ENHANCEMENT OF NATURAL POPULATIONS OF
MOI (POLYDACTYLUS SEXFILIS) IN HAWAII
THROUGH THE RELEASE OF HATCHERY-REARED JUVENILES—
A FEASIBILITY STUDY OF SEA RANCHING

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ABSTRACT

There has been a drastic decline in recent years in the commercial catches of moi (Polydactylus sexfilis) in Hawaii. Encouraged by the success of ranching of non-anadromous fishes in Japan, a study was undertaken to assess the feasibility of enhancing moi populations in Hawaii through the release of hatchery-reared juveniles. The life history and fishery of moi, and the hatchery production of juveniles are discussed from the viewpoint of possible artificial recruitment. Although the moi hatchery technology developed at the Hawaii Institute of Marine Biology is promising, larval survival rates presently achieved are considered too low to support a profitable juvenile-release program. Information is needed on the movements of moillii (juvenile moi) in order to determine the return rates of released juveniles. A general economic evaluation of a "model" moi ranching program indicates that a commercially viable moi enhancement program is possible if the rearing costs were brought down to 5¢ or less per juvenile, and if one million or more moillii could be released annually. This study recommends that, as a prerequisite for the eventual establishment of a moi ranching program in Hawaii, the present hatchery technology for moi should be perfected to achieve larval survival rates of at least 20% and that a tag-recapture study on moillii in the inshore waters be initiated to obtain reliable estimates of their return rates.
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1. INTRODUCTION

The traditional notion has been that the oceans are an inexhaustible source of food capable of meeting the nutritional needs of the growing human population. In recent years there has been a sober realization that the oceans are but a finite food source and that inspite of their immensity and apparent stability, the oceans are highly vulnerable to the deleterious human influence. Overfishing and pollution stand out as the most significant of the human activities influencing ocean harvests adversely. Unless regulated and abated, overfishing and pollution are likely to cause further declines in world fish catches.

It is very encouraging then, that aquaculture is emerging as an alternative method of producing food from the aquatic environment. With proper management, research and incentives, food production through aquaculture is expected to reach as much as 50 million metric tons by the year 2000 (Pillay, 1976).

The artificial enhancement of natural fish populations through the release of fry and juveniles raised in hatcheries is rightly considered as an important kind of aquaculture (Idyll, 1973). This approach would appear particularly useful in cases where the production of fry is relatively easy, but where high feed costs and space limitations make growout aquaculture economically infeasible.

While the economic efficiency of a fry-release program to augment wild stock remains to be demonstrated conclusively for many species (Idyll, 1973), it appears to have proven itself convincingly in the case of anadromous species such as Salmon, as evidenced by the so-called "salmon ranches"
proliferating along the Pacific Coast of North America and elsewhere (McNeil and Bailey, 1976). Japan for many years has released on a massive scale, hatchery-reared fry and juveniles of various non-anadromous fishes and shrimp to improve commercial catches; the results, although based on circumstantial evidence, are reportedly very encouraging (Hanamura, 1976).

Hawaii, by virtue of its oceanic location, is not endowed with a continental shelf which elsewhere generally supports much of the commercial fishery. Limited available land area and the scarcity of freshwater make any large scale inland fish culture impossible in Hawaii.

The Hawaiian moi or threadfin Polydactylus sexfilis (Cuvier and Valenciennes) is a commercially important fish that commands an excellent market price. Recent studies have shown that many aspects of its biology make it well-suited for aquaculture (May, 1976). Studies conducted at the Hawaii Institute of Marine Biology (HIMB) led to the successful spawning of moi in captivity and the rearing (on a limited scale) of larvae to the juvenile stage. Although pilot-scale growout culture of hatchery-reared moi juveniles to marketable size is being considered, it is uncertain at present if such an operation could be expanded into an economically worthwhile enterprise in view of high feed and labor costs and limited suitable areas for culture in Hawaii. We wanted to explore alternative methods by which the hatchery technology developed for moi at HIMB could be utilized effectively in improving the moi fishery in Hawaii, which has declined drastically in recent years (see State of Hawaii, Department of Land and Natural Resources, Division of Fish and Game, Commercial Fish Catch by Species, 1949-1975).

This study was undertaken to examine if moi catches could be enhanced
through artificial recruitment - i.e., through release of hatchery-reared juveniles into Hawaiian waters - and if such an operation would be economically profitable.

This report, following a brief review of the "state of the art" of sea ranching, examines the biology and fishery of moi from the view of artificial recruitment, discusses the progress of hatchery production of moi juveniles, and attempts an economic analysis of costs and benefits in a "model" moi ranching program.
2. THE CONCEPT OF SEA RANCHING

Terminology

"Sea ranching," "ocean ranching," "artificial recruitment" and "culture-based fishery" are some of the many terms in vogue to describe the method of releasing artificially raised fry and juveniles into natural waters and subsequently harvesting them as adults.

Ocean ranching is defined as "a method of aquaculture which involves the release of artificially propagated juvenile fish into marine waters to grow on natural foods to harvestable size" (McNeil and Bailey, 1975). Hanamura (1976) provides a broader definition of what he calls the "culture-based fishery": "production systems that consist of a series of combined processes such as production of artificially produced seed and fry, intermediate nursing and release of fry, protection and preservation of released fish into specific farmed areas and regulation of fishery and farmed resources."

Although more frequently used, the term "ocean ranching" has been recommended by some to apply specifically to anadromous species such as Salmon which, because of their migratory behavior, have a built-in mechanism which facilitates capture by bringing them back to the place where they were released.

Theory

It has long been recognized that many aquatic animals generally pass through a critical period in the early stages of their life history when chances of their survival are minimal. In fishes, a multitude of biotic
and abiotic environmental factors are known to cause heavy mortalities among the embryonic and larval stages, and studies have shown that in the ocean 99.99% or more of the offspring of many species die before the end of the larval stage (May, 1974). It may therefore be argued that any human activity that protects and nurses the vulnerable embryos and fry till they pass the critical stage in their life, should theoretically enhance the abundance of potential adults which subsequently contribute to the commercial fishery, provided the food required by the growing juveniles is not limiting in the environment.

