Aquaculture in New England

J. M. Gates
G. C. Matthiessen
C. A. Griscom

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Authors

J. M. Gates, economist, is assistant professor of resource economics at the University of Rhode Island. G. C. Matthiessen, biologist, is president of the Marine Research Corporation, formerly Marine Research Foundation, Incorporated. C. A. Griscom, physical oceanographer, is employed at the University of Rhode Island Marine Experiment Station.

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1. Introduction

In March 1970, personnel of the University of Rhode Island and the Marine Research Foundation, under contract with the New England Regional Commission, initiated a study of the potential for aquaculture in the New England states. Study objectives were defined as follows:

1. To establish economic, biological and technical criteria for evaluating the suitability of given species for commercial culturing in New England.
2. To apply those criteria to species which are judged to be of present or potential economic importance to New England.
3. For those species consequently found to be the most suitable—either actually or potentially—for commercial development, to define and analyze the most critical economic, biological and technical requirements for their profitable culture, and to determine the extent to which these requirements have been met.

In addition, present and anticipated impediments to the commercial culturing of each species were to be evaluated to the extent possible.

The final report to the Commission was to include a summary of the results of the above work, and conclusions and recommendations on those species and culturing techniques, if any, in which public and private research or investment would be most worthwhile.

This report is concerned, therefore, with the *present* potential for, and limitations on, aquaculture in the New England region. Within the past decade, interest in methods of culturing aquatic organisms for food has increased considerably. This has been due in large part to four things: (a) the fact that certain natural stocks appear to be over exploited; (b) an increasing consumer demand and, hence, a higher market value for certain luxury seafoods; (c) technological advances, and (d) a growing belief that mankind ultimately will rely far more heavily upon the aquatic environment as a food source than it does today.

In this report we regard aquaculture as food production. Other aquacultural activities, for example production of pharmaceuticals, have not been considered.

As charged by the Commission, the direction of research has been the feasibility of promoting a viable commercial aquaculture industry. Consequently, we considered neither public fisheries nor public hatcheries except implicitly as alternate sources of juveniles for a commercial aquaculture industry.

The report has been written for the New England Regional Commission, and the contents are directed primarily toward questions specified by the Commission. It is hoped, however, that the contents will prove of value to research personnel in public agencies and to prospective investors.

We wish to point out that the subject of legal and institutional impediments has been given brief consideration. It is our opinion that the problem is sufficiently complex to warrant a separate study.

The facts and opinions presented here are based on literature research and on personal interviews and visits to various laboratories and private culture facilities. Certain sections of this report have been submitted to various authorities, listed in the acknowledgements, for their critical review. The authors wish to express their thanks for the time and cooperation provided by these individuals, whose assistance is greatly acknowledged.

It was understood at the outset of this investigation that, despite the recent interest in aquaculture as a commercial endeavor, its development as a profitable industry in the United States faces certain serious obstacles. This is particularly true of marine aquaculture. Although significant advances in the culture and rearing of aquatic plants and animals have been made in recent years, many of these have been accomplished on a limited, if not experimental, scale. *It is clear that the successful culture of a particular organism in a laboratory environment in no way assures its profitable culture on a commercial scale* for reasons that will be discussed in this report.

With the notable exception of the oyster industry, particularly as it has recently developed in the Long Island Sound area, there are presently very few food-producing endeavors in the New England states that could be termed *aquaculture*. If the definition proposed by Ryther and Bardach (1968) is accepted, aquaculture is an operation "that subjects the organisms in question to at least one (but usually more than one) manipulation before their eventual harvest or capture." The reasons for the limited success of aquaculture are complex, but it appears that the major underlying factor may simply be lack of sufficient profit incentive. Unlike the Japanese, who have made, perhaps, the most significant advances in this area, Americans rely upon aquatic resources for only a small percentage of their basic foods. Therefore, until the significance of aquaculture has attained a higher priority in the public mind, its progress will be slow.

It seems probable that, if certain technological, economic and institutional barriers could be eliminated, the potential of commercial aquaculture in New England would be considerable. The purpose of this report is to attempt to define, for this region, the current limitations and restrictions upon aquacultural development and to attempt to indicate where opportunities for useful research or profitable culture presently appear to be greatest. If some of the obstacles to aquaculture—technical, economic, legal and social—appear to have received emphasis, it should be recognized that many aquacultural endeavors in the past have failed primarily because the participants involved were not fully aware of all the difficulties associated with the profitable rearing of aquatic organisms. They often projected their production capacity solely by extrapolating data derived from experimental systems.

2. Development of Criteria for the Selection of Species

In this section, certain criteria are developed in order to select the species most suitable for commercial culture. By sequential application of the criteria, it is possible to eliminate from a broad spectrum of species, those which currently have less potential for an industry of significant size. Such a "filtering" process makes it possible to concentrate in detail upon present and potential methods of culturing those species of greatest promise.

The reasons why certain species have been eliminated from serious consideration will be discussed in detail, from both a bio-technical and economic point of view. The net effect of the selection process has been to reduce to five the number of species, or groups of species, that appear to warrant serious consideration for commercial aquaculture in New England at this time.

The selection of criteria, and their application, has been based upon literature research, interviews with members of industry and the scientific community, and personal judgement and experience. It has been guided by the understanding that the interest of public agencies such as the New England Regional Commission is in projects in which development could result in substantial increases in regional income and employment.

We do wish to emphasize the following points:

1. Rejection of a species on the grounds of limited impact on the regional economy does not necessarily mean that individuals should not engage in aquaculture of the rejected species.
2. We recognize that certain species currently judged unsuitable by these criteria may in future years become suitable. This change could occur as a result of technological development, shifts in consumer preferences etc.

The criteria used fall into two distinct categories —biological and economic. The biological criteria include environmental adaptability and adaptability to intensive culture, including a consideration of the present state of cultural knowledge. The economic criteria include market volume and price considerations, interregional competition and natural supplies.

Certain taxonomically-related species are similar in their environmental requirements, mode of reproduction etc., and may satisfy most criteria; in this case, the species for which prospects appear most promising, is selected from the group for intensive examination (see chapter 3). For example, several salmonids—rainbow trout, Atlantic, Chinook and silver salmon—are highly similar in their requirements under culture and satisfy most or all of the criteria outlined. We focus the discussion of salmonids in chapter 3 on the silver (Coho) salmon. The implicit assumption is that, while an aquaculturist may culture more than one member species of an accepted group of species, initial efforts might be most successful if concentrated on the selected species.

