the subject of controversy in recent years. The remarkable diversity of wildlife resources and the relatively undisturbed nature of the refuge atolls and rocky islands were used as justification in designation of the refuge as a Research Natural Area in 1967. However, the well-intended scientist can create problems as well, and severe restriction on access and activities on some islands and in the water is necessary. Tripartite research on some islands and in the water are necessary. Tripartite research in the future should address these poorly understood problems and develop measures to minimize impacts.

I can sum this up by rephrasing my opening message: the refuge in the Northwestern Hawaiian Islands will outlast all of us. Without ever taking a thing away from it, the refuge is a resource of incomparable value to the state, the country, and the world. The Fish and Wildlife Service continues to take its role as custodian of that resource very seriously. I submit that a major reason why this cooperative study of a relatively undisturbed ecosystem is even possible is because the resources have been protected under refuge status. Future human use of the Northwestern Hawaiian Islands, including potential exploitation of fishery resources, must be compatible with wildlife and habitat management objectives. We welcome the results of the tripartite and Sea Grant studies, as they will be invaluable in the formulation and evaluation of management alternatives. We also welcome your guidance and offer our input into evaluation of future research efforts.

PRELIMINARY RESULTS FROM ECOSYSTEM MODELING AT FRENCH FRIGATE SHOALS

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ABSTRACT

The marine ecosystem at French Frigate Shoals is discussed and preliminary results of the modeling work are presented. Application of the Bulk Biomass Model produces biomass estimates and turnover rates for species groups at French Frigate Shoals which consist of seabirds, monk seals, tiger sharks, small sharks, turtles, small pelagics, carangids, reef fishes, lobsters, snappers and groupers, shrimps, nearshore scombrids, and benthos.

French Frigate Shoals
ecosystem modeling
Bulk Biomass Model

INTRODUCTION

The objective of our ecosystem modeling is to draw on the expertise and results of the people and projects of the Northwestern Hawaiian Islands (NWHI) program to develop a quantitative and dynamic model of the marine ecosystem around French Frigate Shoals (FFS) in the NWHI. Because the model is dynamic, it may prove to be useful as a management tool and may also help to identify components of the ecosystem where additional research attention is needed.

Our approach to modeling begins with the top carnivores and works down to the primary producers. We have identified 13 species groups which form the components of our ecosystem. Rather than initially try to model the entire NWHI, we have restricted our modeling work to the ecosystem at FFS.

METHODS

The mathematical Bulk Biomass Model, which is described in detail by Laevastu and Favorite (1978), served as the tool for our ecosystem modeling. This model produces estimates of the biomass of the species groups in the ecosystem which is at equilibrium, based on growth, mortality, and consumption values specified by the user. The ecosystem is said to be at equilibrium conditions when the biomass of a species group is unchanged from one year to the next, although seasonal changes within a year are permitted. This is achieved when biomass growth equals its removal due to predation, natural mortality, and fishing mortality.

The population size of species which are the apex predators, typically birds and mammals, are considered fixed and are not changed during iterations of the model. The biomass of all other species groups are varied during the iterations until equilibrium conditions are met. The biomass values for species groups estimated at equilibrium conditions are heavily dependent on accurate estimates of the quantitative composition of the diet for each species group (Livingston, 1978). This report will deal only with the application of this tool to the ecosystem at FFS.

The ecosystem

We have defined 13 species groups which represent the components of the reef and nearshore ecosystem. These groups which will subsequently be described in detail are: seabirds, monk seals, tiger sharks, small sharks, turtles, small pelagics, carangids, reef fishes, lobsters, benthos, snappers and groupers, nearshore scombrids, and shrimps.

French Frigate Shoals

French Frigate Shoals is located at 166°10'W, 24°50'N, approximately midway along the chain of islands and banks comprising the NWHI. It is described by Bakus (in Bryne, 1979) as a "crescent-shaped reef on a circular submerged platform about 18 miles 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, ∿ 1 acre) near the center of the platform. The highest elevation is generally 5 feet above sea level except for La Perouse Pinnacle (135 feet 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 our modeling is the reef and nearshore community. We have defined the reef habitat as the area from 0 to 55 m (0 to 30 fathoms) (Gosline and Brock, 1976). The nearshore community is defined as the area ranging from 55 to 365 m (30 to 200 fathoms). These definitions applied to FFS yield a reef habitat of 761.6 km^2 and a nearshore habitat of 407.7 km^2. The sum of these regions consists of a circular area centered at FFS with a radius of approximately 20 km (Table 1).

Seabirds

Studies from the U.S. Fish and Wildlife Service (FWS) 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*; wedge-tailed

TABLE 1. AREA BY DEPTH AT FRENCH FRIGATE SHOALS

Reef Habitat		Nearshore Habitat	
Depth (fathoms)	Area (km^2)	Depth (fathoms)	Area (km^2)
0-10	461.5	30-40	34.9
10-20	264.9	40-50	37.3
20-30	35.2	50-100	95.7
Total	761.6	100-200	239.8
		Total	407.7

shearwater, *Puffinus pacificus*; Laysan albatross, *Diomedea immutabilis*; and black-footed albatross, *D. nigripes*. The total seabird population is estimated by FWS to be 320,000 birds (C. Harrison, U.S. Fish and Wildlife Service, Honolulu, Hawaii 96850, personal communication, October 1979). Detailed studies of stomach contents of birds in the NWHI have been undertaken jointly by the National Marine Fisheries Service (NMFS) Honolulu Laboratory and FWS. Based on this information, we estimate the diet of the birds to be 65% small pelagics including flyingfish, opelu, and squid, 10% juvenile tunas; 10% juvenile carangids; 10% juvenile snappers; and 5% zooplankton.

Monk seals

A census of the Hawaiian monk seal indicates a population of about 200 adults and pups in 1978 (Fiscus et al., 1978). Stomach contents of dead seals, regurgitated samples, and feces have been studied to determine their diet (National Marine Fisheries Service). Based on this work, we estimate that their diet is 85% reef fishes including eels and octopus, 5% lobsters, and 10% benthos. The extent of predation on seals by sharks is uncertain. While numerous seals are seen with scars which could have been caused by shark attacks, observations at Laysan provide little direct evidence of such attacks even though sharks are abundant in the shallow waters (B.W. Johnson and P.A. Johnson, National Marine Mammal Laboratory, National Marine Fisheries Service, Seattle, Washington 98115, personal communication, October 1979).

Tiger sharks

The tiger shark, *Galeocerdo cuvier*, is the predominant apex predator at FFS. Analysis of stomach contents from tiger sharks caught in the NWHI suggest that their diet consists of 45% reef fishes, 20% seabirds, 24% smaller sharks, 4% small pelagics, 4% lobsters, 2% turtles, and 1% monk seals (M. DeCrosta, Hawaii Cooperative Fishery Research Unit, University of Hawaii, Honolulu, Hawaii 96822, personal communication, December 1979).

A measure of the relative abundance of tiger sharks in the NWHI was obtained by Taylor and Naftel (1978). Eighteen sets of shark longlines at Pearl and Hermes Reef and FFS with a total of 388 hooks produced a catch rate of 10.31 tiger sharks/100 hooks. A report on shark fishing around Oahu suggests that a catch rate of six tiger sharks/100 hooks represented a density of 1.21 tiger sharks/km of 10-fathom contour (Lawrie, 1977). Extrapolating this density estimate for the NWHI catch rate, we obtain a figure of 2.08 tiger sharks/km or a total of 415 tiger sharks at FFS. We feel that most of these sharks would feed in the reef habitat where food is more abundant.

Small sharks

This is a group of nearshore warmwater sharks other than the tiger shark. Based on observations and catches at FFS, this group includes the grey reef shark, *Carcharhinus amblyrhynchos*, the galapagos shark, *Carcharhinus 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 great 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 fish, bottom-dwelling fish, stingrays, crustaceans, squid, and octopus. Based on analysis of stomach contents (M. DeCrosta, personal communication, December 1979), we estimate their diet as: 75% reef fishes, 5% lobsters, 10% small pelagics, 5% carangids, and 5% snappers and groupers in the reef habitat; and 58% small pelagics, 20% carangids, 15% snappers and groupers, 5% small sharks, and 2% reef fishes in the nearshore habitat.

Relative abundance for this group of sharks has been estimated in the NWHI at 9.8 sharks/100 hooks, based on longline catches (Taylor and Naftel, 1978). Around Oahu, a catch rate of 2.3 sharks/100 hooks was estimated to correspond to a density of 0.7 sharks/km along the 10-fathom contour (Lawrie, 1977). Extrapolating this density based on the catch rate for NWHI, we estimate a density of 2.9 sharks/km along the 10-fathom contour or 597 sharks at FFS. Visual observations of researchers who have worked at FFS suggest that this number is too low. We have arbitrarily chosen density figures of 10 sharks/km^2 for the reef habitat and 5 sharks/km^2 for the nearshore habitat. Based on a mean weight of 30 kg, we obtain biomass estimates of 300 kg/km^2 for the reef habitat and 150 kg/km^2 for the nearshore habitat.

Turtles

This group consists of the green turtle. Census counts indicate a population of 50 to 100 resident adult and 100 to 200 resident juvenile turtles at FFS (Balazs, 1979). However, during the breeding season, the population increases from 200 to 500 adults. Their diet consists principally of the following types of algae: *Codium arabicum*, *Caulerpa racemosa*, *Turbinaria ornata*, *Spyridia filamentosa*, *Rosenvingea orientalis*, and *Lobophora variegata* (Balazs, 1979). Their main predator is the tiger shark.

Small pelagics (small pelagic fishes and mollusks)

This group consists of small surface pelagic fishes and squid including flyingfish, exocoetids, opelu, *Decapterus* spp., akule, *Trachurops* crumenophthalmus, needlefish, belonids, and halfbeaks, hemiramphids. We estimate the diet of this group to be 80% zooplankton, 7% phytoplankton, and 13% small pelagics. Information which would enable direct biomass estimation is very limited. We have reliable figures on the seabird population of FFS and the bird diet. Based on this information, the minimum biomass of small pelagics necessary to meet bird predation would be 3,000 kg/km^2 in the nearshore habitat and 300 kg/km^2 for the reef habitat.

Carangids (carangids and large carnivores)

This is a group of active, fast-swimming carnivores which includes the white ulua, *Caranx ignobilis*; omilu, *C. melampygus*; ulua, *Carangoides ferdau*; kahala, *Seriola dumerili*; uku, *Aprion virescens*; and barracuda, *Sphyraena barracuda*. These carangids are found both in the reef and nearshore regions. Based on an analysis of stomach contents (M. DeCrosta, personal communication, December 1979), we estimate the diet of this group to be 15% zooplankton, 60% reef fishes, 15% lobsters, and 10% carangids in the reef region; and 15% zooplankton, 60% small pelagics, 5% reef fishes, 10% snappers, and 10% carangids in the nearshore region.

Researchers have remarked on the apparent low abundance of carangids at FFS relative to other banks in the NWHI. The biomass estimate of 400 kg/km^2 for both reef and nearshore habitat used for this area is based on very limited fishing data and transect dives (H. Okamoto, Hawaii Division of Fish and Game, Honolulu, Hawaii 96813, personal communication, December 1979; and E. Hobson, Southwest Fisheries Center Tiburon Laboratory, National Marine Fisheries Service, NOAA, Tiburon, California 94920, personal communication, December 1979).

Reef fishes (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).

Studies of the reef habitat and transects are currently ongoing at FFS (H. Okamoto and E. Hobson, personal communications, December 1979; R.W. Grigg, Hawaii Institute of Marine Biology, University of Hawaii, Kaneohe, Hawaii 96744; and J. Parrish, U.S. Fish and Wildlife Service, Honolulu, Hawaii 96850, personal communications, October 1979). These observations suggest that 12% of the area from 0 to 18 m (0 to 10 fathoms) is rich in reef fishes, 17% is moderate, and 71% is sparse. We will assume 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 (1,460 lb/acre); for a moderate habitat 16,815 kg/km^2 (150 lb/acre); and for a sparse habitat 1,569.4 kg/km^2 (14 lb/acre). This gives an average density of reef fishes at FFS of 15,000 kg/km^2 (134 lb/acre).

The density estimates of 163,666 kg/km^2 (1,460 lb/acre) for a rich habitat is in agreement with two estimates of standing crop determined from a rotenone study in Kaneohe Bay of 123,310 kg/km^2 (1,100 lb/acre) and 92,819 kg/km^2 (828 lb/acre) (Brock et al., 1979). Further, Goldman and

Talbot (1975) concluded from a survey of the literature that a maximum standing crop in a coral reef is about 201,780 kg/km^2 (1,800 lb/acre).