From the viewpoint of commercial fisheries based on and resulting from the culture and release of juvenile fish, this method offers two important advantages (Hanamura, 1976):

1. The maximum sustainable yield in any fishery is known to be influenced by "recruitment" (Cushing, 1975). So much so, an improvement in any or all of the sequential phases in the biotic production of recruits can be expected to increase the maximum sustainable yield. A comparison of the theoretical maximum sustainable yield in conventional fisheries with that in culture-based fisheries is illustrated in Figure 1.

Because it is possible to reduce mortality of fish eggs, fry and juveniles under the controlled environment of a hatchery, the number of recruits per unit spawner can be several times larger than observed in the wild (Figure 2). The egg-to-fry stage survival in the Pacific salmon which in nature rarely exceeds 20%, can be, and is routinely raised to as high as 90% in salmon hatcheries (McNeil and Bailey, 1976).

Inasmuch as the number of recruits produced per spawner is substantially higher in a culture-based fishery, the number of adult spawners needed to
Figure 1. Theoretical reproduction curves for fisheries based on natural populations (A) and on artificial enhancement (B). Note the greater maximum sustainable yield (MSY) possible, and smaller optimum spawning population (OSP) needed, in culture-based fisheries (B) (adopted from Hanamura, 1976).
Figure 2. Survival curves during the egg–juvenile period in the natural environment and in culture-based fisheries (adopted from Hanamura, 1976).
maintain a stable population can also be kept to a minimum. In the traditional salmon fisheries, only 50-70% of the returning adults are captured, the remaining being allowed to enter streams and spawn. In Japan, where millions of hatchery-reared salmon juveniles are released annually, only 10% of the adults are needed to maintain a stable population, thereby allowing a significantly greater harvest of salmon (Hanamura, 1976).

2. Through the artificial enhancement of juvenile fish populations in the sea, it is possible to exploit indirectly the basic productivity of phytoplankton, zooplankton and benthos (upon which the larval and juvenile fishes feed) which are not otherwise harvested directly.

As in any human activity dealing with the natural environment, there are certain negative aspects of ocean ranching the impact of which should be assessed before any large-scale release programs are undertaken.

One important question is whether the productivity of a given oceanic or coastal zone is able to support larger fish populations resulting from a juvenile release program. This question could only be answered on a regional basis to be really meaningful. Nevertheless, reliable estimates indicate that the present total harvest represents only about a third of the total natural production in coastal waters, and that the oceans can support at least twice the present commercial harvest (Ryther, 1968; Mayo, 1975). The average annual commercial catches of moi in Hawaiian waters during recent years have dwindled to less than one-tenth of the record catches of the 1930's (see p. 21). If it is true that the moi fishing effort has not declined drastically and that the overall biotic and abiotic factors remained essentially unaltered, the Hawaiian waters may be able to support substantially greater quantities of moi than are currently harvested.
The second environmental question concerns the possible effects of supplementing wild stocks by releasing hatchery-reared juveniles on the structure of natural marine communities in a given area. No reliable information is available to assess the environmental impact of such "ranching" operations. In cases where the released juveniles tend to spread far and wide in the oceans, as in salmon, the impact could conceivably be minimal. On the other hand, the situation may be different in the case of non-anadromous species such as moi which tend to remain in the coastal waters. Critical studies need to be done to evaluate the effects. However, insofar as the hatchery-reared fish merely make up for the effects of overfishing or other unnatural causes of decline in moi populations, or compensate for low points in natural fluctuations in recruitment, the addition of these juvenile fish to Hawaiian inshore waters would not be expected to have an adverse environmental effect.
3. A REVIEW OF RANCHING OF SALMON AND OTHER SPECIES

Anadromous Species

Of the hundred and odd anadromous fish species known (Calaprice, 1976), nearly all are of economic importance and contribute substantially to fish harvests in different regions of the world. These species, by virtue of their predictable migratory patterns, lend themselves ideally to "population enhancement" by artificial recruitment or sea ranching. Anadromous fishes spawn in fresh water rivers and streams, where the eggs hatch. The larvae, depending on the species, spend varying periods of time in fresh water and then migrate to the open ocean. The fish, feeding on the vast food resources of the ocean "ranges," grow to maturity and return to their ancestral fresh water bodies for spawning.

Among the anadromous fishes whose fishery potential has been enhanced through artificial recruitment, salmon has a long history of measurable success, dating back a century or more in the Scandinavian countries, Japan, U.S.A., and Russia. The Pacific salmon (Oncorhynchus sp.) alone accounts for more than 90% of the nearly 2,000 million anadromous fish juveniles reared artificially and released into natural waters every year (McNeil, 1976).

The drastic decline in salmon catches during the early part of the century has been attributed to overfishing, water pollution and the general degradation of the spawning habitats of the salmon (McNeil, 1976). The persistent decline of salmon catches during subsequent years, quite probably caused by the same factors, provided the impetus for concentrated efforts to augment salmon stocks by artificial means. The outcome was the establishment of a number of salmon hatcheries along the Pacific coast of North America.
and elsewhere, which produced millions of salmon juveniles for release into natural waters.

The criteria which make salmon the most attractive candidate for ocean ranching are: 1) the adults return to freshwater streams to spawn where the most vulnerable stages - the eggs and larvae, could be better protected by regulatory measures and enhanced by artificial means, than in the open ocean; 2) their unique homing behavior during the spawning migration, besides providing extremely reliable release-return data for cost assessment, acts as a "herding" mechanism and also facilitates the selection of release sites which would be logistically ideal fishing sites when the adults return to spawn, and 3) through many years of research and development the salmon hatchery technology is perfected to the extent that the benefit/cost ratio is maximized in ranching operations.