By applying both biological and economic criteria, we have obtained two major categories: rejected species and accepted species. From the latter category we have selected five species for subsequent analysis in chapter 4.

Bio-Technical Criteria

Environmental Adaptability

Many species of aquatic organisms throughout the world have been found suitable for aquaculture and they form the bases for local or regional industries. Even though many of these operations are economically viable or technically feasible in the particular region in which they are pursued, they will not be so in the New England states if the species are physiologically unsuited to this area. Thus, the initial screening of aquatic species as a means of evaluating their potential for culture in New England should eliminate those that are physiologically incapable of tolerating the environmental conditions of this area.

For purposes of culture, water temperature can be regulated. In many aquacultural operations in temperate and semi-tropical latitudes, temperature regulation is, in fact, a vital part of the culture system. Due to cost considerations, every effort is made to minimize the amount of heated water required; the species under culture is usually, at some stage of its life cycle, exposed to ambient temperatures. Temperature manipulation is usually used to hasten reproductive processes, insure the survival of larvae at times of the year when reproduction does not normally occur or to accelerate the growth rate of juveniles. As a result of costs, temperature manipulation is rarely, if ever, relied upon throughout the complete maturation process.

Use has been made of the cooling water discharge from steam electric systems—both nuclear and fossil fuel—as an inexpensive source of heated water for culture purposes. There is little question that these effluents could be a highly useful aquacultural tool. However, for species that could not survive in the event of plant shutdown and consequent temperature decrease, total reliance upon steam electric system effluents for survival would seem to involve an unjustified risk.

As an initial basis for selecting a species for culture in New England, it should be able to tolerate, at least through a significant portion of its life cycle, the temperature extremes characteristic of New England. On this basis, many species otherwise worthy of consideration are eliminated, including common pompano *(Trachinotus carolinus)* which succumbs to temperatures below 10°C and the pink shrimp *(Pennaeus duroarum)* which occurs for the most part in tropical or semi-tropical waters.

The rationale for this criterion is as follows: aquaculture is, from a technical standpoint, in its infancy. Within the past ten years, many aquacultural projects have been initiated in the United States, and many have failed. Particularly with respect to marine species, relatively few projects are operating on a profitable basis. Certainly, as in any new endeavor, this picture should brighten as the technology improves. However, it is essential that species selected for culture should provide the culturist with minimum disadvantages and offer the maximum chance for success.

This view is reflected by Iverson (1968):

> The species best for farming are those that are indigenous to an area. Through scientific farming of these species, the fish farmer will get the greatest production. He should not delude himself that transplanting species into a new environment will result in very rapid growth and high production. Such results are rare. Much has been written about the relatively successful transplants, but little about the unsuccessful ones.
>
> Clearly animals are most successful in the geographic areas where their best living conditions can be found. Trying to farm a species at the ends of its range is foolhardy because these animals live on a marginal basis. With a change in environment and conditions for the better, the species occasionally becomes abundant, but if the conditions become less favorable mortality will be high.

Adaptability to Intensive Culture

Ryther and Bardach (1968) have listed the following characteristics of organisms that lend themselves to commercial culture: (a) ability to reproduce in captivity; (b) hardiness of eggs and larvae; (c) food requirements that are readily satisfied, and (d) relatively fast rate of growth.

Although few species satisfy all these requirements, certain species fall so far short as to preclude, at this stage, large-scale attempts at culture. In the case of other species, so little is known about their reproductive habits and larval and juvenile requirements in captivity, that recommending their commercial culture would seem unjustified.

The blue crab *(Callinectes sapidus)* is a species of commercial importance that has been cultured through various stages of its life cycle, although largely experimentally and not in New England. The difficulties in rearing this species through its rather prolonged larval period, and in satisfying its rather extensive food requirements, when weighed against its ultimate market value of about ten cents per pound, tend to argue against its commercial culture. (Idyll, 1969)

Similarly, the northern shrimp *(Pandalus borealis)* is an oceanic species that has not yet been reared successfully in captivity. In cases where this has been attempted, the larvae generally have not survived. (Knowlton, personal communications)

Most offshore groundfish and pelagic finfish species do not now appear to be logical candidates for intensive culture. The culturist has little practical information regarding reproduction of these species. Their nutritional requirements during their larval stages are uncertain and their adaptability to intensive culture is questionable. It is difficult at this state to conceive, for example, of culturing tuna on a practical basis. Even though certain species of flatfish, i.e. plaice and sole, have been cultured in Europe, the technical and economic difficulties encountered tend to discourage similar efforts in New England.

As a second basis for selection, therefore, sufficient technical information should be available regarding environmental requirements in captivity of the species in question. In short, the species has already been cultured through most, if not all, stages of its life cycle, at least on a pilot scale.

To summarize selection criteria to this point: Those species that appear most qualified for further consideration are those that (a) are physiologically adaptable to a New England environment, and (b) have been cultured, even to a limited extent, under conditions corresponding to the New England environment.

Economic Criteria

In addition to biological considerations, economic factors must be analyzed in the selection of species that possess high potential for commercial culture in the New England region. Economic factors include market price and volume, potential competition from other regions and natural supplies. Selection of species is based on judgments stemming from bio-technical and economic data extant at the time of selection. Changes in technology, biological knowledge, consumer preferences and/or natural supplies could alter the selection of appropriate species. The selection results should, therefore, be reviewed periodically.

Market Price and Volume

Two economic conditions were assumed necessary for a species to warrant further analysis: There must be a high unit price and a significantly large sales volume. One product with a high unit price but relatively low volume is the bloodworm, which yields over one dollar per pound to the digger. A product with high price and high volume is the American lobster. In this analysis, the bloodworm has been rejected, but the lobster has been retained for further consideration. Other species with both high price and high volume include the salmonids, oysters, and hard and soft clams. Examples of species with a low unit price, but a high market volume, would include certain groundfish such as flounder, haddock, and cod. They also have been rejected in this analysis.

Many species exhibit substantial seasonal price fluctuations. If aquacultural production permits control of time of harvest, then prices higher than annual averages may be obtained. For example, trout supplies and prices are quite stable over the year, reflecting the control exercised by culturists. The opposite is true of salmon species, where supplies and prices fluctuate with salmon runs. At this time, the only significant control which exists for salmon supplies is cold storage inventory control.