Estimates of the composition of reef fishes by weight from the Great Barrier Reef indicate that 10% are planktivores, 36% benthic feeders, and 54% carnivores (Goldman and Talbot, 1975).

Lobsters (lobsters and crabs)

This group includes the spiny lobsters, Panulirus marginatus and P. penicillatus, the slipper lobster, Scyllarides squammosus, and various crabs. The abundance of lobsters appears to be relatively low at FFS. Trapping data and transect studies indicate that the lobster population here is very low compared to other regions in the NWHI (R. Uchida, Southwest Fisheries Honolulu Laboratory, National Marine Fisheries Service, NOAA, Honolulu, Hawaii 96812, personal communication, October 1979). Based on this information, we selected a density of 200 kg/km^2 in the reef region and 50 kg/km^2 in the nearshore habitat. Lobsters are bottom feeders which prey primarily on benthos.

Benthos

The benthic community is typically rich, diverse, and well-developed. Organisms in this community include the sponges, algae, benthic fish, gastropods, bivalves, holothuroids, annelids, asteroides, ophiuroids, echinoids, crustaceans, and anthozoans. Members of the benthos may be carnivores, herbivores, or detritivores. An ongoing project is studying this community at FFS (R. Grigg and J. Parrish, personal communication, October 1979).

Snappers and groupers

This is a commercially important group of food fishes including opakapaka, Pristipomoides filamentosus; kalikali, P. sieboldii; gindai, P. zonatus; onaga, Etelis carbunculus; ehu, E. marshi; uku, Aprion virescens; hapu'upu'u, Epinephelus quernus; and butaguchi, Caranx cheilio. Fishermen report that these bottomfishes are caught predominantly between 75 and 220 m (40 and 120 fathoms). They are all active, carnivorous fish which prey on small fish, shrimp and other crustaceans, and macrozooplankton. Based on analysis of stomach contents, we estimate their diet to be 15% zooplankton, 60% benthos, 5% snappers, and 20% shrimps (R. Humphreys, Southwest Fisheries Center Honolulu Laboratory, National Marine Fisheries Service, NOAA, Honolulu, Hawaii 96812, personal communication, December 1979).

Based on our analysis of an intensive bottomfishing experiment in Guam (Ikehara et al., 1972), we arrived at an estimate of bottomfish biomass as 4.3 x 10^3 kg/nmi of the 100-fathom contour. We estimate the length of the 100-fathom contour at FFS to be 85 nmi and assume that 90% of the snapper and grouper biomass are in the nearshore region. We obtain estimates of snapper and grouper density in the reef region as 48 kg/km^2 and in the nearshore region as 808 kg/km^2.

Shrimps

This group, consisting primarily of Heterocarpus ensifer and Penaeus spp. is found in abundance between 225 and 375 m (125 and 200 fathoms). Estimates of density from trapping and trawling in the main islands are 50 kg/km^2 over this habitat range (Struhsaker and Yoshida, 1975). They are detritivores.

Nearshore scombrids (nearshore scombrids and carnivores)

This is a group of commercially important tunas and tunalike fish, and includes skipjack tuna, Katsuwonus pelamis; kawakawa, Euthynnus affinus; yellowfin tuna, Thunnus albacares; and ono, Acanthocybium solandri. Mahimahi, Coryphaena hippurus, and the rainbow runner, Elagatis bipinnulatus, also belong in this group. The members of this group are all pelagic or nearshore pelagic species which largely occupy the surface waters. The kawakawa is an inshore pelagic fish and 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). Based on stomach content analysis, we estimate the diet of this group to be 20% zooplankton and 80% small pelagics.

The input data required by the Bulk Biomass Model are summarized for all species groups in Tables 2, 3, and 4.

TABLE 2. GROWTH AND FOOD CONSUMPTION RATES IN PERCENTAGE OF BODY WEIGHT PER MONTH

Species Group	Growth Rate	Food Consumption Rate
Tiger sharks	--	48
Monk seals	--	240
Seabirds	--	450
Small sharks	6	48
Turtles	3	180
Small pelagics	8	30
Carangids	4	60
Reef fishes	10	30
Lobsters	6	23
Benthos	6	24
Snappers and groupers	3	30
Shrimps	5	30
Nearshore scombrids	6	30

Note: Natural mortality due to factors except predation is 0.2%; fishing mortality = 0.

TABLE 3. INITIAL DENSITY ESTIMATES USED AS INPUT

Apex Species	Reef Habitat (Number)	Nearshore Habitat (Number)
Seabirds	40,000	280,000
Monk seals	150	50
Tiger sharks	250	150

Prey Species	Reef Habitat (Biomass (kg/km^2))	Nearshore Habitat (Biomass (kg/km^2))
Small sharks	300	150
Turtles	7	7
Small pelagics	300	3,000
Carangids	400	400
Reef fishes	15,000	500
Lobsters	200	50
Benthos	15,000	3,000
Snappers and groupers	50	800
Shrimps	5	50
Nearshore scombrids	50	350

TABLE 4. FOOD COMPOSITION (PERCENTAGE OF DIET BY SPECIES GROUPS)

Reef Habitat	Nearshore Habitat
Small sharks: 75% Reef fishes 10% Small pelagics 5% Lobsters 5% Carangids 5% Snappers and groupers	Small sharks: 58% Small pelagics 20% Carangids 15% Snappers and groupers 5% Small sharks 2% Reef fishes
Turtles: 100% Benthos	Turtles: 100% Benthos
Small pelagics: 80% Zooplankton 13% Small pelagics 7% Phytoplankton	Small pelagics: 80% Zooplankton 13% Small pelagics 7% Phytoplankton
Carangids: 60% Reef fishes 15% Lobsters 15% Zooplankton 10% Carangids	Carangids: 60% Small pelagics 10% Snappers and groupers 10% Carangids 5% Reef fishes 15% Zooplankton

TABLE 4. FOOD COMPOSITION (PERCENTAGE OF DIET BY SPECIES GROUPS) (Continued)

Reef Habitat	Nearshore Habitat
Reef fishes:	Reef fishes:
54% Reef fishes	54% Reef fishes
36% Benthos	36% Benthos
10% Zooplankton	10% Zooplankton
Lobsters:	Lobsters:
100% Benthos	100% Benthos
Benthos:	Benthos:
50% Zooplankton	50% Zooplankton
30% Phytoplankton	30% Phytoplankton
20% Benthos	20% Benthos
Snappers and groupers:	Snappers and groupers:
60% Benthos	60% Benthos
20% Shrimps	20% Shrimps
15% Zooplankton	15% Zooplankton
5% Snappers and groupers	5% Snappers and groupers
Shrimps:	Shrimps:
100% Benthos	100% Benthos
Nearshore scombrids:	Nearshore scombrids:
70% Small pelagics	70% Small pelagics
25% Zooplankton	25% Zooplankton
5% Nearshore scombrids	5% Nearshore scombrids
Seabirds:	Seabirds
65% Small pelagics	65% Small pelagics
10% Nearshore scombrids	10% Nearshore scombrids
10% Carangids	10% Carangids
10% Snappers and groupers	10% Snappers and groupers
5% Zooplankton	5% Zooplankton
Seals:	Seals:
85% Reef fishes	85% Reef fishes
10% Benthos	10% Benthos
5% Lobsters	5% Lobsters
Tiger sharks:	Tiger sharks:
54% Reef fishes	54% Reef fishes
30% Small sharks	30% Small sharks
7% Lobsters	7% Lobsters
7% Small pelagics	7% Small pelagics
2% Turtles	2% Turtles

RESULTS AND DISCUSSION

The estimates of biomass, consumption, and turnover presented in Table 5 are based on computer runs simulating 80 years of ecosystem time with the input data from Tables 2, 3, and 4. There are still slight time trends in the biomass values for several of the species groups so these results do not yet represent an equilibrium solution; however, they are probably sufficiently close to an equilibrium solution to be useful for the purposes of discussing the model and input values. We have used relatively low food consumption rates for all species groups so the resulting biomass values represent the minimum sustainable biomass (Laevastu and Favorite, 1978).

TABLE 5. AVERAGE BIOMASS (IN WET WEIGHT, KG/KM^2) (B), ANNUAL CONSUMPTION (PRODUCTION) (IN WET WEIGHT, KG/KM^2) (C), AND TURNOVER (T = C/B) FOR REEF AND NEARSHORE REGIONS

Species	Reef Region			Nearshore Region		
	B	C	T	B	C	T
Small sharks	63.7	54.0	0.85	18.7	16.2	0.87
Turtles	9.3	3.6	0.39	3.5	0.7	0.20
Small pelagics	537.9	593.6	1.10	4,942.7	5,878.6	1.19
Carangids	157.0	135.1	0.86	937.4	1,022.0	1.09
Reef fishes	14,395.5	17,370.7	1.21	521.0	760.3	1.46
Lobsters	178.1	141.4	0.79	44.3	42.0	0.95
Benthos	9,580.9	13,981.6	1.46	1,235.3	1,970.3	1.60
Snappers and groupers	133.3	88.7	0.67	1,058.8	1,173.6	1.11
Shrimps	22.4	24.0	1.07	30.3	18.5	0.61
Nearshore scombrids	59.9	54.0	0.90	425.8	378.0	0.89
Total	25,138.0	32,446.7	1.29	9,217.8	11,260.2	1.22
Zooplankton	--	32,130.0	--	--	22,571.0	--

For most of the species groups, the estimated biomass values in Table 5 are not far from the initial estimates. This is particularly reassuring for reef fishes where we feel we have a reliable initial estimate. One exception is the estimated shark biomass, which appears low. This is due to heavy and perhaps, an unrealistic estimate of predation on smaller sharks by tiger sharks.

Data compiled after our computer work, which quantifies the distribution and relative abundance of benthos at FFS, coupled with standard production computation suggest that the production of benthos in the reef habitat should be about three times the value we obtained (R. Grigg, personal communication, February 1980). This information will be used to change our input estimates for future computer work. In the nearshore habitat, our estimated production agrees with his calculations.

Our estimated annual production for the reef region, excluding the benthic, zooplankton, and phytoplankton production, is 18,465.1 kg/km^2. This agrees with an estimated production of 22,000 kg/km^2/yr for a similar community on a reef in Bermuda (Bardach, 1959).

We have not attempted to model the phytoplankton and zooplankton production for the ecosystem. The computer program does, however, determine the total ecosystem zooplankton requirement based on the inputed diet composition values for all the species groups. The annual zooplankton consumption for the reef region is 32,130 kg/km^2 and for the nearshore region is 22,571 kg/km^2. Based on a transfer coefficient of 10%, this zooplankton production requires a phytoplankton production of 321,300 kg/km^2 and 225,710 kg/km^2 in the reef and nearshore regions, respectively. Primary production for the nearshore region has been estimated as 365,000 kg/km^2 (J. Hirota, Hawaii Institute of Marine Biology, University of Hawaii, Kaneohe, Hawaii 96744, personal communication, December 1979).

The predation on the species groups by seabirds, seals, and tiger sharks is approximately twice as high in the nearshore region as in the reef region (Table 6). This is due to the predation of birds on small pelagics in the nearshore region.

TABLE 6. ANNUAL CONSUMPTION BY APEX PREDATORS (SEABIRDS, MONK SEALS, AND TIGER SHARKS) IN KG/KM^2

Species	Reef Region	Nearshore Region
Small sharks	43	9
Turtles	3	1
Small pelagics	288	1,967
Carangids	48	273
Reef fishes	871	145
Lobsters	53	7
Benthos	83	10
Snappers and groupers	43	303
Shrimps	0	0
Nearshore scombrids	43	302
Total	1,475	3,017

FUTURE RESEARCH

There are two directions for future research. First, research directed toward improving estimates of biomass, growth rates, food composition, and food conversion is needed to improve the accuracy of the input to the model. Some of this research is already planned as part of the specific projects in the NWHI investigation. However, in some cases, specific projects are being proposed at NMFS to obtain the necessary data. One example of this is an intensive bottomfishing experiment we are planning at a small and isolated bank to estimate the standing stock of snappers and groupers per nautical mile of a given depth contour.

The second aspect of future research consists of model sensitivity analysis, simulation, and modification. We will vary input parameters to reflect our degree of certainty about the input values and observe the changes in equilibrium biomass values. We will simulate various fishing strategies to observe their impact on the ecosystem. Finally, we will consider modifications of some of the mathematical relationships in the model to incorporate our best understanding of the biological processes at French Frigate Shoals.