It is during the egg-fry stages in the salmon life history that heavy mortalities, up to 80%, occur (McNeil and Bailey, 1976). By artificially rearing juveniles under controlled conditions of the hatcheries where survival rates of more than 90% are possible, and releasing them into the ocean, it is possible to harvest up to 30% more of the returning adult salmon than if the population abundance depended on natural recruitment alone (Hanamura, 1976) (see Fig. 1).

A dramatic illustration of the effects of "seeding" on salmon fishery in Japan is shown in Figure 3 and compared to that in Alaska where no seeding programs existed until recently (McNeil, 1976).
Figure 3. Trends in Pacific salmon catches during 1940-1972 in Alaska and Hokkaido, Japan. Significant improvement in salmon catches in Hokkaido in recent years are attributed to artificial recruitment (adopted from McNeil and Bailey, 1975).
Vast improvement of the chum salmon (*Oncorhynchus keta*) fishery in Japan in recent years is attributed to an intensified fry-seeding program; 500-800 million salmon fry reared artificially are released annually into the northern rivers of Japan with an estimated return rate of 2% (range: 0.5-3.5%) (Hanamura, 1976; Kobayashi, 1976).

Prior to 1960, salmon fry used to be released into natural waters almost soon after hatching. This procedure may have contributed to a loss of 70-80% of the released fry before they reached the sea. Subsequently, the fry were retained in the hatcheries for up to four weeks, fed and then released. The beneficial effects of the delayed release were reflected in the salmon catches in subsequent years (Hanamura, 1976).

Delayed release of salmon fry appears to offer other advantages as well, in terms of fishery management. It was discovered, for example, that Coho and Chinook salmon released later than usual in the Puget Sound area (Washington State), stayed in the same area rather than migrating offshore, thus remaining available to sport fisherman (Moring, 1976). Tag recoveries also showed that Coho salmon delayed 90 days at hatchery before release contributed 60 times more to the 1971 Puget Sound fishery than Coho released at normal time (Moring, 1976).

The returns in many salmon ranching operations have been extremely encouraging. In the North Pacific, more than 30% of the 67,000 tons of Coho and Chinook salmon caught in 1970 were attributed to hatchery-reared and released fish (Mayo, 1975). The return ratios (by weight) of Coho salmon in Lake Michigan have been as high as 32:1 (Mayo, 1975).
Salmon has also been suggested as a suitable species for international ventures in ocean ranching on a global basis. Joyner (1975, 1976) proposed a scheme, whose economic feasibility is under study, for indirectly utilizing the untapped krill (Euphausia sp.) in the Antarctic waters. He suggests that fry of the Arctic races of chum, pink and sockeye salmon reared in the coastal fresh water bodies of Chile and Argentina could be released into the southern ocean. The juvenile salmon, taking advantage of the West Wind Drift, would move to the region of the Antarctic Convergence where the krill abound. Mature salmon returning to the coast of South America where they were originally released, would form a viable commercial fishery.

Economic analyses made by the National Marine Fisheries Service for salmon ranching from the Columbia River Basin hatcheries show the benefit/cost ratio to be 7:1, although a more realistic estimate, taking into account the cost of catching fish, gear inefficiency, inflation and other factors, appears to be a ratio of 1.5:1 (Mayo, 1975). No detailed economic analyses are available for salmon ranching in Japan, but a gross estimate puts the benefit/cost ratio at 20:1 (Hanamura, 1976).

Compared to the Pacific salmon (Oncorhynchus), the Atlantic salmon (Salmo sp.) has not responded well to enhancement measures by artificial recruitment.

The sturgeon (Acipenser and Huso) is another anadromous fish the fishery of which has been dramatically augmented by hatchery releases in Russia and Iran. Russia releases nearly 100 million juvenile sturgeon annually into natural waters (McNeil, 1976).
Non-anadromous Species

A realistic assessment of the economic benefits of "seeding" non-anadromous species is hampered by the lack of reliable release-return statistics. The absence of predictable homing migrations during spawning in these species renders it extremely difficult and expensive to gather such data. Japan is one of the very few countries where for the last few years, artificial recruitment of non-anadromous species has been carried out on a massive scale; the results, because of the limitations mentioned above, are speculative at best.

The fry of sweet-fish (Plecoglossus), red seabream (Sparus major), kuruma shrimp (Penaeus japonicus), and various shellfish species are released annually into Japanese waters with some encouraging results. Subsequent to the prawn seedling release (to the tune of 120-156 million fry annually), prawn catches in the Inland Sea reportedly improved from 500 tons to 1,000 tons per year (Japan Fisheries Association, 1974). However, in all these cases, the cause-effect relation remains inconclusive.

Not all the artificial recruitment programs in Japan were successful. Despite the release of millions of artificially raised fry every year to abate and augment the drastically declining herring and sardine fisheries, the situation has not improved (Hanamura, 1976). The same appears to be the fate of artificial recruitment methods to improve the cod and flounder fisheries in North Japan.

Inasmuch as moi is a non-anadromous fish, it would be extremely useful in formulating a realistic program for moi enhancement in Hawaii, if more information were available on the technological and economic aspects of the artificial recruitment program for non-anadromous species currently in operation in Japan.
4. MOI: BIOLOGY AND FISHERY

Life History

Information reported here on the life history of moi, *Polydactylus sexfilis*, is gathered from Lowell (1971), Kanayama (1973), May et al. (1975), and May (1976).

Adult moi inhabit surf zones, reef faces, shoreline caves (so-called "moi holes") and mud-sand areas in the waters of all Hawaiian Islands. The fish is essentially a bottom feeder, fishes (predominantly holocentrids and labrids) and crustaceans (crabs and shrimp) comprising its primary diet.

Moi are protandric hermaphrodites. The juveniles first develop into males. As they grow older (22-40 cm size) the ovarian tissue starts out as a thin layer on the ventral side of the testes and gradually replaces the testicular tissue. During the sexual transformation period the fish are hermaphroditic, their gonads being represented by a pair of ovotestes. Self-fertilization, however, is impossible inasmuch as only the testicular component is functional in the hermaphrodites. Sex transformation is initiated probably during March - September period and completed during November - May period. Thus, the duration of the hermaphroditic stage in moi appears to be about eight months. As the hermaphrodites grow larger, they change to females, individuals larger than 36 cm being generally female.