Market volume has been suggested as an important factor influencing the likelihood of success of a substantial aquaculture industry. It is sometimes argued that new products can expand current market volume, and it is true that under some conditions development of new product forms can increase total demand for a primary product. The conditions under which such increases are likely can be determined by detailed analysis of markets. For certain high-priced, low-volume species it is very tempting to gloss over the market volume criterion by resorting to this "new product" argument, i.e. that new products create new markets. This argument ignores a more rational approach: Use existing supplies to first demonstrate that (1) a new product form potentially exists, (2) the new product is acceptable to consumers and (3) existing supplies are inadequate at prevailing prices to meet the demand for the new product. Demonstration of these conditions is normally executed by private industry. If these are not demonstrated, market volume considerations should be based on current per capita market volume. Without detailed market analysis, only speculative assumptions can be made about potential high volume for a species.

The market process is also subject to some economies of scale which reinforce the case for a minimum market volume criterion. For example, advertising costs per unit of product tend to vary inversely with market volume. The same is true of distribution costs.

Application of the market volume criterion requires specification of a minimum annual sales level; in this study we have used a level of a $\$10^6$ *increase* in annual sales.[1] The associated percentage increase

[1] *This study usually uses scientific notation to express large or small numbers. The following relationships are provided for the reader:*

1.5×10^6 = one and one-half million
1.0×10^6 = one million
0.5×10^6 = one-half million = 5.0×10^5
1.0×10^5 = one hundred thousand
1.0×10^4 = ten thousand
1.0×10^3 = one thousand
1.0×10^{-6} = one-millionth
1.0×10^{-9} = one-billionth

in supplies at current ex-vessel prices was computed. If the supply increase exceeded 50 percent, the species was rejected. If the supply increase was less than 50 percent, its effect on prices was estimated by multiplying the proposed increase in supplies by the estimated price flexibility coefficient of the product in question. If the anticipated price decline was less than ten percent, the species was not rejected. If the anticipated price decline exceeded ten percent, the supply increase was compared to the projected rate of growth in demand. If projected growth in demand could not absorb the associated supply increase within ten years, the species was rejected. The rate of growth of demand was projected by assuming a 1.5 percent growth in real per capita income and multiplying this rate of growth of income by estimated income elasticity.[2]

Ideally we would like to compare prices at their reduced level with production costs. However, it was impossible with the paucity of data and time to synthesize estimates of production costs for more than a few select species. Our operating assumption has been that production costs would rarely be much below current prices. Under this assumption, substantial price reductions would not be consistent with viable commercial production. The price decline caused by an increase in supply would confer benefits on consumers. However, the focus of this analysis is not one of social benefit cost analysis, but of commercial viability.

It is necessary to reiterate the following points. (1) *Rejection of a species on the basis of the minimum sales criterion does not mean that individuals should not engage in production should they so desire.* It simply recognizes that the potential aggregate payoff from research and development funds is quite small. To an individual producer this payoff may appear quite large. (2) *The minimum sales criterion implies nothing about the optimum size of production units.* It refers to the potential scale of the "industry," which may be comprised of numerous small firms, a single large firm or any industry structure between these two extremes.

Interregional Competition

The significance of interregional competition lies in the fact that a species which does not have consumer acceptance in the region in which it is produced must be exported to regions in which it is accepted. Interregional shipments would require that New England producers compete favorably with those in other areas. The importance of interregional competition is exemplified by channel catfish *(Ictalurus punctatus)*. If one were to ignore unfavorable bio-technical considerations, production in New England might appear feasible. However, production is expanding rapidly in southern states where natural conditions are favorable. Furthermore, these states are closer than New England to feed supplies, a major item in production costs, and to major product markets. Consequently, New England does not appear to have a strong competitive position vis-à-vis the South in catfish production. Not only is local demand limited, but exports to southern demand centers would incur a transportation cost higher than that faced by Southerners who have production cost factors in their favor.

Natural Supplies

Natural supplies are of obvious importance to successful aquaculture. Discovery of new supplies or fluctuations in availability of native stocks can influence the potential market value of the same species grown under controlled culture. The flow of production yielded by a given fishery depends partially upon the size of the population stock. The population stock at any point in time is influenced by past catch rates. The interaction of fishing effort (and hence catches) and population stocks is frequently summarized in the abstract by a yield-effort curve. An idealized example of such a curve is presented in figure 1.

The level of effort (E) and its associated level of catch (L) are of particular relevance. The point where L_{max} and E_{max} intersect is termed the maxi-

[2] *Price elasticity (Ep) is an index of the responsiveness of quantity demanded to variations in price, holding income constant. It is defined as the percent change in quantity demanded, associated with a one percent change in price. The inverse of price elasticity is termed price flexibility (Npq). Knowledge of price elasticity enables a projection of the impact of a given percentage increase in supplies on market price.*

Income elasticity (E_y) is an index of the responsiveness of quantity demanded to variations in per capita income, holding price constant. It is expressed as the percent change in quantity demanded associated with a one percent change in per capita income.

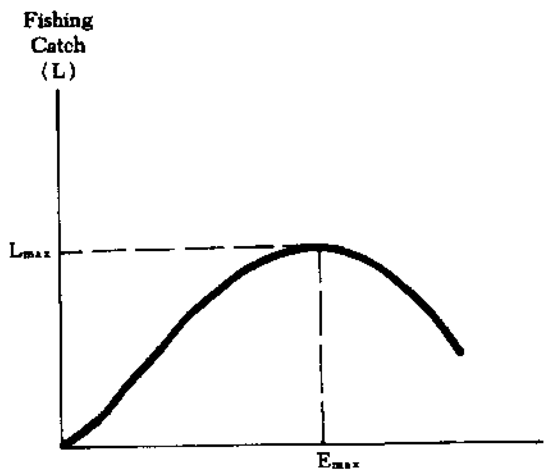

Figure 1. Hypothetical yield-effort curve for a fishery.

mum sustainable yield (MSY) of the fishery. Increases in effort beyond this point may result in temporary increases in catch through stock depletion. Eventually, however, landings will be decreased below L_{max} although greater fishing costs are incurred by the associated increase in effort. A fishery in which annual landings are in the neighborhood of MSY will not have sustainable supply increases in the future. Demand increases will be absorbed by discovery of new supplies and/or acquaculture and/or price increases. Conversely, if current landings are considerably less than MSY, increases in landings may occur in the future.