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ECONOMICS OF FISHERIES DEVELOPMENT FOR THE HAWAIIAN ARCHIPELAGO

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ABSTRACT

This paper contains the preliminary results of work carried out under an ongoing research project on the economics of fisheries development and management for the Hawaiian Archipelago. A feasibility analysis of alternative paths of fisheries development is presented using three classes of tuna (ahi) longliners as prototype vessels for planned development of the tuna resources. The high fuel requirements of the larger vessels appear to impose a major constraint on their profitability for long-distance operations. Some very preliminary results are also presented of an analysis of the relationship between prices and quantities of tuna species sold daily at the Honolulu fresh fish auction.

fisheries development
fish consumption
feasibility study
financial analysis
fish marketing
tuna (ahi)

INTRODUCTION

Economic studies of Hawaii's commercial fishing industry indicate that it has slowly declined for the past several decades. One of the earliest studies of the industry predicted that if the trends continue, "the industry will vanish as a viable economic activity in the near future" (Hale, 1964). Due to various constraints, programs to stimulate the expansion of the aku and ahi fisheries did not meet with success. More recent studies point to equally dismal prospects for removing the constraints to expansion of the industry (Shang, 1969; Ahsan et al., 1972; Comitini, 1977). These studies also suggest that the problems do not appear to be insurmountable if prices should improve sufficiently to provide an incentive for injecting new capital into the industry. There also appears to be an opportunity for expansion into more distant fishing grounds, provided appropriate technologies are adopted.

Prices for most fish products have experienced a steady rise along with the inflationary price increases for all food products, especially meats, in the latter half of the 1970s. For the most valued species, the relative price increase is comparable with that of meat products (Bell, 1978). These recent price trends have apparently increased the attractiveness of new investment opportunities for species within waters of the Hawaiian Archipelago, e.g., tunas, shrimps, lobsters, and bottomfishes. Several new vessels have been built or are under construction to exploit these fisheries. Vessels from the U.S. West Coast have taken part in trial fishing efforts northwest of Midway Islands. The recent Hawaii Fisheries Development Plan predicts continued development of more distant fisheries and addresses the problems and prospects for facilitating developing the potential of these species with long-range vessels operating from Honolulu (Department of Land and Natural Resources, State of Hawaii, 1979).

Recent evidence of per capita consumption of fish and shellfish in Hawaii indicates that there is a market potential to substitute (or expand) domestically caught fish for imported fish (Hudgins, 1979). In 1977, for example, interstate shipments and foreign imports accounted for approximately 74% of the total Hawaiian supply of commercial fish and shellfish. Per capita utilization of commercial fish and shellfish from interstate and foreign imports actually rose from 71.8% in 1970 to 73.5% in 1977. In 1977, per capita utilization of commercial fish and shellfish by the resident population amounted to 58.6 pounds. Per capita consumption of commercial fish and shellfish in that year was 22.7 pounds as against only 12.8 pounds nationally, mostly in fresh and frozen forms.

On the minus side, inadequate infrastructure is viewed as a constraint on the future expansion of the fishing industry in the state. In addition, very recent increases in fuel costs have outstripped the rise in fish prices. This, together with general cost inflation, threatens to offset product price increases and dampen investment incentives.

The preliminary information reported in this paper is the result of ongoing research conducted as part of the Sea Grant project "Economics of Fisheries Development and Management for the Hawaiian Archipelago."

The objectives of this research are as follows:

1. To determine the social and economic returns of fisheries development in the Northwestern Hawaiian Islands
    a. To determine the major factors--economic, social, ecological, and political--which may be affected by or in turn affect the form and extent of the fisheries development
    b. To synthesize economic costs and benefits of alternative strategies for development

   c. To determine social costs of alternative forms and degrees of fisheries development

2. To project optimum fisheries development strategies for different sets of socio-political conditions

It is expected that the results of this study will provide planners and decisionmakers with economic estimates of the expected effects of a wide range of actions and activities relative to expansion of U.S. fisheries in the Hawaiian Archipelago and adjacent areas. These include:

1. Bioeconomic implications of fisheries expansion on commercial species of the region
2. Expected overall profitability of fishery development
3. Expected returns on capital required for systems needed to support major fisheries development
4. Economic implications of regulations for the protection of ecosystem values

In this paper, costs and returns for fishing vessels of different sizes operating at different distances from port and some preliminary market price comparisons are examined.

RESULTS AND DISCUSSION

Under this project, Mr. Stuart Nakamoto, marine economics graduate student, has developed a simulation model to permit analysis of costs and returns of Hawaii fisheries. This Fisheries Industry Simulator for Hawaii (FISH) model was used to examine costs and returns of fishing for ahi from different sized vessels different distances from port (Honolulu).

The data base, including vessel performance, catch per effort estimates, prices, costs, and other financial information, was gleaned from a variety of sources. The required information and data relied heavily on a combination of established sources of knowledge such as the recently developed Hawaii Fisheries Development Plan and expertise of people familiar with the Hawaiian fishing industry.

Based on the data used, the expected return on investment for three size classes of ahi longliners is presented in Tables 1 through 4. Vessel sizes under consideration (80 feet, 100 feet, 120 feet) and their specifications are shown in Table 1. Of particular interest is that although catch rates per day are assumed to increase with the size of vessel due essentially to the laying out of more gear per vessel, the fuel consumption requirements increase concomitantly with the size of vessel, actually being twice as high for a 120-foot vessel compared with an 80-foot vessel.

TABLE 1. SPECIFICATIONS AND OPERATING RATES FOR THREE CLASSES OF AHI LONGLINERS

	Ahi Longliners		
	80 Feet	100 Feet	120 Feet
Crew (no.)	6	6	7
Hold capacity (1,000 lbs)	80	120	200
Fuel capacity (1,000 gals)	10.5	14.0	17.5
Construction cost ($1,000)	635	1,015	1,905
Delivery cost ($1,000)	30	35	40
Average fuel consumption-transit (gal/hr)	35.2	56	72
Average fuel consumption-fishing (gal/hr)	20.6	27.9	37.7
Catch rates			
Target (lbs/day)	2,204	3,308	4,410
Other (lbs/day)	945	827	1,550
Catch composition (%)			
Fresh ahi	3.5	4	3.7
Frozen ahi	66.5	76	70.3
Other	30	30	26.0

Note: Data common for all vessel classes
Average transit speed - 10 knots
Average fishing speed - 3 knots
Food (man-day) - $11
Crew share - 40% x gross revenue minus fuel and food
Price composition - fresh ahi ($3/lb); frozen ahi ($1.10/lb); other ($.40/lb)

TABLE 2. CONSTRAINTS ON MAXIMUM TRIP LENGTH (DAYS) FOR THREE CLASSES OF AHI LONGLINERS

Vessel Size (feet)	500 Miles			1,000 Miles		
	Fuel (gal)	Hold (lbs)	Days	Fuel (gal)	Hold (lbs)	Days
80	19,000	29,000	15	16,000	33,000	9
100	17,000	33,000	14	14,000	36,000	6
120	16,000	37,000	12	13,000	41,000	6

Source: Projected Operating Data

TABLE 3. MONTHLY INCOME AND FINANCIAL ANALYSIS FOR THREE CLASSES OF AHI LONGLINERS OPERATING 500 MILES AWAY FROM HONOLULU

	Ahi Longliners		
	80 Feet	100 Feet	120 Feet
Revenue ($1,000)	62.7	86.5	109.5
Operating costs ($1,000)	37.2	51.4	64.8
Contribution margin ($1,000)	25.6	35.2	44.7
Fixed costs ($1,000)	11.4	18.1	32.6
Depreciation ($1,000)	3.7	5.8	10.8
Interest ($1,000)	3.6	5.7	10.5
Return to management ($1,000)	14.2	17.1	12.0
Benefit/cost ratio	1.29	1.25	1.12
Internal rate of return (%)	63.2	48.3	24.7
Net present value ($1,000)	129.4	155.8	109.9
Break-even catch (lbs/day)	1,963	2,776	4,868
Break-even fishing time (days)	5.39	6	7.96
Break-even average price ($/lb)	.60	.70	.81

Note: Vessel life = 15 years
Salvage value = 0
Interest rate = 10%
Debt to equity ratio = 3:1
Taxes not included
Fuel cost = $1.10

Table 2 shows the constraints on the maximum trip length in days for these same vessels at 500 and 1,000-mile distances. Although the hold capacity appears to justify longer trips for the larger vessels, the greater fuel requirements would operate to constrain the length of the trip, and thus fishing time of the larger vessels. This becomes more pronounced as the distances fished increases from 500 to 1,000 miles.

Tables 3 and 4 illustrate the monthly income and financial analysis for these classes of ahi longliners for operating at distances of 500 and 1,000 miles, respectively. The 80-foot vessel is shown to be the most profitable or least unprofitable, in terms of the rate of return, and has all-around lower break-even requirements for fishing not only at 500 miles or 1,000 miles from Honolulu, but along any part of the Hawaiian Archipelago. Given the cost assumptions and the target catch rates as shown in Table 1, the 120-foot ahi longliner would not be a feasible operation at either 500 or 1,000 miles from Honolulu, while the other two are not feasible at 1,000-mile (or beyond) distances.

TABLE 4. MONTHLY INCOME AND FINANCIAL ANALYSIS FOR THREE CLASSES OF AHI LONGLINERS OPERATING 1,000 MILES AWAY FROM HONOLULU

	Ahi Longliners		
	80 Feet	100 Feet	120 Feet
Revenue ($1,000)	41.9	49.3	58.1
Operating costs ($1,000)	30.3	39.9	48.1
Contribution margin ($1,000)	11.6	9.4	10.0
Fixed costs ($1,000)	11.4	18.1	32.6
Depreciation ($1,000)	3.7	5.8	10.8
Interest ($1,000)	3.6	5.7	10.5
Return to management ($1,000)	0.2	-8.7	-22.7
Benefit/cost ration	1.01	0.85	0.72
Internal rate of return (%)	12.2	negative	negative
Net present value ($1,000)	20	-793	-2,068
Break-even catch (lbs/day)	3,122	5,349	9,831
Break-even fishing time (days)	9	9	11
Break-even average price ($/lb)	.95	1.34	1.63

Note: Vessel life = 15 years
Salvage value = 0
Interest rate - 10%
Debt to Equity ratio = 3:1
Taxes not included
Fuel cost = $1.10/gallon

If the data base is sufficiently representative of the conditions facing a prospective fishermen, these results would raise doubts about the propriety of building larger vessels for fishing greater distances away from the main Hawaiian Islands, or even from Midway Islands. The cost of fishing appears to rise disproportionally to the expected increase in catch.

An alternative run through the data was made. This time the fuel capacity constraint was relaxed for all three classes of vessels fishing out to 1,000 miles from Honolulu. In other words, the hold capacity for each vessel became the only constraint on the length of a trip out to 1,000 miles. It was found that, although the results for all classes of vessels were more favorable than with the fuel capacity constraint, still the 80-foot vessel is relatively more profitable than the other two classes in terms of rate of return and break-even requirements for fishing out to 1,000 miles.

It should be pointed out that, in addition to the limitations imposed on the analysis of the data base, this version of the FISH model assumes a constant catch rate per unit of effort. A second version of FISH is being developed. The model which will incorporate resource and marketing constraints in a Schaefer model catch and effort format, may give different results. Both versions assume biological resource as given and measurable. Such biological information is not available at this time.

The above results appear to be in conflict with decisions being made by individuals now investing in vessels to fish in archipelago waters. Current experience in fishing for albacore suggests larger vessels are better off probably because of their greater hold capacity. How they have surmounted the fuel problem is not clear.

In summary, based on present data base and assumptions of the simulated model, the returns to investment and management from fishing appear to be low for 80-foot vessels operating continuously over 1,000 miles from land and negative for larger units. To the extent improvements in the data may reflect improved performance, higher catch rates, improved prices, etc., the economic viability of the operation would increase. The type of operation postulated would probably be unrealistic for most operators. Seasonal factors affecting catch and prices may dictate a fishing strategy which aims at taking a mixture of species for different distances and locations at different times during the year.

A critical question facing the fishing industry is whether fish prices will continue to rise at a rate that will offset the effects of increased catches on prices in local markets. For this reason there is a high degree of interest in fish marketing in Hawaii. The research team has undertaken a study of the effect of quantities landed and other factors which are thought to influence prices on 27 species of fish sold at the Honolulu fish auction. These data, compiled on a daily basis, cover a 13-month period from December 1978 through December 1979. Although data collection is incomplete, some preliminary comparisons for ahi were made for the month of December. Figure 1 shows a plot of the price per pound and number of pounds of ahi sold on a daily basis for December 1978 and December 1979. Each month was divided into two parts because it seemed that the volume of activity was more volatile in the second half. An attempt was made to capture the specific influences on price in the two time periods for 1978 and 1979 in the form of a log-linear regression equation of price and quantity with time as a shift variable. These are shown in Table 5.