Studies on the egg maturation cycle and observations on mature fish in captivity indicate a protracted spawning period in this species, probably April or May through October, with peak spawning during July - August period.
The fish spawn at four-week intervals with highly predictable regularity. Maximum spawning activity over a period of 3-7 nights around the last quarter of the moon suggests the existence of a well-defined lunar spawning rhythm. The number of eggs released at each spawning has been estimated to be 150,000 to 200,000 eggs.

Moi eggs, which measure approximately 0.8 mm in diameter when released into water, are pelagic and hatch in 14-24 h depending upon the water temperature. Neither the developing eggs nor the newly hatched larvae have ever been captured in inshore waters. It is conceivable that soon after spawning the eggs are carried away into offshore waters by the prevailing tides in conjunction with the lunar spawning rhythmicity, but the ecological significance of such transport is not clearly understood. Dispersal into new habitats and escape from inshore predation are suggested as possible advantages.

The newly hatched larvae exhaust their yolk reserves in 2-3 days and then commence feeding on zooplankton. Sporadic capture of young juveniles (<50 mm) offshore indicate that they inhabit oceanic waters and that they are size-selective predators feeding on zooplankton (mainly mysids, euphausiids, crab zoeae, amphipods, etc.). The juveniles return soon after to the inshore environment. The inshore juveniles, called "moilii" locally, attain a size of more than 90 mm. The return of the juveniles from the offshore to the inshore environment is marked by a change in body coloration from the offshore striped pattern to the usual silvery grey adult coloration, and also by a change in diet. The inshore moilii are usually opportunistic benthic feeders with crustaceans dominating their food. The moilii inhabit the
breaker zone and shallow sandy areas. By the end of the first year they grow to 22-23 cm (fork length) size at which stage they are ready to function as mature males. Functional males measuring 18 cm have also been reported. Sex transformation appears to be initiated sometime during the second year of the moi's life.

Movements

In any sea ranching operation there is a justified need to substantiate the basic assumption that a certain portion of the released juveniles eventually return as adults and contribute to the fishery in the region of original release. This is not difficult in the case of anadromous species such as salmon which as adults migrate back to the releasing site, but a conclusive demonstration is not accomplished easily for non-anadromous species, a fact which led Idyll (1973) to question the practicality of releasing hatchery-reared juveniles to augment natural stocks. The recent Japanese efforts with the artificial recruitment of non-anadromous species, nevertheless, have been promising enough to provide the impetus for the present study.

A thorough understanding of the movements of moi, a non-anadromous fish, in its larval, juvenile and adult phases in the Hawaiian waters is essential not only to estimate the extent of availability of the released fish to the fishermen but also to determine the potential sites for releasing the hatchery-reared moiili.

No information is available on the movements of the moi larvae. Developing eggs or newly hatched larvae have never been collected, although the fish is known to spawn in inshore waters. It is believed that the
developing eggs and larvae are transported offshore where they grow until their inshore return. The significance and the mechanism of the offshore transport of moi larvae are yet to be elucidated. Certain oceanic current eddies and gyres originating off promontories around the Hawaiian Islands have been suggested as a possible mechanism for the offshore transport and inshore return of many reef larvae (Sale, 1970; Leis and Miller, 1976). It is entirely possible that moi larvae are transported similarly. The possibility that year-to-year fluctuations in moilii recruitment in the inshore waters are correlated with similar fluctuations in the prevailing oceanic current patterns, lends credence to this hypothesis.

Extensive tagging experiments were conducted during 1962-1968 by the Division of Fish and Game, State of Hawaii, to understand the growth and movements of moilii (Kanayama and Morris, 1965; Kanayama, 1973). During 1964-68, nearly 3,500 juveniles ranging from 80 to 150 mm in fork length were tagged, using initially a dart tag and later a modified internal anchor tag. Tagging mortality and tag losses were high (approximately 30%). The internal anchor tag used may not have been the most suitable tag for juvenile moi. More recently available tags such as the nose wire tag now being used extensively for salmon fingerlings, and perhaps certain biochemical markers should be tested on moilii in future tagging experiments, for the selection of a tag which causes the least mortality and best recoverability is essential for a successful study of the moilii and moi movements.

The tag recovery rates in the tests by Kanayama and Morris were poor, at least not high enough to provide the needed information. The few recoveries they got were at or near the site of release, the farthest being 20 miles away, caught 173 days after release.
20.

Thus, the limited evidence available suggests that moilii movements are fairly restricted. Discussions with fishermen also suggest that schools of adult moi move but little. There is a need for more information, nevertheless, to help plan an effective moi ranching program in the future.

**Fishery**

Although moi contributes substantially to the commercial fishery in Hawaii, there is at present no exclusive fishery for moi. The bulk of the moi catches landed annually are incidental to akule (*Trachurops crumenophthalmus*) which are caught with "akule nets" (an encircling seine with a bag attached to it). Akule as well as moi are often located with the help of spotters in aircraft. One spotter informed me that a good-sized school of moi adults (up to 5,000 lbs) can be spotted from an altitude of 2,000 ft. without difficulty.

Moi are also caught by sport/fishermen who use gill nets, throw nets and pole and line. They are captured generally throughout the year, the majority of the catches being landed during the May - August period. Kanayama (1973) provided a detailed analysis of moi fishery statistics for the 1948-68 period in Hawaiian waters.

Yearly catches of moi for the last 25 years have been compiled by the State Fish and Game Department (Figure 4). Inasmuch as not all commercial catches of moi are reported by fishermen to the government agencies, and as catches taken by sport fishermen are not included, the official figures of moi landings shown here can be considered to be significantly lower than the actual landings. One reliable fishermen informed me that he netted nearly 3,000 lbs of moi in one operation in 1975, and yet the State statistics show total moi catches in 1975 to be only 1,987 lbs.
Figure 4. Commercial moi catches in Hawaii during 1948-75 and their relation to the market value of moi.
No information is available on the magnitude of moi catches by sportfishermen who are not required by law to report their catches. Enquiries revealed, and the State authorities agree, that the annual moi landings by sportfishermen are probably at least as high as the commercial catches.