The relevance of natural supplies can be stated in terms of future price trends. If current landings are near MSY, market prices may be expected to rise in the future. The rate of price rise will depend on the rate of growth of demand even if fishing effort is stabilized at E_{max}.[3] If fishing effort is permitted to increase beyond E_{max}, the physical yield of the fishery will be diminished and prices will rise more rapidly than the rate of growth of demand. Conversely, if current landings are considerably less than MSY, future price rises will tend to be less than the rate of growth of demand. The difference in growth rates of price and demand in this case will reflect the dampening effect of increased supplies on price. For example, the inshore lobster fisheries of the New England states are near their MSY point and future prices will rise quite rapidly unless new stocks are exploited.

Conversely, landings of clams by the New England and Middle Atlantic states and the Atlantic coast provinces of Canada were less than 8.0×10^4 pounds in 1966 (National Marine Fisheries Service, Working Paper No. 55, 1970). This total includes surf clams. By contrast, 3.36×10^8 pounds is the estimated MSY of hard and soft clams in the northwest and west central Atlantic, many times greater than current landings by the coastal states of the area (Canada Department of Fisheries and Forestry, 1969). Future price rises will probably occur but will be limited by increased exploitation of abundant natural stocks.

[3] *The rate of growth of demand is discussed in connection with income elasticity of demand. See footnote 2.*

3. Application of the Criteria

Rejected Species

In this chapter, the criteria discussed in chapter 2 are applied to several species in order to explain why certain species have been rejected for detailed discussion later. The New England species sometimes considered for culture, but rejected in this section, include the Atlantic sea mussel, bloodworm, winter flounder, rock crab, sea scallop, soft-shell clam and several miscellaneous species. Discussion of each of these follows.

Atlantic Sea Mussel (Mytilus edulis)

The Atlantic sea mussel is an extremely common species that occurs in abundance in the intertidal and sub-tidal zones throughout New England. The mussel is considered a delicacy in many parts of Europe, and it is cultured intensively in some places, e.g. in the Bay of Viga in Spain. In general, however, this species has been of only limited commercial value in this country, where it is more frequently regarded as a pest than as a potentially valuable food product. In recent years, most of the U.S. production has been centered in New England, primarily in Massachusetts and secondarily in Maine. From 1960 through 1967, mussel landings in the United States ranged from 3.20×10^5 pounds meat weight valued ex-vessel at $\$3.4 \times 10^4$ in 1964 to 8.03×10^5 pounds valued at $\$1.01 \times 10^5$ in 1967. Ex-vessel prices were approximately $0.08 to $0.10 per pound.

A production target of $\$10^6$ would increase U.S. production by 1000 percent, at current ex-vessel prices. It appears that a European export potential may exist for mussel production, but exploitation of this potential does not require aquaculture. If a profit potential exists in the U.S., natural supplies could be harvested for this purpose.

Characteristics of the sea mussel favorable for commercial culture:

1. The sea mussel is a hardy species, capable of withstanding prolonged exposure to warm or freezing temperatures when established between the tide lines. By means of its byssal threads, it can establish dense colonies on virtually any type of substratum other than soft mud.

2. Like most other bivalve mollusks, the mussel is highly fecund. A mature female may release up to ten million eggs at a single spawning.

3. Growth rate is relatively rapid, particularly if the mussel is established below the low tide mark (Scattergood et al, 1949). It has been estimated a mussel may attain the desired market size of three inches within a three-year period (Matthiessen and Toner, 1963), and possibly sooner. According to Dow (1970), off-bottom culture techniques may produce marketable mussels in 12 to 18 months. Since the mussel is a filter-feeder, subsisting upon phytoplankton and particulate organic detritus, its nutritional requirements are immediately available in the water column.

4. Due to its habits of attachment, mussels are readily cultured by suspension techniques by which intensive yields can be obtained from relatively small areas. Ryther and Bardach (1968) report an annual yield of 240 metric tons of mussels per acre per year in parts of Spain where raft culture techniques are employed.

5. The mussel has been induced to spawn in captivity, and the larva has been reared successfully through metamorphosis (Loosanoff and Davis, 1963). However, due to the general abundance of parent stock and because annual reproduction appears to occur rather consistently wherever adult beds are established, artificial techniques for supplying juveniles on a regular basis would probably not be required.

Characteristics of the sea mussel unfavorable for commercial culture:

1. In the northeast sector of its range, i.e. eastern Maine and the Maritime provinces of Canada, the mussel occasionally becomes toxic and unfit for consumption (Medcof, 1947). Incidents of mussel poisoning have been attributed to seasonal blooms of the phytoplanktonic dinoflagellate, *Gonyaulax tamerensis*, which, when ingested by the mussel, make the flesh poisonous (Walford, 1958). Periods of toxicity appear to be restricted to the late summer and early fall.

2. In certain areas, the mussel may develop pearls, which, because of the resulting annoyance when chewed, limit market value.

3. In order to be attractive and presentable for market, the mussel must be washed and its byssal threads removed. Although this procedure is time consuming, it is perhaps no more so than cleaning oysters for the half-shell market.

In summary, the major limitations upon mussel culture at present appear to be economic rather than technical. Present demand for this species does not yet warrant the expense involved in culture. Furthermore, natural supplies are abundant. Should this marketing picture change, the mussel would appear to be well suited for commercial culture in New England.

Bloodworm (Glycera dibranchiata)

The marine bloodworm is a common resident of muddy intertidal flats along the New England coast. Dow (1969) has indicated that this species has perhaps the highest unit value of any marine organism; as much as $5.25 per pound may occasionally be paid for it. The bloodworm is marketed almost exclusively as bait for sport and commercial fishermen. As pointed out by Iversen (1968), the number of sport fishermen in the United States is increasing more than two and one-half times as fast as the population; by the year 2000, there will be over 62 million sport fishermen in this country. Thus, methods for culturing this species in commercial quantities are being seriously considered.

In recent years, U.S. bloodworm landings have been rather steady at approximately 8.0×10^5 pounds, valued ex-vessel at approximately $\$10^6$. Most of the U.S. production is centered in Maine which landed 8.32×10^5 pounds in 1968 and 7.82×10^5 pounds in 1969, valued at $\$10^6$.

A production target of an additional $\$10^6$ would be a 100 percent increase in supplies at current prices.

Characteristics of the bloodworm favorable for commercial culture:

1. The bloodworm is extremely fecund, with large females bearing anywhere from two to nine million eggs (Creaser et al, 1967).

2. This species is primarily a detritus-feeder rather than a carnivore (Klawe and Dickie, 1957). As such, its nutritional requirements under culture might be satisfied relatively inexpensively.