Actually, the signs and coefficients of the regression equation capture quite closely the aberrations in the movements of prices and quantities in the month of December for these two years. Time appears to have a more significant independent influence on price than quantity. This is hardly surprising since demand for fresh ahi shifts constantly during the holiday season. The results appear to be better for 1979 than for 1978. The quantity sold at the fresh fish auction does appear to have a significant influence on price in two of the four periods studied. However, the small sample size and exceptional month of December is not necessarily a reflection of the results that will be obtained for our study of data over the course of a whole year. The comparison in Table 6 indicates that it is difficult to generalize what will happen to prices of ahi with

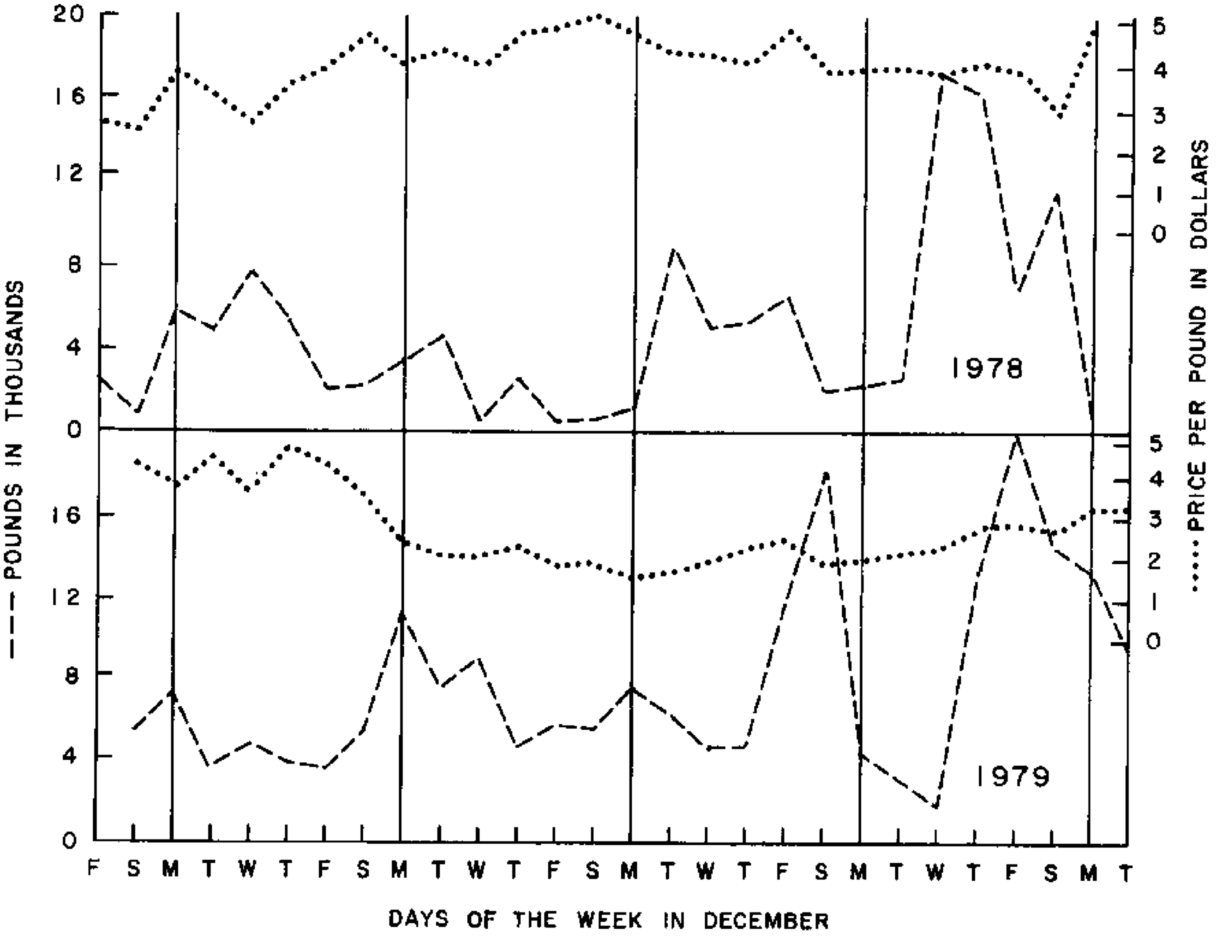

Figure 1. Prices and quantities of ahi sold during December 1978 and December 1979

larger or smaller quantities for sale on the auction block from week to week for a single month. The overall volume sold on the market for the whole month may be a more important factor, as shown by the significant rise in volume over time.

The foregoing results provide a preliminary look at what happens during a restricted time period in a narrow segment of the market. The larger question of the effects of large delivery catches from the more distant fisheries on prices and hence profits of local fishermen and those who would be engaged in the expanded fisheries remains unanswered.

CONCLUSIONS AND FUTURE RESEARCH PLANS

Preliminary findings suggest that due to high fuel and other operating costs, fishing out to the farther reaches of the Hawaiian Archipelago may not be a feasible undertaking. These findings, however, are based on fixed assumptions about vessel specifications, fuel use and costs, catch rates, market prices, etc. The computerized simulation analysis allows

TABLE 5. REGRESSION EQUATIONS FOR DETERMINATION OF PRICE OF AHI, DECEMBER 1978 AND DECEMBER 1979

1978	1979
December 1-13 ($n = 12$)	December 1-13 ($n = 13$)
$\ln P = 0.3791 + 0.0529 \ln Q + 0.0611\, t;\ R^2 = .684$	$\ln P = 4.8342 - 0.3746 \ln Q - 0.0746\, t;\ R^2 = .914$
(0.9590) (1.0896) (4.3509)	(5.7922) (3.8047) (8.1178)
December 14-26 ($n = 13$)	December 14-26 ($n = 13$)
$\ln P = 2.2611 - 0.0686 \ln Q - 0.0162\, t;\ R^2 = .540$	$\ln P = -0.4724 + 0.0242 \ln Q + 0.0531\, t;\ R^2 = .756$
(8.6231) (2.6637) (1.6802)	(1.0143) (0.4418) (5.0432)

TABLE 6. HONOLULU AUCTION SALES OF AHI FOR DECEMBER 1971, 1978, AND 1979

Year	Month		Week 1		Week 2		Week 3		Week 4		Week 5	
	lbs (x1,000)	price/lb ($)	lbs (x1,000)	price/lb ($)	lbs (x1,000)	price/lb ($)	lbs (x1,000)	price/lb ($)	lbs (x1,000)	price/lb ($)	lbs (x1,000)	price/lb ($)
1971	110.1	1.57	3.7	1.13	4.4	1.05	2.3	1.09	3.3	2.15	6.0	2.38
1978	122.2	3.59	3.8	2.86	1.9	4.08	4.5	4.40	7.6	3.86	6.0	3.80
1979	183.5	2.69	4.7	4.08	7.3	2.28	6.8	1.93	9.6	2.28	12.9	2.93

Note: Prices are weighted averages

for variable assumptions and development schemes. As development and study of the resource base continue, data will improve and provide a stronger basis for determining the relative feasibility of particular operations or strategies and also the optimum strategy for the future development of fisheries within the Hawaiian Archipelago. For example, a demonstration that the catch of large boats could appreciably exceed those estimates in the foregoing analysis will change the picture considerably. Likewise, a sharp sustained increase in fish prices over the levels assumed could alter the profitability picture dramatically.

The second phase of study calls for a general analysis of societal costs and benefits of fisheries development strategies in the Hawaiian Archipelago. The results of economic analysis of several development options will be incorporated with an analysis of other relevant costs and benefits to accomplish this.

ACKNOWLEDGMENTS

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THE HAWAII FISHERIES DEVELOPMENT PLAN

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ABSTRACT

Hawaii's commercial fishing industry, once an important component of the state's economy, became lethargic in the late 1950s and only recently has shown signs of reawakening. The 1978 Hawaii Legislature, in conjunction with the state administration, mandated that the Hawaii Department of Land and Natural Resources identify the problems and requirements of the local fishing industry and prepare a set of remedial actions. This 15-month effort was completed in December 1979. The Hawaii Fisheries Development Plan includes an analysis of the resource potential of the major underutilized species, a profile of the existing fishing industry, developmental strategies to remove constraints, and an integrated array of recommended developmental programs. Resource potential, primarily migratory tuna stocks and deep demersal species of the Leeward Hawaiian Islands, is estimated at 74.0 to 117.5 million pounds per year. Adverse ecological impacts of the developing fisheries are assumed to be minimal.

fisheries
resource
planning
Leeward Islands

INTRODUCTION

Hawaii's fishing industry has long been an enigma. Surrounded by an ocean and serving a population of seafood lovers, the local fleet has not substantially increased its landings in the past 30 years. Is this a sign of stability--a resource being utilized in balance? Or is this a static condition caused by inertia?

Leaders of the local fishing industry asked these and many other questions during a series of informal meetings in 1977. All who attended those meeting felt that industry could expand, but what was the potential? What was holding back fisheries development? What needs to be done? Where do we start? It was agreed that the first step should be a comprehensive planning effort. In taking their case to the state administration and the legislature, the industry leaders were well-received. Governor George R. Ariyoshi gave priority status to fisheries development, and the 1978 Hawaii Legislature passed nine resolutions addressing fisheries issues. The most significant of these resolutions (HR 122 and SR 125) called for a fisheries development master plan, with Act 243 providing $150,000 to the Department of Land and Natural Resources for that task. The intent of HR 122/SR 125 was clear: to determine where the opportunities lie and prepare a comprehensive plan to optimally utilize the state's fisheries resources. This is the purpose of this document.

The three-person staff of the Fisheries Development Plan Project was hired in October and November 1978, with a directive to present a final document to the legislature in December 1979. Contracts were let to three consultants in early 1979 to perform detailed analyses of resource potential, constraints restricting growth of the industry, and a profile of past and present fisheries. Early on, it was realized that the current fisheries data base was inadequate and required diversification and in-depth analysis. Coastal Zone Management funds were used to establish a four-person statistical staff attached to the project.

OBJECTIVES

The objectives of this planning effort were: (1) to assess the potential of Hawaii's commercial fishery; (2) to determine the survey and research needs required to foster further development of the industry; (3) to define developmental programs for each promising fishery; and (4) most importantly, to stimulate implementation of a coordinated fisheries development program.

In order to prepare this comprehensive plan, a great deal of information had to be accumulated, sorted, and analyzed. To provide a framework for these analyses, a number of questions were asked:

- Do we want or need an expanded fishing industry?
- Are there additional fisheries resources to be harvested?
- If so, why hasn't the industry expanded?
- What are the physical, technical, and institutional constraints restricting growth of the fishing industry?
- What specific actions are required to remove these constraints?
- What are the costs and benefits of the required actions?
- What will be the ecological consequences of increased fishing effort?
- Who will implement the programs, and who will supply the development funds?

These questions provided the basis for the planning effort. The plan essentially follows the logical progression from <u>need</u> to <u>resource availability</u> to <u>constraints</u> to <u>required actions</u>.

In general, the highest priorities in this planning effort were assigned to those commercial fisheries showing the greatest potential net economic benefits. For the most part, these are distant water fisheries which will require long-range vessels and modern support services. Thus, the offshore underutilized fisheries were treated in more detail than the nearshore fisheries which offer little hope for substantially increased landings. Geographically, the resources within 1,500 miles of the main Hawaiian Islands are addressed, particularly those in proximity to the Northwestern Hawaiian Islands (Figures 1 and 2).

RESULTS

Hawaii's historic identification with the sea has not been matched by commercial utilization of ocean resources. To a great extent state, county, and federal programs aimed at increasing the utilization of fisheries resources have been uncoordinated and lack continuity. Private investment and public assistance have been prioritized in tourism, Hawaii's growth industry. Indeed an important component of Hawaii's marine activities has been tourist-related charter fishing and diving. This use of nearshore fisheries resources is expanding.

Hawaii's fishing industry produces a small percentage of overall state income. Income directly from the harvesting sector is 0.2% of the Gross State Product (1978), no more than 0.8% of GSP. Approximately 1,600 persons are employed on a full-time basis. Estimated tax revenues from commercial fishing, processing, and distribution is $3 million.