Whereas the accuracy of the reported moi landings remains questionable, the continued declining trend in moi catches in Hawaii is undisputed. Among the various possible explanations for this decline, a decline in fishing effort might be considered first. Unfortunately no data are available on the commercial fishing efforts specifically directed to moi. If the total number of fishermen in Hawaii is any reflection of the fishing effort at all, the latter can be readily ruled out as a possible explanation. The number of licensed fishermen in Hawaii (which includes both commercial fishermen and sportfishermen) has in fact been increasing in recent years (Figure 5).

It is therefore possible that the decline in catch is related to a decline in the Hawaiian moi population, which could have been brought about by indiscriminate capture of moilii (juvenile moi), pollution and other factors. Many of the State Fish and Game authorities and commercial and sportfishermen I interviewed firmly believed that excessive and indiscriminate capture of juveniles is the most important cause for the decline of moi catches.

Since 1958, the State of Hawaii has adopted various regulatory measures to protect and manage moi resources with varying degrees of success. The pertinent regulations currently in effect in the State of Hawaii are: 1) no more than 50 moilii (moi smaller than 7 inches) may be captured or possessed by one person per day; 2) on the island of Oahu, the bag limit is only 15 moi per person per day; 3) moi may not be captured by using nets with mesh size
Figure 5. Relation between commercial moi catches and the number of licensed fishermen in Hawaii during 1960-75.
smaller than two inches, and 4) moi less than 7 inches in length may not be
speared or sold, and no speared moi may be sold. Because of enforcement
problems, these regulations appear to be respected more in their breach
than in their observance.

Kanayama (1973), based on a review of the biology and fishery of moi,
recommended that the peak breeding season of moi (June - August) be closed
to commercial and sport fishing in order to help replace the stocks. He
also recommended that the minimum size of moi that can be sold in the market be
raised from the present legal limit of 7 inches (total length) to a size
of 12 inches (total length). But Kanayama's recommendations apparently have
not so far received the State's endorsement, as no such regulations are on
the books.

Evidence from State catch records, interviews with fishermen, and our own
moili catch records show that year-to-year fluctuations in the abundance of
both adult and juvenile moi are sometimes considerable. The causative
factors remain unknown, but in view of the long offshore pelagic stage through
which larvae and juveniles of moi pass before migrating to shallow inshore
areas (see page 17), it is possible that year-to-year variations in
oceanic currents around the Hawaiian archipelago result in variations in the
numbers of fish which make it back to shore, thus giving rise to the observed
fluctuations in the abundance of moili and moi.

A moili release program, if practicable, might function as a means of
maintaining moi populations at a level close to the carrying capacity of the
environment during years of poor recruitment and offsetting losses due to the
unchecked, indiscriminate capture of moili.
Although some work on the life history of the moi was done in earlier years (Kanayama, 1973; Lowell, 1972), it was only in 1973 that research specifically oriented to the exploration of the aquaculture potential of this species in Hawaii was initiated at HIMB. The selection of moi as an aquaculture candidate was based primarily on its importance in local commercial and sport fisheries, and its high market value.

The production of fry, young animals which can be released to augment natural stocks, or grown to marketable size, is a critical step in any successful aquacultural undertaking (Bardach, Ryther and McLarney, 1972). For this reason, the initial efforts at HIMB were focused on the spawning and larval rearing of moi under artificial conditions. Development of this phase of the work is described below in detail.

A. Hormone-induced Spawning: Prior to the discovery that moi spawn spontaneously in net enclosures during the normal spawning season, a few attempts were made during 1973 to artificially induce spawning of moi by injecting hormones (chiefly human chorionic gonadotropin [HCG]), with limited success. Although hydration and ovulation were accomplished, the percentage fertilization was very low (maximum: 32%). The number of eggs obtained from induced spawning was also low. Obviously, more experiments on hormone-induced spawning would be needed to establish the optimal dosage and time sequence for the administration of hormones. It would also be desirable to conduct further experiments to understand the temperature and photoperiod (hatchery) conditions, so that the natural six-month spawning season might be extended. The effect of artificial
lunar cycles on laboratory-held spawners could also be examined to explore the feasibility of inducing year-round spawning in the laboratory by a manipulation of certain environmental parameters. If not, hormone-induced spawning (see above) would have to be perfected for extended hatchery production.

It should be noted here, however, that the natural spawning season of the moi is six months long, a duration generally quite sufficient to support a commercial-scale aquaculture program. By comparison, salmon, which are the only truly ranched species at present, have a natural spawning season of limited duration, four to six weeks.

B. Natural Spawning: The fact that the moi spawn spontaneously (without hormonal inducement) in net enclosures made it possible to collect moi eggs during the spawning season with relative ease. The fish spawn with predictable regularity during the last quarter of the moon every month during the May - October period. Generally, 30-40 fish, males and females in the ratio of 2:1, are contained in large floating net enclosures. The eggs released and fertilized in these enclosures are collected continuously using an air-lift pump (May et al., 1976). Since 1976, moi eggs used for experimental work have been obtained exclusively by this method. Of the large number of pelagic eggs released by each female (70,000 to 500,000, Kanayama, 1973; May, pers. comm.) an estimated 71-90% are lost through the net by turbulence and diffusion (May et al., 1976). This is another reason why spawning under controlled laboratory conditions should be considered for a greater yield of fertilized eggs. Transferring fish to a fine-mesh spawning net or "hapa" prior to the predicted time of spawning is now being considered as a means of improving egg collection efficiency.
The fertilizer eggs are transferred to circular tanks (3.05 m diameter) containing normal sea water. Gentle aeration is provided continuously while the egg develop. They hatch in about 24 h, the incubation period being related to water temperature (Santerre and May, in press). Up to 90% hatch successfully by this method.