3. According to Klawe and Dickie (1957), the bloodworm is far less a wanderer than the sandworm *(Neanthes virens)*. Therefore, the problem of maintaining large numbers of worms in a particular area until they reach marketable size is minimal.

4. The bloodworm is tolerant of a wide range in salinity and occurs in both estuarine and oceanic environments.

5. This species reaches most favored market size in about three years. However, as a result of high demand, it may be of commercial value after its first year (Creaser et al, 1968).

Characteristics of the bloodworm unfavorable for commercial culture:

1. According to Klawe and Dickie (1957), the rate of natural reproduction of the bloodworm in any given area may vary from year to year for a number of reasons. These investigators experienced considerable difficulty in rearing larvae of this species under artificial conditions and reported that little is known of the environmental requirements of the larval and post-larval stages.

2. The bloodworm is customarily harvested from the intertidal flats by hoe. Consequently, a minimum of equipment and, hence, of capital investment is required. Although this is highly advantageous to the individual fisherman, it is also true that any species so easily accessible and readily harvested at minimum expense poses certain economic problems to the culturist who intends to invest in the acquisition and maintenance of private beds, and possibly in the controlled rearing of the species. Specifically, (a) entrance and egress in the natural fisheries may lead to unstable prices and (b) without adequate property rights in the form of a lease, the culturist may face losses due to his inability to deny public access to growing beds.

In summary, the bloodworm has certain characteristics that suit it for commercial culture. If cultured under natural conditions, without efforts towards intensive management, it would appear that a suitable area of roughly 300 acres might yield as much as 225,000 pounds of bloodworms each year. It is possible that such yields might be significantly increased if intensive management practices were applied. It is not now known whether reproduction might be guaranteed through hatchery techniques. Although bloodworm prices are quite high, the species is rejected by the market volume criterion. Mortality rates from the efforts of both the harvester and the sport fishermen are reportedly high. Methods for reducing these marketing losses might be a more productive area for research than aquaculture per se.

Soft-shell Clam (Mya arenaria)

The soft-shell clam is a common inshore species ranging in its Atlantic Coast distribution from Labrador to the Carolinas. Although it occurs most commonly in intertidal areas, it may also be fished intensively below the low water mark, as in Chesapeake Bay and in various salt water ponds in the New England area.

The soft-shell clam has had an ex-vessel price of $0.30 to $0.40 per pound since 1960. At 1967 prices, the increased production required to generate gross sales of $\$10^6$ would be 2.5×10^6 pounds. This would represent a 25 percent increase in supplies. Using an estimated price flexibility coefficient of −1.6 from the National Marine Fisheries Service (Working Paper No. 55, p. 14), this supply increase would depress prices by 40 percent. Since this percentage exceeds the ten percent level discussed in connection with the market volume criterion, in chapter 2 we next considered the rate of growth of demand, as described in the following paragraph.

Assuming a 1.5 percent annual growth in real income and an estimated income elasticity of 0.25 (N.M.F.S. Working Paper No. 55, p. 14), a 0.38 percent annual growth in demand is projected. This would result in approximately four percent growth in demand in ten years, which is not sufficiently rapid to absorb the above 25 percent supply increase.

Characteristics of the soft-shell clam favorable for commercial culture:

1. This species is extremely hardy. It reportedly ceases to grow only when water temperatures drop to 3°C (Turner, 1948), and thrives at temperatures in excess of 26°C (Matthiessen, 1960). With respect to salinity, it has been planted successfully in waters ranging from 5 o/oo to over 31 o/oo (Belding, 1930). It may successfully populate a variety of sediment types, ranging from soft mud to coarse gravel. Intertidal populations can endure prolonged exposure between tides, accompanied by significant seasonal variations in air temperature.

2. In the southern portion of its range in New England, this species may grow extremely rapidly. According to Turner (1948), in Rhode Island waters this clam may reach a legal marketable size of two inches in length in one year. North of Cape Cod, the rate of growth is somewhat slower, but even in northern Massachusetts and western Maine, marketable size may be attained within three years.

3. As is true of most other bivalve mollusks, this species is sedentary rather than fugitive. Because of its normal occurrence in intertidal or shallow water areas, it is readily accessible for harvest.

4. This species acquires its food directly from the water column or water-sediment interface in the form of phytoplankton or particles of organic detritus. Therefore its nutritional requirements are satisfied readily and inexpensively.

5. At least in the natural environment, the soft-shell clam may thrive in extremely high densities. Populations of 50 legal-sized clams per square foot have been reported (Turner, 1948), although such densities are rarely attained. A well-managed flat, however, may yield over 100 bushels per acre on an annual basis (Wallace, 1967).

6. The clam may be harvested rapidly and efficiently, with little breakage, by hydraulic dredging gear.

Characteristics of the soft-shell clam unfavorable for commercial culture:

1. A commercial operation, in order to be viable, must be assured a reliable source of supply of juvenile stock. It is for this reason that certain of the larger oyster growers in New England have been forced to invest in oyster "hatcheries," since natural reproduction is not reliable. Consistent reproduction of the soft-shell clam year after year in any given area cannot be guaranteed; artificial methods of rearing the young might be required for sustained production. However, efforts to produce clams by conventional hatchery techniques have for the most part failed (Zuraw et al, 1967). Loosanoff and Davis (1963) and Stickney (1964) have succeeded in inducing this species to spawn in captivity and in rearing the larvae through metamorphosis, but only on a limited scale. In short, to date it has proven to be a difficult species to propagate under controlled conditions.

2. The soft-shell clam is extremely vulnerable to natural predators, which include the green crab *(Carcinides maenas)*, horseshoe crab *(Limulus polyphemus)*, and the boring snail *(Polynices heros* and

P. duplicata). Experimental plantings by Spear and Glude (1957) resulted in mortalities as high as 95 percent during a single growing season. Turner (1953) has also reported cases of extremely high mortalities among populations in which histories have been traced through consecutive years. Even in areas fenced to exclude predators, heavy mortalities have been reported for reasons not clearly understood (Turner, 1950); in one instance this reached 85 percent. Virtually nothing is known about diseases and their causes among clam populations, but widespread mortalities may occur that cannot be attributed to predation.

In summary, despite certain characteristics of the soft-shell clam that make it a highly desirable species for commercial culture, it has for the reasons given failed to be cultured consistently on a commercial scale. Existing clam flats have been managed relatively successfully through predator control and regulated harvesting. However, these efforts have followed the natural occurrence of the clam with locations not subject to control. As of now, profitable clam culture on a private commercial basis awaits further developments in methods for rearing the larval and juvenile stages to stages where they might be successfully managed in nature. Market conditions as discussed earlier are also unfavorable, and significant additions to the regional economy appear unlikely. For these reasons this species is rejected.