A profile of Hawaii's fishery is full of contradictions. Today, 2,900 people are licensed fishermen, an increase over the 1966 low of 700 people, but still less than the prewar high of 3,500. The number of aku (skipjack tuna) vessels, which are the mainstay of the commercial fleet, has declined from 32 in 1948 to 14 in 1978. Total catch has fluctuated between 20 million pounds in 1965 and nine million pounds in 1969, with no discernible trend (Figures 3 and 4).

Hawaii's fisheries are of a modest scale, compared with those of other coastal zone states, but are more developed than most of the other oceanic island groups of the Pacific. The fishing techniques, vessels, and equipment have changed little in the past half century. Almost all fishing is done within 20 miles of the main islands, where resident resources and the migratory stocks are quite limited. It appears that the productivity of a number of the non-migratory inshore stocks has been considerably reduced by fishing pressure. The strong demand of Hawaii residents (as well as the tourist population) cannot be satisfied by the present fisheries, and there is a heavy reliance on imports. Of approximately 30 million pounds of seafood consumed annually in the state, 23 million pounds are imported. Even the famous mahimahi, which is thought by many as the most typical Hawaiian fish (after the more famous but less edible humuhumunukunukuapuaa), is largely imported from Taiwan and Ecuador. This situation seems destined to continue.

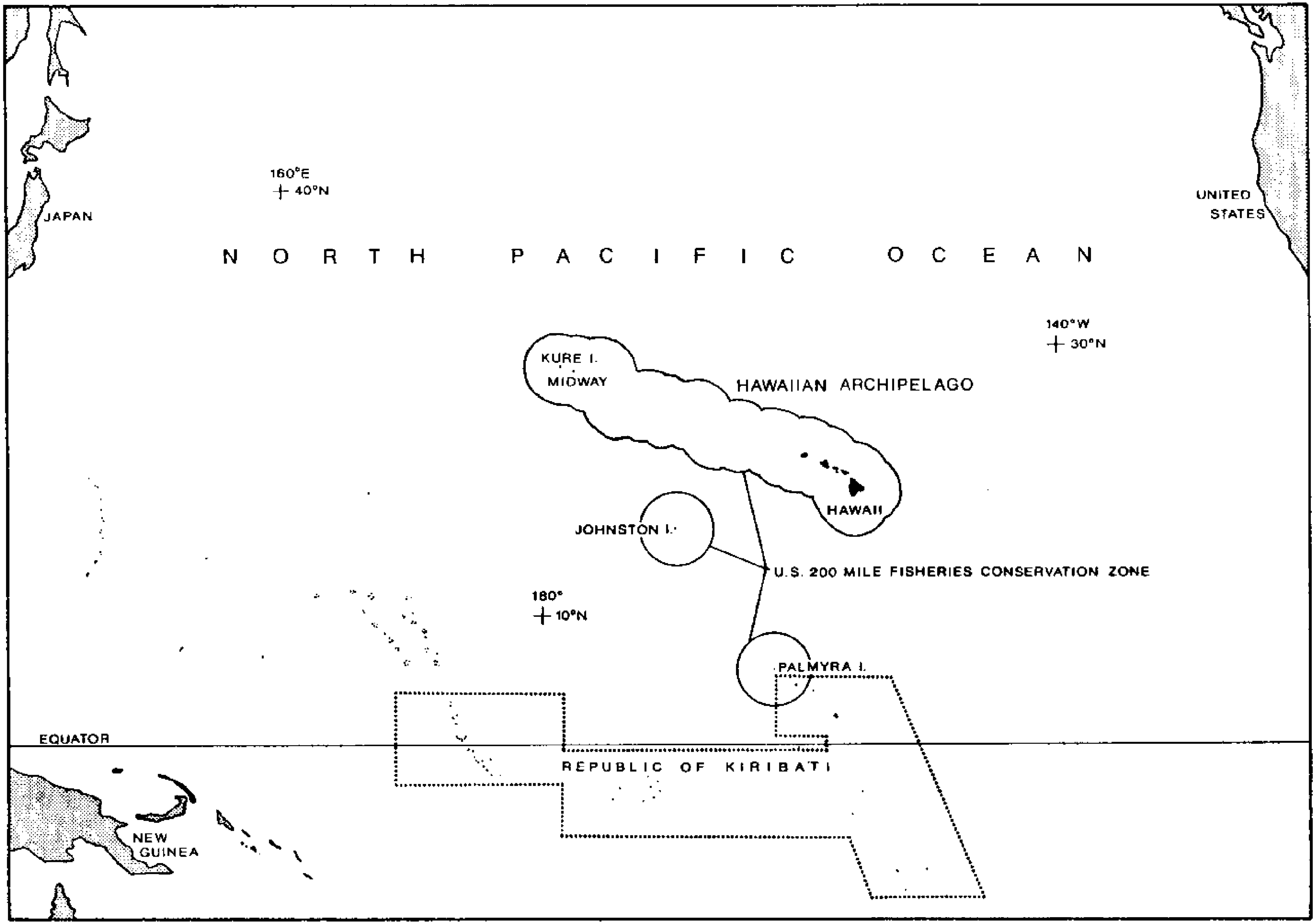


Figure 1. Hawaiian Islands and U.S. 200 Mile Fisheries Conservation Zone

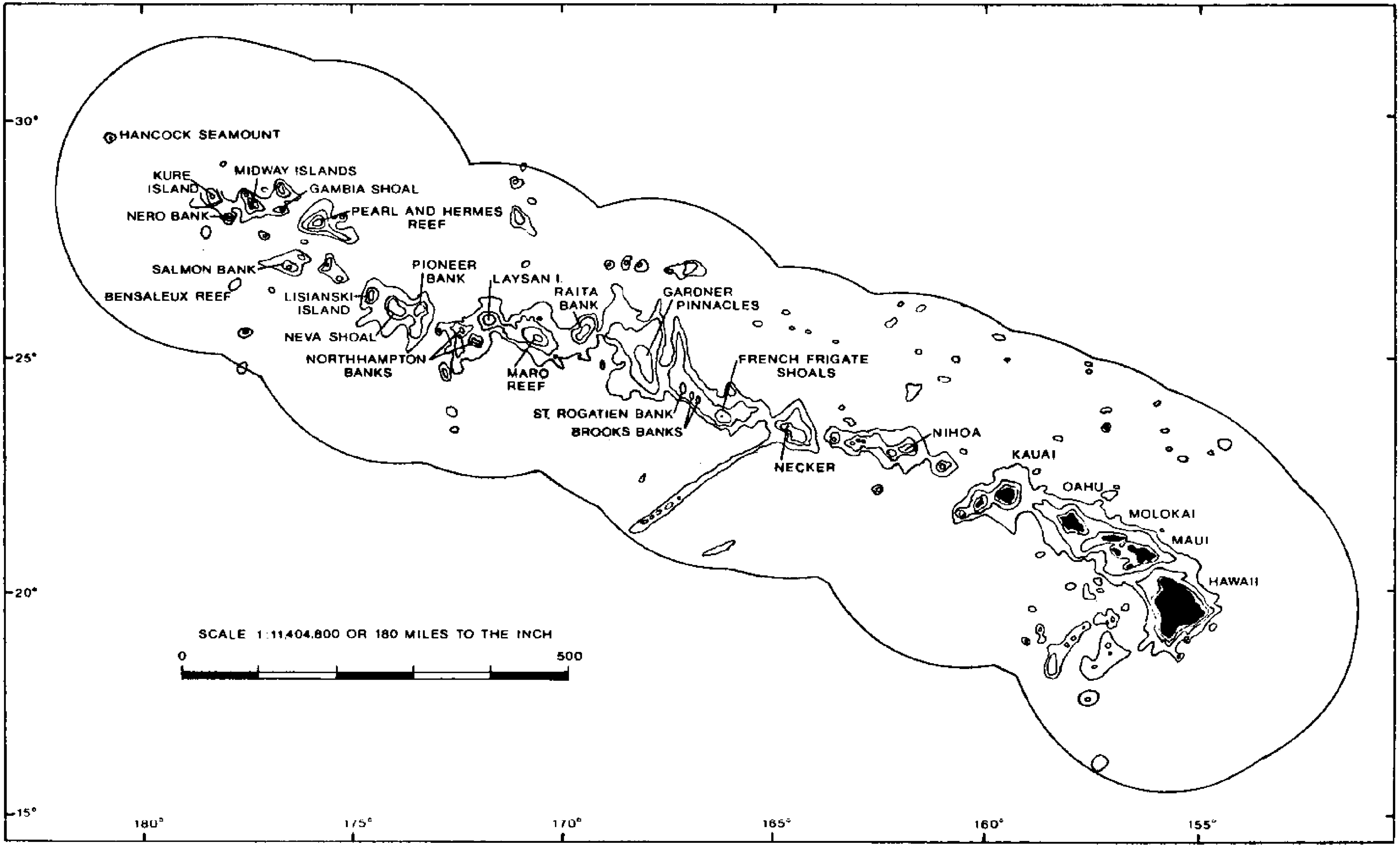


Figure 2. Hawaiian Archipelago

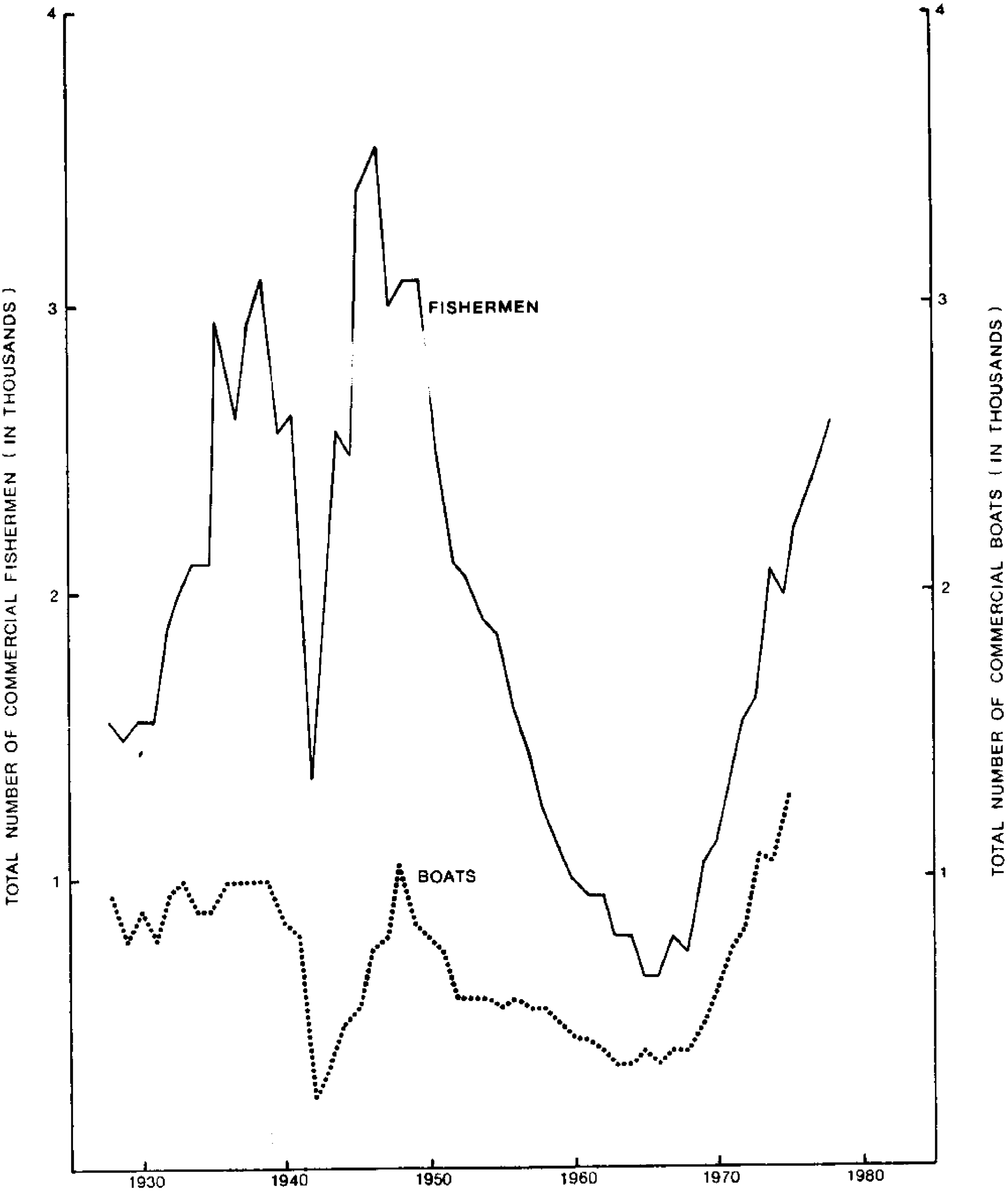
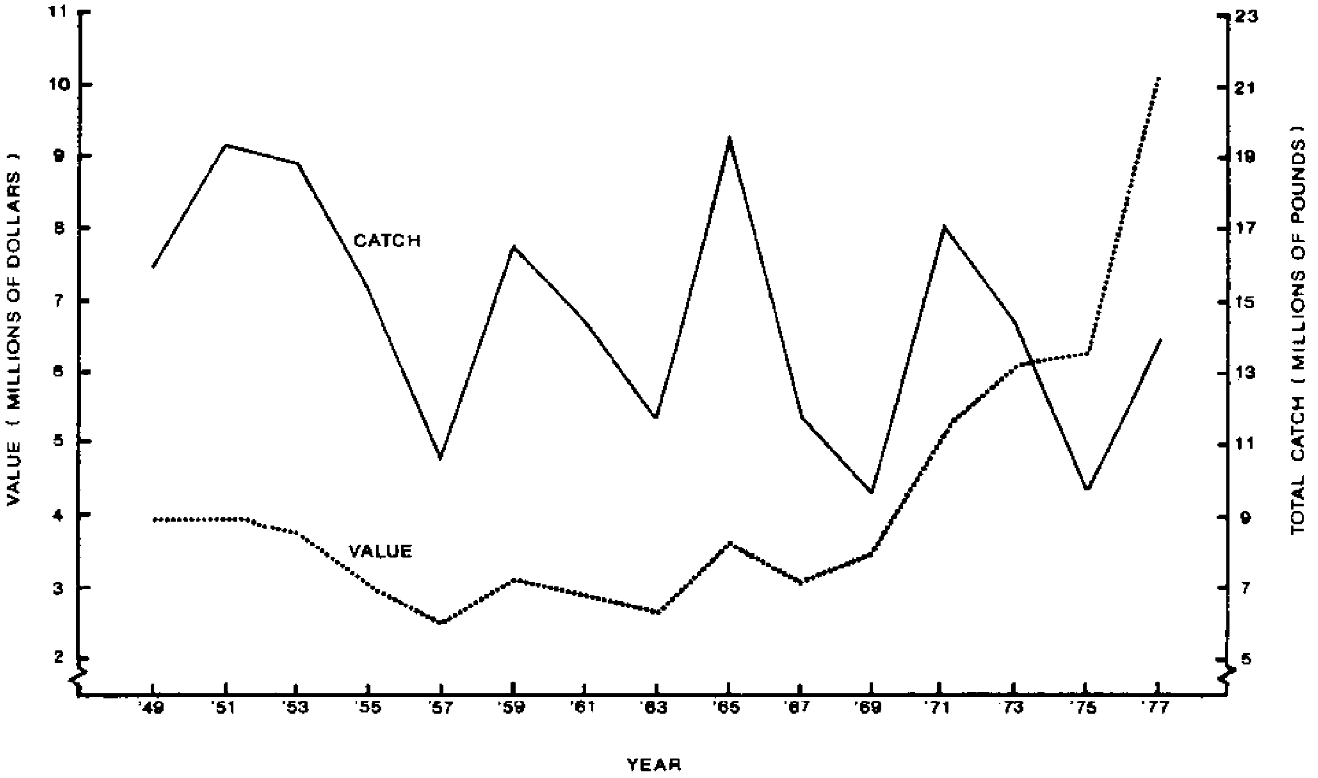