C. Larval Rearing: As the larvae exhaust their yolk reserves (2-3 days), they are provided their first live food, rotifers (Brachionus plicatilis) ideally at a density of 5-20/ml. After about two weeks, Artemia nauplii can be fed to the larvae, and beginning about a month after hatching, the young fish will consume non-living foods such as macerated fish flesh and dried crustacean meal.

Survival rates from hatching to yolk absorption are generally high, but high mortalities occur during the feeding stages of larval development. In addition, as the larvae or juveniles switch from live food to non-living foods, high mortality has occasionally been observed, and evidence of nutritional deficiencies sometimes appear after metamorphosis. During the past three years, not more than 5% of the newly hatched larvae in the experimental hatchery at HIMB were able to reach the juvenile stage.

D. Technical Problems in Larval Rearing: A major bottleneck in efforts to improve larval survival of moi seems to be the inadequacy of the present rotifer culture to meet the food demands of the growing larvae. The abundance of rotifers is dependent upon its food supply, the alga, Chlorella sp. While this alga is extremely easy to culture indoors on a laboratory scale, large-scale outdoor cultures of Chlorella at the experimental hatchery on Coconut Island have been subject to persistent contamination by dinoflagellates which destroy the Chlorella population, making mass rotifer culture extremely difficult.
if not impossible. There is clearly a vital need to perfect the Chlorella-
rotifer culture system so that large quantities of larval food could be produced.

The present dependence on rotifers and *Artemia* for larval food could be
relieved if artificial, dry diets could be formulated that moi larvae would
accept and thrive upon. A hatchery where larvae could be grown using artificial
foods would be assured of a constant and abundant supply of food and, hence,
 improved larval survival. A project has been proposed to formulate an artificial
food of appropriate particle size using ingredients such as euphausiid meal and
test it on moi larvae for acceptability, digestibility and nutritional adequacy.

Since such non-living foods, if uneaten, tend to accumulate and decay, the
water-fouling characteristics of such foods and necessary counteracting
measures (such as changes in tank design) should also be investigated.

Although the major portion of larval mortality of moi in rearing trials
conducted so far is attributable to the quantitative inadequacies in larval
food production, the qualitative aspects of the larval and juvenile nutrition
seem to be equally important. The nutritional deficiency syndromes noticed
occasionally in the present culture system after weaning from living to
nonliving foods suggest that much needs to be learned about the nutritional
requirements of older larvae and juveniles. If the desired release size for
moi is taken to be about 70 mm fork length, the size at which the "moilii"
enter the inshore waters, the period between weaning from living foods to release
would last about two months (from the age of 30 days to 90 days). During this
period, a qualitatively adequate and economical diet needs to be available.
Further work should be conducted to elucidate the nutritional requirements of
the juvenile moi, so balanced artificial foods could be prepared using
locally available ingredients.
Diseases have fortunately not posed a serious problem in moi hatchery operations at HIMB. Incidence of diseases caused by microbial infection is minimized by incubating moi eggs in large circular tanks with an enormous water volume compared to the volume of the eggs incubated. The sizable mortalities which have occurred during the growth of the larvae are attributed to nutritional deficiencies rather than to microbial infections.

If the major problem of larval rearing, which seems to be related almost exclusively to nutrition, can be solved, previous rearing attempts with moi and other species suggest that the achievement of 20% survival from the egg to the juvenile stage is within the realm of possibility.
6. ECONOMIC ANALYSIS

Investment in any large-scale aquacultural enterprise is generally subject to a thorough analysis of the profitability of the operation. In growout aquaculture, where fry produced in hatcheries are grown in ponds and other holding facilities to marketable size, fairly detailed tables of costs and returns are available for such widely farmed species as catfish, carp, Malaysian prawn and trout (Bardach, Ryther and McLarney, 1972). Sea ranching as a profit-oriented enterprise is relatively recent, and as such not much published information is available on its economics. For salmon, it has been shown (Mayo, 1975; Mathews et al., 1976) that sea ranching is more efficient and profitable than pen-culture. Although Japan has been carrying on artificial enhancement for various non-anadromous species, no published data are available on the economics of hatchery production and release and of the fishery resulting from it. It is claimed, nevertheless, (Japan Fishing Association, 1974; Hanamura, 1976) that the returns are quite encouraging in many cases.

Attempts to analyze the economic efficiency of a proposed moi ranching program are difficult because there is at present no commercial moi hatchery in operation, either in Hawaii or anywhere else in the world; nor is there a moi fishery that is the direct result of a juvenile-release effort. The account presented here is therefore of a model moi ranching program, a model whose variables and their ranges are selected to be as applicable to moi as possible, given the present state of knowledge. It is hoped that this analysis will define the requirements that should be met and goals that should be achieved before a commercially viable moi ranching program could be launched.
The costs in a sea ranching operation include rearing costs from the egg to a juvenile stage suitable for release and any costs involved in harvesting the adults. The benefits include money obtained by the sale of adult fish captured subsequently. The benefit/cost (B/C) ratio is calculated using the following formula:

\[
B/C = \frac{N \times R \times W \times P}{C}
\]

where
\(N\) = number of juveniles released
\(R\) = proportion of \(N\) returning to the fishery
\(W\) = weight of individual fish at capture (lb)
\(P\) = local market price of fish ($/lb)
\(C\) = cost of raising \(N\) juveniles ($)

(The cost of harvesting returning fish is excluded in the present analysis.)

1. Rearing Costs

Since there is no commercial or even pilot-scale moi hatchery in operation now, no exact figures on rearing costs are available. Any cost estimates calculated from the experimental hatchery at HIMB would be entirely unrealistic. I considered the figures available for other farmed species to select an appropriate range of rearing costs for moi. The rearing costs in catfish culture are reported to be 4 to 6 ¢ per fingerling, depending on the size of fingerlings suitable for stocking (Brown et al., 1969; Garner and Halbrook, 1972). In general, rearing catfish fingerlings appears to cost about 1¢ per every inch, 6 to 8 inches being the most recommended fingerling size for stocking (Meyer et al., 1973). Salmon hatcheries on the Columbia River are able to raise fry at 1.6¢ per
individual (Mayo, 1975). The rearing costs for mullet, a fish of marine and brackish water habitats, and hence particularly relevant to moi production, may be $0.05 to $0.10/fry when a large-scale mullet hatchery goes into operation in Hawaii (C. E. Nash, pers. comm.).