Winter Flounder (Pseudopleuronectes americanus)

The winter, or blackback flounder is a species common to all of coastal New England, where it is highly valued for food. This species commonly spawns in bays and estuaries, where the young may remain for the first few years of their existence. Because of its food value and apparent tolerance to a reasonably wide range of environmental conditions, and because closely related species have been cultured intensively in captivity (Shelbourne, 1965), some consideration has been given to commercial culture of the winter flounder in New England. However, the ex-vessel price of this species, about $0.15 per pound, is rather low to justify the costs of capital facilities and acquisition of suitable food.

Characteristics of winter flounder favorable for commercial culture:

1. By means of stripping ripe adults, the eggs of this species have been fertilized in captivity, and viable larvae are readily obtained.
2. The winter flounder is relatively fecund; a large female may produce over one million eggs annually (Bigelow and Schroeder, 1953).
3. The species appears to be hardy, capable of tolerating a wide range in both temperature and salinity. It may be found in abundance in areas heavily polluted by industrial and domestic wastes, and on bottom areas varying in sedimentary characteristics from soft mud to firm sand.
4. The winter flounder reaches marketable size when only three-fourths of a pound in weight, or roughly ten inches in length, at about three years of age.
5. Although the adult of this species is capable of extensive migrations (Coates et al, 1970), the juvenile may remain within the area in which it was spawned for two years or more (Perlmutter, 1947).
6. The adult flounder does not appear to be particularly selective in its feeding habits, reportedly being omnivorous to a degree and feeding upon algae as well as such small marine animals as worms, clams and crustaceans.
7. A related species, the plaice *(Pleuronectes platessa)*, with presumably rather similar environmental requirements has been reared from fertilized egg to maturity under controlled conditions and in significant quantities (Bardach, 1968).

Characteristics of winter flounder unfavorable for commercial culture:

1. The food requirements of the larval and postlarval stages of this species are not well understood. On the basis of experiences with related species, it is presumed that the winter flounder requires animal protein to a degree and must, therefore, be provided small animals maintained in culture for this purpose, e.g. brine shrimp or marine worms, or finely ground meat. Therefore, satisfaction of nutritional requirements may be costly in both time and money. According to Shelbourne (1969), pelletized food is not satisfactory for the larval or juvenile stages of the plaice.
2. Because of spatial requirements, it does not appear feasible to culture flatfish to maturity in commercial quantities under totally artificial conditions. Transfer of the hatchery-reared young to en-

closed lochs or lagoons, where they may mature to marketable size, appears to be the most promising approach. However, according to Bardach (1968), considerably more must be learned about methods for preventing oxygen depletion, predation and disease before even this approach can become economically feasible. Furthermore, some form of enclosure would be necessary, since a winter flounder may wander considerable distances from its spawning and nursery areas when two years old or more.

In summary, the winter flounder has certain characteristics favorable for commercial culture. However, although it is an important commercial species, its present market price of approximately $0.15 per pound, ex-vessel is too low to justify the cost of hatchery operation and maintenance, the feeding of the larval and post-larval stages and the construction and maintenance of impoundments required for rearing the juveniles to maturity.

Sea Scallop (Placopecten magellanicus)

As a result of declining stocks on Georges Banks since 1966, the sea scallop has become an increasingly high-priced food item. In January 1970, exvessel prices of domestic scallops reached a record high of $1.46 per pound. Over 24×10^6 pounds of sea scallops were consumed in 1969. Because imports are now approximately twice the volume of domestic landings (Surdi and Whitaker, 1970) and because it should be possible theoretically to culture this species by the same techniques developed for other species of bivalve mollusks, the sea scallop has been considered for aquaculture in New England.

Characteristics of the sea scallop favorable for commercial culture:

1. The sea scallop is tolerant of low temperatures and, in fact, appears to grow most rapidly at temperatures approximating 10°C. In this respect, it would have a distinct advantage over most bivalve mollusks in terms of culture in northern New England.

2. As far as is known, this species subsists upon phytoplankton and particulate organic matter in the water column (Posgay, 1950). Therefore, its nutritional requirements are readily satisfied without supplementary foods.

Characteristics of the sea scallop unfavorable for commercial culture:

1. This species has proven difficult to rear under culture. Posgay (1953) had little difficulty in inducing adults to spawn under controlled conditions, but the larvae failed to survive to metamorphosis. Posgay (personal communication) reports that other investigators in Canadian laboratories have experienced similarly poor results. Although the reasons for poor survival are not understood with certainty, it is suspected that the nutritional requirements of the larvae of this species may be complicated and not readily satisfied by the algal foods conventionally employed in shellfish hatcheries. Quite recently, larvae have been raised successfully through metamorphosis by biologists in Maine (Dow, 1971).

2. As compared to the bay scallop *(Aequipecten irradians)*, the growth rate of the sea scallop is relatively slow. It is estimated that this species needs a minimum of two years to attain 40 millimeters in shell height, a size the bay scallop may reach during its initial growing season (Merrill and Posgay, 1967).

3. The growth rate of many species of bivalve mollusks may be accelerated by elevating water temperature above normal. In the case of the sea scallop, however, maximum growth rate occurs at around 10°C; its growth rate declines at higher temperatures, and complete mortality is generally reached at temperatures approximating 23°C (Posgay, 1953).

4. This species is a relatively active swimmer, and juvenile scallops reportedly have been observed swimming near the surface on Georges Bank where the depth exceeded 25 fathoms. Regardless of the reliability of these observations, it is evident that private culture operation would require some mechanism for containing the scallops.

5. The meat yields of sea scallops are low in comparison to those of bay scallops of similar size. According to Baird (1954), the weight of the muscle of a 50-millimeter sea scallop approximates 2.6 grams. Belding (1931), on the other hand, determined the meat weight of bay scallops in this size range as approximately seven grams.

In summary, despite its current high market value and its physiological adaptability to the low temperatures characteristic of northern New England, the sea scallop does not appear to be a logical candidate for culture at the present time. Certainly the initial and most serious obstacle to culture is the inability to obtain juvenile stocks on a reliable and annual basis, whether by natural or controlled methods of reproduction.