Figure 3. Commercial fishermen and boats in Hawaii

Total Landings



Total Landings Excluding Aku

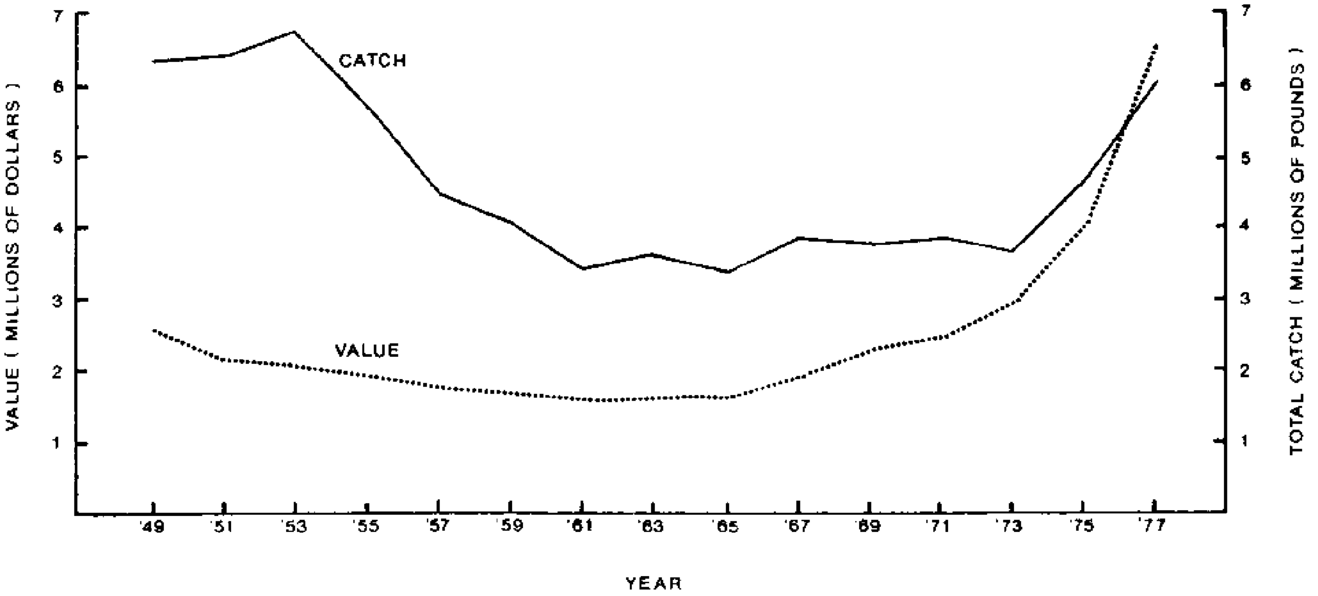


Figure 4. Reported marine fish landings in Hawaii

Yet, on the positive side, the nearshore fisheries of Hawaii seem to have successfully maintained a long-term ecological balance between the resources on the one hand and the demands of the market on the other, without drastic changes in the supply picture. Further, the possibilities of taking advantage of Hawaii's offshore fishery, especially in the Leeward Hawaiian chain, appear bright.

Resource potential

It must be emphasized from the outset that efforts to define any marine fisheries resource are fraught with difficulty. This is particularly true when dealing with underutilized populations. The estimates of potential sustainable yield for the most promising fisheries are presented in Table 1. These estimates are based on the best available scientific data, National Marine Fisheries Service surveys, and published foreign reports. When possible, statistical yield models were applied to catch/effort data to derive estimates of sustainable yield. When the data were inadaquate, estimates of potential were based on extrapolation of landings from current fisheries to large geographical areas. Because of the imprecision involved, lower and upper ranges of potential were estimated.

The estimates of fisheries resource potential within the Hawaiian region range from 74 million to 117.5 million pounds per year. This represents an additional harvest of 60.7 to 104.1 million pounds per year, Most of this potential (47.0 to 71.0 million pounds) exists in the open-ocean tunas, with 13.7 to 33.1 million pounds for all other species. The boundaries of the potential tuna fishery have been arbitrarily defined as 1,500 miles from Honolulu, while most other fisheries will be prosecuted within the 200-mile Fisheries Conservation Zone (FCZ) surrounding the Hawaiian Archipelago. Essentially all of the bottomfish, lobster, shrimp, akule, and opelu potential exists within the Northwestern Hawaiian Islands to the northwest of Kauai. The potential seamount groundfishery for alfonsins and armorheads exists to the northwest of Kure Atoll, mostly outside the FCZ.

Economic benefits

The direct economic benefits to Hawaii from the fisheries development program fall into five categories: (1) direct income to harvesters and processors; (2) increased employment; (3) an overall social benefit; (4) tax revenues; and (5) increased efficiency for existing fishing operations. Indirect benefits are also expected to occur: (1) greater stability in fresh fish supply, with the possibility of lower retail prices; (2) increased technical knowledge in fishing and processing techniques; (3) diversification of Hawaii's industrial structure; (4) promotion of neighbor islands development; and (5) increased appreciation of Hawaii's social and cultural heritage as an island community.

The most direct and measureable economic impact of an expanded fisheries development program is the potential impact of increased catch on Hawaii's personal and corporate income. We estimate that the 1990 Gross State Income will increase by $53 million (1979 prices) based

TABLE 1. PRESENT LANDINGS (1978) AND POTENTIAL SUSTAINABLE YIELDS IN THE HAWAIIAN REGION

Species or Group	1978 Landings (lbs)	Additional Potential (lbs)	Total Potential (lbs in millions)
skipjack tuna - aku	6,794,000	20,000,000	26.8
albacore tuna (surface)	569,000	10 to 20,000,000	10.6 to 20.6
albacore (subsurface)	125,000	6,000,000	6.1
bigeye tuna	460,000	10 to 20,000,000	10.5 to 20.5
yellowfin tuna	2,122,000	1 to 5,000,000	3.1 to 6.1
bottomfish (deepsea)	770,000	1 to 2,600,000	1.7 to 3.3
bottomfish (inshore)	1,044,000	900,000 to 1,300,000	1.9 to 3.3
seamount groundfish	--	4 to 10,000,000	4.0 to 10.0
bigeye scad - akule	415,000	450,000 to 1,400,000	.8 to 1.8
round scad - opelu	299,000	1 to 1,400,000	1.3 to 1.7
sharks	21,000	600,000 to 2,400,000	.6 to 2.4
billfish	741,000	1 to 2,500,000	1.7 to 3.2
spiny lobster	34,000	700,000 to 1,400,000	.7 to 1.4
shrimp	2,000	4 to 10,000,000	4.0 to 10.0
kona crab	28,000	50 to 75,000	.08 to .1
TOTAL	13,423,000	60,700,000 to 104,075,000	74.0 to 117.4

on an immediate development program generating an increase in catch of 50 million pounds, worth $30 million ex-vessel. This represents a fourfold increase over current catch levels. By the year 2000 total catch could increase over current levels of 86 million pounds ($55 million ex-vessel), or an increase in Gross State Income of $92 million. The processed value of the increased catch is $62 million for 1990 and $107 million by the year 2000, a value roughly equivalent to 70% of current pineapple sales. The increase in processed value for the cannery (aku and albacore) represents more than a doubling of current production, which today is 60 to 80% dependent on imported tuna.

The present discounted value of direct income derived from the projected increase in fish catch through a development program is $168 million through the year 2000. In comparison, it can be predicted that without government assistance, the resultant growth of the fishery wholly through private investment would be substantially less. This is particularly true given the infrastructural and financial constraints on fisheries development. Without a coordinated development program, we project an increase in the fleet of only 57 vessels by the year 2000, as compared to 185 vessels in the development scenario. The present discounted value of additional direct income from unaccelerated growth would be $52 million through the year 2000, a reduction of $117 million, or 70% less. The employment effect would be equivalently reduced.

State tax revenues are an important measure of the benefits derived from industrial development. Development costs are borne by the general public, while many of the economic benefits accrue to individuals. The state recoups part of this expense through its 1/2% excise tax and its personal income taxes. The sales tax on ex-vessel sales would be $152,000 annually by 1990 and $266,000 by the year 2000. Income taxes would generate approximately $3.6 million annually by 1990 and $6.4 million by the year 2000. This is not overly impressive in terms of total state tax revenues, but certainly warrants state investment at the levels visualized.

General constraints to development

The general constraints restricting growth of the fishing industry can be categorized as: (1) institutional, (2) harbors, (3) other infrastructure, (4) marketing and product promotion, (5) financing, and (6) fuel costs.

The commercial fishing industry has a long history of diversity, which unfortunately has been paralleled by diverse government responsibilities for fisheries resources and operations. As general comment, it is clear that there is a need for an overall systems planning approach to marine resources in Hawaii. The existing mechanisms for coordination have not been efficient and have limited participation by both industry representatives and the public. There has been substantial duplication of effort in research and data collection, while at the same time, many types of information necessary for fisheries development have been neglected. Thus, one general constraint to fisheries development in Hawaii has been the appearance of government action which in fact too often was offbase or irrelevant.