I chose three levels of rearing costs, 2¢, 5¢, and 10¢ per juvenile moi for an assumed annual production of 100,000 juveniles. Reduction in costs depends on perfecting hatchery technology and management. An assumption is also made that rearing cost per juvenile will be lower at increased levels of production due to economies of scale. Accordingly, rearing costs were lowered proportionately at production levels of one and two million juveniles.

2. Magnitude of Production

The fecundity and spawning frequency of the farmed fish, larval survival rates and the physical size of the hatchery are the most important factors governing juvenile production in a hatchery. For moi, fecundity is not a limiting factor, each female being able to produce 100,000 or more eggs at each spawning. The fish spawn about six times during the spawning season (May - October). The natural six-month spawning season is relatively long compared to many other cultured species and presents no major problems. The optimal, initial stocking densities for marine fish larvae vary according to the species (Girin, 1975). The initial density for moi larvae is not determined, but a figure of five larvae/liter seems not unreasonable, based on results for other species (it should be noted, however, that experimental rearing of larval moi has thus far been conducted at slightly lower initial densities). Assuming a larval survival rate of 20% - which is considered feasible, though not yet attained - production of one juvenile/liter would
be possible. A modest-sized hatchery with ten rearing tanks (each of 15,000 L capacity) may thus be capable of producing nearly one million fry annually (15,000 larvae per tank x 10 tanks x 6 spawnings), provided larval survival rates of at least 20% are achieved. The 2-5% larval survival currently obtained at HIMB would be inadequate for any commercial ventures. With such low survival, not only would a giant hatchery with nearly 100 rearing tanks be needed (to produce one million fry), but analysis indicates that the production costs would far outweigh any sea ranching benefits. Clearly, the improvement of larval survival in moi culture is a vital prerequisite to any release program in the future.

The production of moi juveniles is a two-stage operation involving the rearing of larvae to metamorphosis and then growing them to a juvenile stage suitable for release. The most suitable size for release of moi is not known; however, if it is assumed to be the smallest size at which moilii are seen in shallow, inshore waters, i.e., about 60 mm standard length (Lowell, 1971), such fish would be about 90 days old, having transformed into juveniles at about day 45 (data from tank-reared specimens, R. C. May, pers. comm.). The second stage of rearing would therefore take approximately 45 days but could no doubt be shortened by using higher temperatures and better diets.

For the present analysis, three levels of hatchery production were chosen - 100,000, 1,000,000, and 2,000,000 juveniles per year.

3. Return Rate

The magnitude of the release of juveniles necessary to effect a significant increase in the moi catch would depend on the return rate, i.e., percentage of
released juveniles captured subsequently as adults. Tagging of juveniles to be released and the subsequent enumeration of tagged fish in commercial catches is probably the most reliable method of determining the return rate. More information is also needed on the movements of juvenile moi in Hawaiian waters to determine the extent of their availability to Hawaiian fishermen.

Return rates are determined easily and reliably for anadromous species because of their migration to their home streams for breeding. The returns in salmon ranching are reported generally to be 1-3% (Mayo, 1975; Hanamura, 1976). Small as the percentage might seem, it refers to numbers only; by weight, the returns are highly impressive. The returns for non-anadromous species are believed to be generally of similar magnitude. Hanamura (1976) quoted 0.1-5% as the return rate for Kuruma shrimp in the Inland Sea of Japan.

Three return rates—1, 3, and 5% are chosen for the present economic analysis. An assumption is also made that the return rates are proportional to release at all levels of release.

4. Weight of Moi at Capture

Moi caught and sold in local fish markets range from 0.5 to 1.5 lb in weight, although fish weighing more than 2 lbs are captured occasionally. Through appropriate State legislation it might be possible to raise the minimum weight of moi for capture, thereby allowing moi to grow to a larger size in the wild before being caught. Three weight levels—0.5, 1.0, and 1.5 lb are chosen for this analysis.

5. Market Price

Like many commodities, the price of moi in the market fluctuates widely, being subject to the law of supply and demand. Based on periodic inquiries,
three price levels - $1.00, 1.50, and 2.00 were chosen. These prices are wholesale prices, retail prices being considerably higher.

The benefit/cost (B/C) ratios for the moi ranching model at various levels of the parameters chosen are given in Table I. The values range from 0.05 to a maximum of 12.5. It may be noted here that in contrast to many benefit/cost evaluations in fish farming or ranching, the figures here do not include the cost of harvesting the returning adults. When the assumed return rate is 1% and the rearing cost 5-10¢ per juvenile, the B/C values are virtually all below 1.0 at all production levels and at the highest chosen weight at capture and market value, indicating economic loss. The profitability of the operation improves rapidly, however, as the return rates are increased to 3 and 5%. Considering that the return rates for the anadromous salmon have ordinarily been no more than 1-2% (Mayo, 1975), the assumption of 3-5% return rates for the non-anadromous moi may not appear very realistic. On the other hand, it might be argued that such high return rates are indeed possible for moi since, unlike salmon which migrate great distances in the open ocean, the released fish would confine themselves to the Hawaiian inshore waters and hence be more likely to be captured by the local fishermen. Unfortunately, tag-recapture studies on moili by the State Fish and Game biologists (see p. 18) have not yielded any conclusive figures for the return rates of moi.