Rock Crab (Cancer irroratus)

The rock crab is the only crab species that presently supports a commercial fishery in New England. Although this species is reasonably abundant and ranges from Nova Scotia to Florida, relatively little was known of its ecology and life history until recent work by Sastry (1970). Nevertheless, in view of rising consumer demand for various edible crustaceans, including lobsters, shrimp and certain crab species, the possibilities of culturing this species on a commercial scale have been considered. Several economic criteria are not favorable, however. Ex-vessel prices in 1967 were about $0.05 to $0.12 per pound. The market volume criterion is unfavorable unless cultured rock crab were able to compete with king crab, which seems unlikely. Natural supplies appear abundant, and no evidence of general resource depletion is reported.

Characteristics of the rock crab favorable for commercial culture:

1. This species is tolerant of a wide range in temperature, other than during its larval period (Sastry, 1970), and is available in inshore waters during all seasons of the year.

2. The meat yield from the rock crab is equivalent to that from the blue crab *(Callinectes sapidus)*, which supports a sizeable industry in the mid-Atlantic and southern states, and the rock crab's flavor is reportedly equivalent (Rees, 1969).

3. This species is readily trapped or harvested by trawl and is available closer to shore than its commercial valuable relative of the Pacific Coast, the Dungeness crab *(Cancer magister)*.

4. Larvae may be reared at densities approximating two per milliliter of culture water (A. N. Sastry, personal communication).

Characteristics of the rock crab unfavorable for commercial culture:

1. This species is carnivorous and cannibalistic. The cost of feeding large numbers of crabs, held under artificial or confined conditions, might approximate the market value of the animals themselves, since appreciable losses as a result of cannibalism can be expected.

2. There is large seasonal variation in the meat yield of rock crabs. Even under the most favorable conditions, however, 20 crabs are required to produce one pound of meat (Turner, 1953).

3. Even if the taking of female crabs were permitted by law—which it is not in the state of Massachusetts—the female of this species is generally too small to be processed, i.e. to have its meat removed, efficiently. Therefore, even if it were technically possible to culture large numbers of this species through the larval period, only the males would be worth retaining.

4. The growth rate of this species is unknown, or at least has not been reported in the literature. If it approximates that of the closely related *C. magister*, it can be assumed that, under natural conditions, three years would be required for this species to attain a size suitable for processing.

5. Although Turner (1954) found that the adult crab population of Boston Harbor was essentially non-migratory, it is nonetheless a motile species that would require some means of confinement if cultured in nature.

In summary, the potential for culturing rock crabs on a commercial basis does not appear to be significant at this time, in part because of its carnivorous habits, small size and incomplete knowledge concerning cultural techniques. Certainly, more should be learned of the life history and environmental requirements of this species before any effort is made to culture it on a commercial basis. Moreover, market price and volume criteria are not favorable for its culture.

Miscellaneous Species

A number of additional species have been suggested for commercial culture. We have found that these species either are of relatively low price or have certain other unfavorable characteristics. Therefore, profitable culture in New England would appear highly unlikely. Included in this category are the alewife *(Alosa pseudoharengus)*, shad *(Alosa sapidissima)*, Pacific oyster *(Crassostrea gigas)*, clam worm *(Neanthes virens)* and Irish sea moss *(Chondrus crispus).*

Virtually nothing is known of the requirements of the alewife and shad under culture, and their low price would not justify culture efforts. As indicated earlier, the Pacific oyster is unacceptable for the half-shell trade due to its unpleasing flavor when consumed raw and its comparatively coarse and unattractive appearance in the shell. The clam worm enjoys a rather high price, but, as was found to be true of the bloodworm, it would be rejected by the market volume criterion. Finally, Irish sea moss is not a species that is readily *cultured*; it is harvested where or when it occurs. It too would be rejected by the market volume criterion.

These and other rejected species may warrant further research toward the eventual objective of establishing a commercial industry in New England. However, an important objective of this study has been to identify those species that appear to have the greatest potential for commercial culture *at the present time*. The degree of additional research necessary on their biology and environmental requirements in captivity must be taken into consideration.

Accepted Species

Several species or groups of species satisfy most or all of the criteria, but have not been selected for further analysis in chapter 4. These include several salmonid species and the European oyster. The salmonid species of interest include brook and rainbow trout, Atlantic salmon, red king (Chinook) and silver (Coho) salmon. A commercial trout industry has existed in New England and elsewhere for many years. The Atlantic salmon is unique in that it is indigenous to New England and has an extensive history of culture. We present a brief review of Atlantic salmon in this section. Of the Pacific salmon, the silver (Coho) is the only one which has a significant history of culture in New England. We recognize that a culturist may choose more than one of the salmonid species depending on circumstances of environment, prices and relative success in their culture. In chapter 4, however, we confine further analysis of salmonids to the silver salmon which is one of the better salmonid candidates for aquaculture.

Atlantic Salmon (Salmo salar)

The Atlantic salmon, once so abundant as to have been used for fertilizer in this country, presently occurs in only trace quantities in New England's river systems, and only in the state of Maine. Currently, annual production from these rivers seldom exceeds 500 fish (Netboy, 1968). The Atlantic salmon is a valuable food species, when available, and commands a high market price. Since it would fall in the "luxury food" category and is obviously adapted to the New England environment, its potential for commercial culture is significant.

Characteristics of the Atlantic salmon favorable for commercial culture:

1. Techniques for obtaining the eggs and rearing the larvae and fry of this species under hatchery conditions are established.
2. The Atlantic salmon has been found to be highly responsive to temperature and salinity manipulations. By maintaining water temperatures within a range of 9° to 19°C, Markus (1962) was able to rear newly hatched fry to the smolt stage in ten months. By manipulating both temperature and salinity, Saunders (personal communications) succeeded in rearing 35-gram fish to a weight of 456 grams in seven months and to 2,243 grams (roughly five pounds) in 19 months.
3. This species has a high food conversion efficiency. On a wet-weight-to-wet-weight basis, Saunders (personal communication) has estimated an efficiency of 25 to 30 percent. Using dry foods, a conversion of 1.5 to 2 appears typical for salmon in Canadian hatcheries (R. Macdonald, personal communication).
4. The Atlantic salmon has been raised in captivity to a weight of five pounds at densities approximating one pound of fish per cubic foot of water.
5. This species lends itself to selective breeding, and strains that grow significantly faster than wild stock have been developed (Dalziel and Shillington, 1961).
6. Efforts to rear this species in commercial quantities from fertilized egg to marketable size under totally captive conditions have already been initiated, with indications of eventual economic success (Gunstrom, 1970). In other words, the technology presently exists for producing commercial quantities

of Atlantic salmon under conditions subject to a high degree of environmental control.