At present, all commercial fishing dock space is being utilized to capacity, with no berthing available for the 17 vessels which will join the fleet by mid-1980. It is not certain how many of the 105 applicants on the harbor's waiting list will purchase vessels in the 1980s, but each additional vessel will exacerbate the problem. Projected fleet growth indicates an additional 65 resident and 50 transient vessels may join the fleet by 1990. Fleet growth through the year 2000 is projected at 105 resident and 80 transient vessels. Most of the vessels can be nested two, three, or even four abreast, thus decreasing the amount of absolute dock space required.

The shortage of adequate dock space for commercial fishing vessels is viewed as the major constraint which will inhibit growth of the industry. Unfortunately, this problem is not easily solved. First of all, because harbor planning has concentrated on other priorities, very little space within Honolulu Harbor and Kewalo Basin is available for fishing vessel dock development. Secondly, the cost of wharf development is high; in fact, dock construction will constitute the single largest use of public funds in development of the fishing industry. Finally, the planning process for dock construction is long and tedious, requiring up to five years for design, acquisition of funding, and approval of various permits.

The existing fisheries infrastructure does not adequately support the present fleet, let alone provide for future expansion. "Other infrastructure" refers to fuel facilities, cold storage, processing plants, shipyards, and repair facilities. For the most part basic infrastructure is totally lacking on the neighbor islands. In Honolulu, where the current fishery is centralized, all fishery support facilities are at, or near, capacity. Without adequate infrastructure, the fishing business becomes so inefficient that investment is unattractive to private financial interests.

Hawaii's seafood marketing system is small, but relatively complex. Basically, all local landings, with the exception of most aku, are marketed as fresh fish. Canned tuna and fresh ahi are the only significant exports, and the ahi export system has really only developed in the past five years. Because of the relatively small volume of landings per vessel, the fisherman must depend on high ex-vessel prices to stay in business. The same is partially true for marketers, although their volumes are substantially increased by imported products. Per capita consumption of seafood in Hawaii is almost double the national average; however, local consumer demand is, of course, limited by population size and tourist preferences. To a large extent, the market price of all species is tied to the abundance of two major species--aku and ahi. Landings of the other species are somewhat biologically seasonal, but are mostly related to fishing effort--low during bad weather, unusually high during the holiday season (except when the weather is bad). The end result is a series of peaks (high abundance, lower price) and valleys (low landings, high prices). To the vessel owner, this means periods of discouragingly low prices; to the consumer, periods of discouragingly high prices. With the development of large, long-range vessels, the supplies of most species will increase substantially year-round. This should alleviate painfully high seasonal prices to some extent. On the other hand, periods of overabundance will be intensified. With local demand satiated, ex-vessel prices could drop below the requirements of the vessel operators.

In the past ten years, the acquisition of virtually all vessels larger than five net tons have been financed either by the state of Hawaii or the Hawaii Production Credit Association (HPCA). From 1969 through 1978, state loans on 25 vessels totalled $2.3 million, while HPCA loans on 13 vessels totalled $1,295,100. In the past seven years, National Marine Fisheries Service loan guarantees have been instrumental in backing up 25 public, semi-public, and private loans.

While the figures at first glance seem impressive, the current and future requirements for vessel financing are much more demanding. It is anticipated that planned growth of the fleet could result in 12 new vessels in the next two years, 42 by 1985, 65 by 1990, and 105 by the year 2000. The necessary financing in the next two years will approximate $6 million, based on an average cost of $500,000 per vessel. Vessel costs will, of course, continue to escalate so that identical vessels will cost in excess of $1 million 20 years from now. Thus, the total large vessel financing requirements for the next 20 years will approach $100 million.

The infrastructure requirements for an expanded industry are extensive. Considering all commercial infrastructure--including mooring, fuel, and loading docks, ice plants, freezer and/or processing facilities, marine repair operations, and storage areas--the total capital investment will be roughly $20 to $30 million, not including land.

The fishing industry uses petroleum quite extensively in the harvesting process. A modern 80-foot troller uses about 23 gallons/hour while in transit and 11 gallons/hour while fishing. A 100-foot multi-purpose vessel uses 48 gallons/hour in transit and 25 gallons/hour while fishing, in addition to its auxiliary engine use. An albacore troller plying the Midway/Seamount fishery uses approximately 30,000 gallons of fuel during the season, which amounts to about 20% of its gross revenue. Existing aku vessels are using approximately 60,000 gallons per year, about 10% of their total revenues.

Expansion of Hawaii's fishery as projected by this plan would lead to an increase in fuel use of about 14 million gallons/year. The current problems in the United States with the allocation and distribution of fuel have not yet severely affected the fishing industry.

In Hawaii the refineries report underutilization of diesel fuel in comparison with lighter distillates such as gasoline and jet fuel. Furthermore, the deregulation of fuel prices is expected to reduce marginal fuel use via higher prices and thus rationalize fuel allocation. Nonetheless, problems with fuel use could have a substantial impact on the industry and could increasingly create problems if fuel efficiencies are not realized.

Fishery-specific constraints

In addition to general constraints discussed above, most individual fisheries have specific problems in relation to technology or lack of information on that particular resource. The major fishery-specific constraints are those related to aku, ahi, and shrimp.

The aku pole-and-line fishery is critically hampered by the lack of an abundant, hardy baitfish. The vast aku resources of the Hawaiian region will probably not be harvested by the domestic fleet until this problem is solved. On the other hand, the technology for ahi longline fishing is well-known, as is the size of the resource and catch rates. The economic feasiblity of a Hawaii-based distant water fishery, however, is unknown. Little is known of the shrimp resource or the technology required for efficient harvest. In all three cases, specific research programs will be necessary before development can proceed. Virtually every resource with harvest potential will require additional research.

DISCUSSION

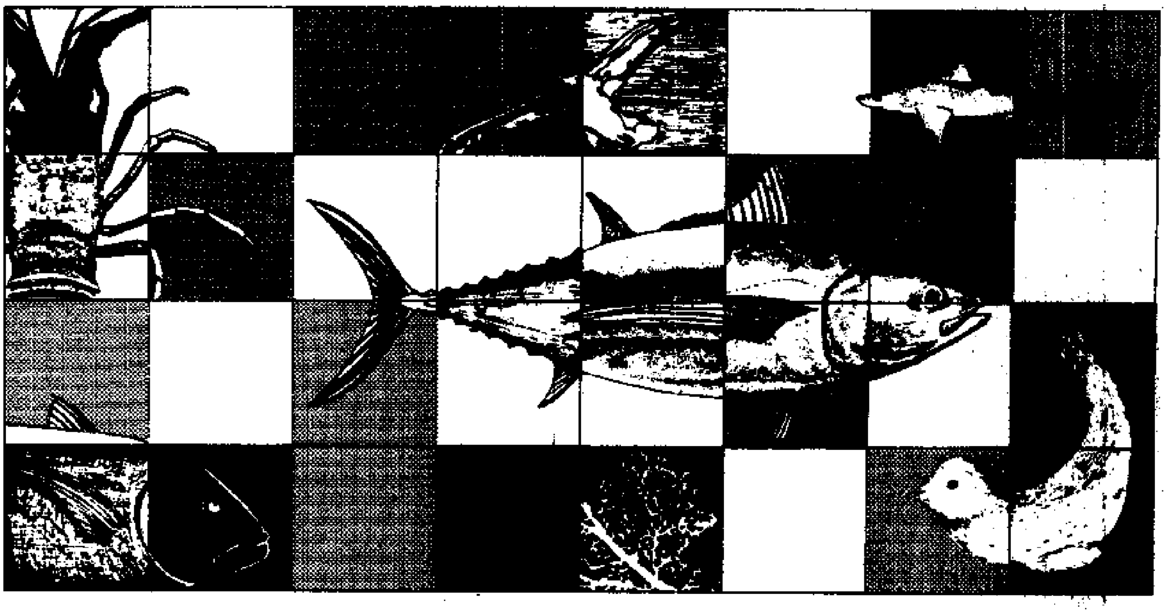
The basic purpose of the Hawaii Fisheries Development Plan is to present a comprehensive, coordinated set of recommended actions which will overcome constraints and result in fisheries development.

The major organizational, programmatic, and infrastructure recommendations are: (1) establish and industry/government Hawaii Fisheries Coordinating Council; (2) establish a Fishing Industry Council; (3) reorganize DLNR's Division of Fish and Game into functional units to place more emphasis on fisheries development; (4) facilitate vessel and infrastructure financing; (5) conduct surveys of latent resources, emphasizing pelagic and Leeward Islands species; (6) develop alternate live baitfish supplies; (7) develop outlying fisheries bases (Midway, Tern Islands, Palmyra); (8) provide adequate docking facilities; and (9) designate sites for infrastructure development.

SUMMARY

Hawaii's commercial fishing industry, once an important component of the state's economy, became lethargic in the late 1950s and only recently has shown signs of reawakening. The 1978 State Legislature, in conjunction with the state administration, mandated that the Hawaii Department of Land and Natural Resources identify the problems and requirements of the local fishing industry and prepare a set of remedial actions. This 15-month effort was completed in December 1979. The Hawaii Fisheries Development Plan includes an analysis of the resource potential of the major underutilized species, a profile of the existing fishing industry, developmental strategies to remove constraints, and an integrated array of recommended developmental programs. Resource potential, primarily migratory tuna stocks and deep demersal species of the Leeward Hawaiian Islands, is estimated at 74.0 to 117.5 million pounds per year. Adverse ecological impact of developing most fisheries are judged to be not significant.

Luncheon Address, Panel Summary, & Concluding Remarks



LUNCHEON ADDRESS

Southwest of Hawaii

J.L. Munro

Dean of the Faculty of Science, University of Papua, New Guinea

The purpose of this meeting has been to review the progress to date of the resource investigations in the Northwestern Hawaiian Islands (NWHI) and to consider possible future courses of the research.

Speaking from the viewpoint of someone from the far southwest corner of the tropical Pacific and the biogeographical center of the Indo-Pacific faunal region (i.e., Papua, New Guinea) I would like to discuss the implications of the NWHI program for reef ecology and reef resource studies elsewhere in the Pacific.

There are several important points about the NWHI program which require recognition:

a. Firstly, it needs to be recognized that these studies are the first realistic attempt to investigate and model a total coral ecosystem.

b. Secondly, that the NWHI chain, by virtue of low speciation and ecological simplicity, is the obvious place to do such studies.

c. Also, that by virtue of their isolation and long history of protection and of their proximity to sophisticated facilities, the NWHI are virtually unique in the Pacific.

d. State and federal governments recognize the value of studying the island resources and are prepared to make financial provision for the research. This is not a common situation elsewhere.

The situation in other parts of the Pacific is very different and we need to recognize other factors:

a. That with the advent of independence for many western Pacific nations, the willingness of metropolitan governments to support research in these countries has actually declined, while the ability and/or willingness of the newly independent countries to support research is very low indeed. Also, many third-world countries are actually suspicious of the motives of visiting research scientists or visiting research vessels and access to reef systems in those countries can sometimes require the exercise of considerable diplomacy. Contrast that with the U.S. situation.

b. That elsewhere in the Pacific and also including the main Hawaiian Islands, most major reef systems have been exploited for many hundreds, it not thousands, of years and for most islands, reefs, or atolls any projection back to the primeval state must remain hypothetical. In the populated areas the populations are now increasing very rapidly and pressures on resources are likewise increasing. There is also some degree of development of large-scale mining, tourist, and agricultural industries with accompanying degradation of reef systems. Contrast that with the NWHI.

c. In the west central Pacific as many as 60 genera of corals may be found on a single reef and 1,000 species of fish in a single bay and a mind-boggling diversity of every other sort of organism. Contrast that with the NWHI.

d. Fourthly, we need to recognize that the capacity for independent research of most third-world countries is very low indeed and it will be many years before third-world scientists can escape from the compelling day-to-day demands of development and educational programs and turn their attention to more abstract problems. Likewise, it will be many years before third-world institutions can afford the high technology approaches to environmental problems of University of Hawaii, National Marine Fisheries Service, and the other marine-oriented institutions of Hawaii.

Thus it seems to me that if the U.S. scientists do not find solutions to coral reef resources management problems, then no one else will. These seem to me to be compelling reasons for supporting the NWHI program to its fullest possible conclusion and thereafter (if not sooner) turning attention southwestward to the rest of oceania were it is patently obvious that the problems of resource management are entirely beyond the human and financial resources of the newly independent states. Of course, there are research programs in progress, particularly in the French territories, Guam, Palau, and Australia and at a few scattered laboratories elsewhere, but these are largely piecemeal investigations which can only deliver piecemeal results. What are needed are investigations, along the lines of the various NWHI studies, done in other more central parts of the Pacific.

Fortunately, there is every indication that the U.S.A. (if not other major powers) has recognized many of these problems. For example, it appears that a fairly definite commitment of long-term funds for research on small-scale fishery stock assessments has already been made.