The B/C value for Coho and Chinook salmon ranching from the Columbia River Basin hatcheries (where rearing cost was 1.6¢ per fingerling, and the return rate 0.97%) was 1.5 (Mayo, 1975). For comparison, some B/C values in growout aquaculture are: 1.13 in catfish farming, where the rearing costs were 5¢/fingerling and the "return rate" up to 75% (Meyer et al., 1973), and 1.18
Table I

Benefit/cost (B/C) ratios in a model moi ranching operation at various levels of magnitude of release, rearing costs, return rate, weight at capture, and market value.

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<th>Weight at Capture (lb) (W)</th>
<th>Rearing Costs ($) (C)</th>
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in milkfish farming in Taiwan (larvae not reared in hatcheries but caught in the wild) (Shang, 1976). Thus, it appears that the B/C values in many well-established, successful fish farming enterprises are generally not more than 1.5. In the proposed moi ranching then, even a 1% return rate might be acceptable, if the rearing costs are brought down to 5¢ or less per juvenile, and if a million or more juveniles could be released annually, with minimum weight at capture and minimum value set at 1.5 lb and $2.00/lb, respectively. It must be reiterated here that substantial reduction in rearing costs to make a release program economically feasible would be possible only if larval survival rates of 20% or more are achieved and if the post-metamorphosis fish could be reared to a size suitable for release on economical feeds.

The foregoing discussion of the B/C values in the proposed moi ranching operation was focused on the potential economic benefits as they related to the commercial moi fishery. But equally important are the benefits to sport fishing, which as stated earlier, probably accounts for at least half of the total moi landings in Hawaii. Inasmuch as the sport fisherman do not sell their catches, "market price" perhaps is not an appropriate yardstick to measure the benefits of moi ranching to the Hawaiian sport fisherman. Furthermore, criteria such as moi size at capture (beyond a certain minimum size) may be irrelevant insofar as the sport fishing is concerned.

If conceived as the total economic benefit to the State, the value of the proposed program could include the rather intangible benefits of providing recreation to the people of Hawaii and the not-so-intangible benefits of attracting more sport fishing tourists (Hoffman and Yamauchi, 1973). Thus, considered in a broad economic perspective, the proposed moi ranching program would perhaps be justified in spite of low return rates, high hatchery production costs and seemingly poor B/C values.
7. CONCLUSIONS AND RECOMMENDATIONS

A critical examination of the theoretical aspects of the concept of population enhancement by artificial recruitment, the enormous success of salmon ranching on the Pacific coast of North America and Japan, and the apparent success of the ranching of non-anadromous species in Japan, show that sea ranching is a biologically sound, environmentally compatible, and commercially viable method of augmenting natural populations.

Based on a review of the known biology, fishery and culture, moi is suggested as a promising candidate for a program of artificial recruitment through the release of hatchery-reared juveniles. The continuing decline of moi catches in Hawaii points to the timeliness of initiating such a program. If moi ranching could at least compensate for the present indiscriminate overfishing of moilii and offset the natural, year-to-year fluctuations in moilii recruitment in Hawaiian waters, it would be a significant contribution to the moi fishery in Hawaii. A brief economic analysis of a "model" moi ranching program indicates that a commercially viable moi ranching is feasible in Hawaii if the present moi hatchery technology is perfected.

There still exist certain lacunae in our knowledge of the biology and culture of moi in Hawaiian waters, which must be filled before any release program could be implemented.

1. An extremely important prerequisite to any artificial recruitment program is the perfection of the present moi hatchery technology. In particular, larval survival in rearing tanks needs to be brought up to at least 20%. This level of survival, although considered definitely feasible, remains to be demonstrated. The currently achieved 2-5% larval survival is inadequate to support a profitable
ranching program. It is recommended that studies be continued to understand the nutritional requirements and other factors optimal for moi survival, and that hatchery technology be perfected to a level adequate for a commercial undertaking. As this development proceeds, detailed accounts of the costs of fry production should be maintained and analyzed so that the economic feasibility of the operation can be determined.

2. Although it is known with certainty that juvenile and adult moi are mostly confined to the protected inshore waters, more information is needed on the movements of moi and moilii populations in order to choose suitable release sites and to learn the extent of the moi's availability to local fishermen. It is recommended that an extensive juvenile tagging program, using the recently developed nose wire tags and other efficient tags, be initiated to elucidate the movements of moilii around the Hawaiian Islands and to estimate the expected return rate of the released juveniles.

3. A critical phase in the life history of the moi still remains unexplained; neither the developing eggs, nor the newly hatched larvae of moi having ever been collected, the presumed oceanic life of the larvae and the juveniles until their return to the inshore environment is not clearly understood. An extensive inshore-offshore plankton sampling study and an oceanographic study of the current patterns which help the larval transport are needed.

4. The State Division of Fish and Game, which in the past carried out regular investigations on the biology and fishery of moi until 1968, has since discontinued moi studies. The Division at present has reportedly no biologist working on this important species. It is recommended that the moi ranching program be supplemented by fisheries biology studies to evaluate it. Thus a
fishery biologist should be attached to the ranching program not later than a year after its inception. This biologist should collect on a continuing basis data on the annual variations in population abundance, juvenile recruitment in the inshore waters, and trends in moi catches which would be extremely valuable in implementing release programs in the future. Efforts should also be made to gather reliable information, hitherto unavailable, on the moi catches by sport fisherman in Hawaii.

5. The large mass of information available on salmon ranching is not particularly relevant to the ranching of non-anadromous species such as moi, and much of the information gathered on the ranching of non-anadromous species in Japan is not in published form. It is suggested that in the future a team of experts including biologists, economists and hatchery technologists be sent to Japan to gather first-hand information on the economics and technology of hatchery production, release and harvest of non-anadromous species, to help plan a moi ranching program in Hawaii.

As a viable moi ranching release program goes into operation, additional methods of enhancing the success of moi ranching may be explored. These could include, for instance, the behavioral modification of moi prior to release by group conditioning techniques to improve their return rates, and construction of artificial shelters in the inshore waters to provide new habitats for the growing of moi. The artificial recruitment of moi could eventually become part of an overall program by the State to manage the inshore food resources in Hawaii.
8. REFERENCES