A U.S. AID/University of Rhode Island workshop last September endorsed the idea that coral reef fisheries should be given particular attention because of their particular importance to the less developed countries and because they are amenable to visual techniques (e.g., transect) in addition to normal fishery techniques. Clearly, too, the reef fishery resource is founded upon the coral reef ecosystem as a whole and no clear understanding of the multispecies reef fisheries will emerge until we have a better concept of the interrelationships within ecosystems. Given the probability that the NWHI program will be drawn to a successful conclusion in the next few years, what could be the next step? I have a few suggestions (for what they are worth) for studies which might give a clearer picture of the problems of coral reef resource management and also, perhaps, clear up a few remaining problems in the NWHI. For example, it seems unlikely that the NWHI program will be able to fully determine whether the northwest to southeast differences in the Hawaiian chain are differences resulting from the atoll-high island sequence or from temperature differences or are ascribable to environmental degradation or to resource exploitation.

Some of the answers might be found by looking southwestward to other parts of the Pacific and, for a start, looking for physical analogues of the islands, atolls, or reefs of the NWHI which differ only in terms of latitude and/or temperature. How will the communities differ? How will growth parameters of the fishes differ? Will stock densities be different?

Alternatively, can we answer questions by looking for islands, atolls, or reefs in the Pacific which are similar in all except one or two aspects? (e.g., Can we find two or three islands in much the same place which differ only in being high, low, or atoll configurations?) Can we find analogues on a north to south or east to west plane? Can we find degraded and undergraded analogues?

From the fisheries viewpoint, are there analogues which are fished by traditional and modern techniques? Are there analogues where different fishing strategies prevail and where the target species include the entire community, predators only, or the middle-sized fishes? Are there analogues in which the tuna baitfish resources (if any) have or have not been fished?

Finally, is it possible to find an atoll or a group of islands in which one can experimentally exploit different sectors or islands using a variety of techniques in order to study the short and long-term changes wrought by different exploitative regimes?

I believe that the day of the general reef survey is over and that only by adopting a comparative approach to the questions of reef community structure and by making comparisons of population parameters will many of the problems be answered.

Hawaii is one of the few places in the world which has the accumulated talent, expertise, and capacity in its research institutions to tackle the sort of investigations I have outlined. Perhaps the present-day NWHI investigators will look beyond the completion of the program and try to lay the basis of future reef research elsewhere in the Pacific. I am sure that many of you have already done so. If you haven't, how about it?

PANEL SUMMARY

Following the presentation of individual papers, a panel discussion was held. Six panelists representing the tripartite agencies, Sea Grant, the fishing industry, and the Western Pacific Regional Fishery Management Council (WPRFMC) were invited to present their views regarding future research needs and management planning for the living marine resources of the Northwestern Hawaiian Islands. The panelists were Mr. Richard Shomura, Director of the National Marine Fisheries Service, Honolulu Laboratory; Mr. Kenji Ego, Director of the Hawaii Division of Fish and Game; Mr. Dale Coggeshall, Pacific Administrator for the U.S. Fish and Wildlife Service; Dr. Jack Davidson, Director of the University of Hawaii Sea Grant College Program; Dr. Stanley Swerdloff, Hawaii Division of Fish and Game; and Mr. Louis Agard, commercial fisherman and member of the WPRFMC. After the panel presentations, the public was invited to enter in the discussion with questions and comments. Dr. Richard W. Grigg of the University of Hawaii served as moderator for the panel and public discussion sessions.

In the interest of space, a summary rather than a verbatim text of the panel and public discussion is presented.

Virtually all of the panelists mentioned the need for wise management of the living marine resources of the Hawaiian Archipelago. While such a statement is uncontroversial, the problem lies in deciding what is "wise management." Kenji Ego reminded the audience of the story of the three wise blind men who could only perceive an elephant in terms of the bits and pieces they could feel. The moral of the story is the need to do research in more than bits and pieces if there is to be any hope of understanding the whole. Ego emphasized the need for cooperative efforts because of the magnitude of the research needed to understand the NWHI ecosystems. Inter-agency cooperation is also needed to avoid polarization of views on the optimum use of marine resources. He warned that in view of increasing population and economic pressures, it would be unrealistic not to expect and not to plan for an increasing push to develop the fishery resources in the NWHI.

Louis Agard echoed this view and pointed to existing federal legislation which mandates that the United States fully utilize the fishery resources contained in the Fishery Conservation Zone. He illustrated his position by explaining that with the extension of U.S. jurisdiction to 200 miles, there is one square mile of ocean for every man, woman, and child in the state of Hawaii. He went on to mention some of the resources contained within the new 200-mile limit in the state of Hawaii: precious corals, lobsters, skipjack tuna, bait resources, and bottomfish. And to the north of Midway Islands beyond the 200-mile zone, he indicated the existence of a potential for a $20 million albacore tuna fishery. He also noted the potential economic benefits of fisheries development in the NWHI in terms of jobs, GNP, and an improved balance of payments. The U.S. is the largest consumer of fishery products in the world but imports over 50% of its consumption.

Richard Shomura also spoke of the economic potential of developing fishery resources in the NWHI but offered several examples of where overzealous development efforts have led to the collapse of a fishery--one case being the California sardine, another the Peruvian anchovy. He warned against making the same mistake in the NWHI, for example, with the baitfish resource. He also pointed out the drastic effects that such an event might have on marine birds which inhabit the National Wildlife Refuge.

Dale Coggeshall pinpointed the problem by defining it as a question of resource allocation, of achieving the optimum for each species somewhere between the extremes of absolute preservation and full utilization at optimum yield. All the panelists and many members of the audience agreed that clearly there are species that are threatened and endangered and deserve absolute preservation. The more difficult question is the determination of optimum yield of other species while taking into account all relevant ecological, social, economic, and political factors that bear on each resource.

Shomura commented on the utility and the limitation of biological models to assist in the development of optimum yield on the NWHI fisheries. With regard to the attempt to develop a bulk biomass model in the NWHI, he recommended that it be expanded somewhat to include pelagic resources. Tripartite and Sea Grant scientists are presently applying this model to reef ecosystems at French Frigate Shoals. Shomura pointed out that some pelagic species like skipjack tuna are capable of eating an amount equal to 30% of their body weight per day and many of the food items in the diet of skipjack are reef-related species. While recognizing the wide variability which is inherent in most biological data, he reminded the participants that some management decisions must be made at the present time and to make these decisions the best scientific information available must be used. He stressed that future research will add to and improve the quality of existing information which can be applied to make better management decisions through an interative process.

Another approach to resource management, suggested by Louis Agard involves the use of test fisheries. By closely supervising a fishery, allowed under a scientific permit, it would be possible to directly assess associated impacts to other species. As an example, fishermen are often blamed for the recent decline of the Hawaiian monk seal population in the NWHI although there is no evidence to support such a claim. According to Agard, a test fishery would provide actual data which can be used for management decisionmaking as well as to validate or improve existing biological models.

Jack Davidson pointed to the usefulness of the economic simulation models, such as the one developed by Mr. Stuart Nakamura, in considering the options available to planners and decisionmakers. Changes in economic parameters can be introduced into the model to test the effects of expected or induced changes. The simulation model does not provide prediction of future conditions, rather, it provides a means to examine economic impact of alternative scenarios. Davidson emphasized that the present model could be used to show the effects on the profits of fishermen, of changes in fuel costs, interest rates, fuel and interest subsidies, and market prices.

In addition to the general concern for more research on problems of resource management and resource utilization in the NWHI, a number of specific research topics were suggested by both the panelists and the public. Stan Swerdloff brought up the need for improved understanding of the physical oceanography of the NWHI and current patterns surrounding the archipelago. He asked, if thermal fronts exist in the surface waters of the NWHI? He suggested that answers to this and other questions concerning physical oceanography were essential before patterns of recruitment and survival for many larval fishes could be worked out. Offering several other examples, Swerdloff said that the migration patterns of certain tunas could possibly be predicted given a knowledge of thermal front patterns in the surface waters of the NWHI. He also mentioned the phenomenon of hale-koa for ahi where these fishes are known to frequent. An understanding of the factors which serve to create a hale-koa for ahi would be of obvious economic benefit.

A number of comments received from the audience called for increased research effort on questions dealing with the critical habitat of Hawaiian monk seals, green sea turtles, and a variety of marine birds which inhabit the National Wildlife Refuge. A topic of particular concern was seabird energetics with respect to the trophic links between seabirds and marine fisheries including potential bait resources and the young of several commercially important species such as akule and opelu. Several members of the panel and the audience reiterated the need to gather more and better data that could be used for modeling purposes. These data are primarily predator-prey related, but they also deal with abundance, growth, and mortality of key species.

Throughout the discussion there was mention of a number of underutilized species in the NWHI such as squid, shrimp, Kona crab, and possibly baitfish, although opinion was divided on the baitfish question. The need for more research on these species was evident and it was repeatedly said that research should precede the development of commercial fisheries. The concept of a test fishery might best be considered in this context.

Near the end of the public discussion period Grigg thanked the panelists and the public for their ideas and suggestions. He pointed out that the next step would be one of implementation by identifying key researchers to do the work and acquiring financial support from a number of potential sources such as the UH Sea Grant College Program, the state, NMFS, WPRFMC, and the U.S. Fish and Wildlife Service. Coggeshall said there is a continuing need for better coordination of the program. He felt more active overall program management and coordination was needed and that a detailed action plan would be extremely useful. Coggeshall also said that the objectives of the original tripartite agreement concerning inventories or stock assessment were being met but more research was needed to answer specific questions of resource management. He praised the conference as being a step in the right direction and complimented all the participants for their excellent presentations. He said there is a need to check our course more often and called for more frequent interchange of ideas. Mr. Doyle Gates, the Administrator of the Enforcement Branch of NMFS in the western Pacific, recommended that another conference be held near the end of the tripartite and Sea Grant studies.

CONCLUDING REMARKS

John P. Craven

I'll be very brief. We've had two conferences. The first one ended at 1600 and the second one began at 1615 this afternoon. I can differentiate between these two conferences by alluding back to a story which I think I first heard in Sunday school. This afternoon I heard a brand new version of the story. In the Sunday school version as I recall it (taking some license of course) there were three wise blind scientists and because they were scientists they had a very delicate touch and when they felt the tail of the proverbial elephant they were sure that what they felt was a rope. Now that's the nature of research and the first conference we had was a conference which dealt with scientists trying to delicately measure all that of importance within the archipelago and I call this RESEARCH. The second conference we had was a conference which I will call ACTION: when people were sometimes pulling elephant's tails with the inevitable result. Now what is the relationship between these two conferences? The first conference met our expectations, the papers were logical, the evidence given was nondogmatic, data were collected empirically, and it was some of the finest science I've ever heard. I thought Jim Shaklee's paper was absolutely magnificent. And that does not detract from the rest but in terms of the opportunity to see, hear, understand, and appreciate good science--we've had it the last two days. And I was going to comment on future research plans but I don't think that's necessary now because it seems, to me, the research is headed in exactly the right direction.

But the second conference says a lot to the researcher. It says that any of you who thought that all action would wait until all of you had finished your research had better reassess the situation. What we have to do, of course, is continue our research, but continue it with the realization that actions are going to take place within the archipelago. Now this isn't necessarily bad. It's actually more the norm if you consider the likelihood of catastrophic events such as typhoons and hurricanes or even more normal storms occurring during the framework of time and space that much field research is conducted. The variability caused by such events can therefore be expected to be inherent with the data collected. Obviously, scientists are used to dealing with such natural variability. In fact scientists must exert special effort to be sure their data include such events so as to understand the dynamics of the systems under study. So I think that what you have to do as researchers is note the actions that take place so when events like 1,700 lobster traps are placed around an island in the archipelago, we are present and ready to measure the impacts. As researchers we have to be fast on our feet.

Now all of us are elephant touchers or tail pullers even though we may approach science with different missions in mind. There are those economically oriented or esthetically and environmentally oriented and I am not suggesting that as such, you do not carry out your responsibilities. In fact that is what it is all about and we are all action oriented. What I am asking that you do is the best possible science in the face of cataclysm, storm, tempest, fire, and foe. And not to rail against such actions but rather go out and gather your data so that it can be used to assess the significance of such possible impacts. And it seems to me that is the message that is here, and I would like to say it's been a fabulous two days. I hope to see it replicated not necessarily annually but as soon as the gathering of new information dictates. And I think we ought to preserve the nature of the research as nondogmatic, logical empiricism in its highest form continuing in the example you have provided at this symposium. Thank you.