Characteristics of the Atlantic salmon unfavorable for commercial culture:

1. Synthetic dry foods employed at most salmon hatcheries are expensive, ranging from $0.10 to $0.40 per pound depending upon the variety used. Lindroth (1963) has indicated that over one-third the total operating costs of a hatchery in Sweden resulted from purchase of food.

2. Although population densities in excess of one pound of fish per cubic foot of water may be maintained, the water—in the absence of natural raceways—must be renewed at frequent intervals, i.e. every one to two hours (R. Hawkins, personal communications; Leitritz, 1960). The cost of pumping sufficient water in a large-scale facility may be considerable. Obviously, there are no pumping costs in natural raceways, but the ability to exercise control over such environmental factors as temperature may be sacrificed.

3. Disease control has always been a serious problem in the rearing of finfish under high density conditions. In an artificial environment, infectious diseases may flourish due to ease of transmission, high water temperatures designed to accelerate the growth rate, and dietary deficiencies (Sindermann, 1969). Fish are also sensitive to such chemical factors as excessive nitrogen and either low or supersaturated oxygen concentrations.

4. The Atlantic salmon is regarded by many biologists as the most difficult of the salmon to rear in captivity (J. Eagleton, personal communication).

In summary, the Atlantic salmon has considerable potential for commercial culture in New England, largely because it is a species of high market value—in excess of $0.70 per pound—that has proven adaptable to intensive culture. We have chosen to regard Atlantic salmon as an alternate to the silver salmon in view of its similar environmental requirements and markets. We recognize that a culturist may choose to culture either or both, depending on market conditions and relative success in culturing the two. Scientists who have cultured Atlantic salmon have indicated that it is one of the most difficult of the salmon to rear. In chapter 4 we, therefore, focus further analysis of salmonids on the silver salmon.

European Oyster (Ostrea edulis)

The European oyster *(Ostrea edulis)* was imported into this country from Holland in 1949 for the purpose of establishing an oyster industry in Maine (Loosanoff, 1962). This species spawns at lower temperatures than does the American oyster, *Crassostrea virginica*, and therefore was thought to be more likely to self-propagate in northern New England. Since its introduction, it has succeeded in reproducing naturally both in New England waters and on the Pacific Coast where it was later introduced (Loosanoff et al, 1966). Since this species is prized for the half-shell trade and may command an even higher price than *C. virginica* in certain markets—as on the Pacific Coast (Matthiessen, 1970)—it would appear to offer an economic incentive for commercial culture.

Characteristics of the European oyster favorable for commercial culture:

1. As mentioned above, this species will normally reproduce at temperatures considerably lower than those required for reproducing *C. virginica*. Imai (1967) reports that spawning may occur at temperatures as low as 15°C, whereas *C. virginica* rarely spawns at temperatures below 20°C. This species would, therefore, provide greater flexibility in its culture in various regions of New England.

2. Conventional hatchery techniques have been employed successfully in the rearing of this species under controlled conditions (Breese, 1969; Imai, 1967; Loosanoff and Davis, 1963; Walne, 1956).

3. The larvae of this species are tolerant of a wide temperature range, being capable of growing satisfactorily and metamorphosing at temperatures ranging from 17.5°C to 30°C (Davis and Calabrese, 1969). These authors report that satisfactory growth of the larvae of *C. virginica* is possible only at temperatures above 22.5°C.

4. This species is a filter-feeder with nutritional requirements readily satisfied in the natural environment.

5. This species is adaptable to intensive culture. When grown in floating trays, it may be cultured to maturity at densities approximating 100 oysters per square yard (Belknap, personal communication). Moreover, its growth rate is rapid, and marketable size may be attained in a period of two years.

Characteristics of the European oyster unfavorable for culture:

1. Despite the fact that this species has reproduced naturally in northern New England, successful "sets" have been sporadic from year to year. It appears probable that a viable commercial operation would have to depend at least in part upon supplementary reproduction through hatchery methods if its supply is to be assured.

2. Controlled reproduction of this species has met with inconsistent results (Walne, 1956), and inducement of spawning in the laboratory reportedly may be difficult (Loosanoff and Davis, 1963).

3. As is true of other bivalve mollusks, this species may be subject to heavy predation by enemies, most particularly starfish and oyster drills, in the natural environment. Adequate methods of predator control would be a necessity in any bottom culture operation.

In summary, the European oyster has certain characteristics favorable for commercial culture in New England. Certainly its ability to reproduce naturally and thrive in waters of relatively low temperature offers an important advantage over many species. However, hatcheries might well prove necessary for sustained production. The costs and technical difficulties inherent in hatchery operations must be recognized. We have chosen to regard the European oyster as an alternate to the eastern oyster in view of its similar environmental requirements and markets. We recognize that a culturist may choose to culture either or both depending on market conditions and relative success in culturing the two. In Chapter 4 we focus further analysis of oysters on the eastern oyster.

Species Selected for More Intensive Analysis

By the processes of elimination described above, involving application of technical and economic criteria, the following species emerge as the most suitable for commercial culture in New England at this time:

Eastern oyster	*(Crassostrea virginica)*
Hard clam	*(Mercenaria mercenaria)*
Bay scallop	*(Aequipecten irradians)*
Silver salmon	*(Oncorhynchus kisutch)*
American lobster	*(Homarus americanus)*

We have not included the application of criteria to these species in this section because the discussion in chapter 4 will be adequate and needless repetition will be avoided. It is emphasized that technological as well as economic developments could alter this list. At the present time, however, these five are among the better species and warrant greater consideration than others for public research and private investment.

In addition, an aquaculturist might wish to experiment with certain other species with similar cultural requirements. For example, Pacific and European oysters might be considered in conjunction with eastern oysters; the former because of its rapid growth rate; the latter because of its high price and tolerance of low temperatures. Similarly, while silver salmon is selected for further analysis, a culturist might choose to experiment with Chinook and/or Atlantic salmon.

Multiple Species Systems

It may prove desirable to culture more than one species in an aquacultural system. If two or more species have symbiotic relationships under culture, then culture of the two may result in lower costs than if either is produced separately. Similarly, if species are non-competitive in their spatial, environmental, labor or food requirements, greater efficiency in use of labor and/or plant capacity may be possible by joint culture. Many pathogenic organisms in nature are host specific and occur in epidemics, the frequency of which increases with spatial density of the host species. Should such organisms be a problem in aquaculture, joint production of species might reduce disease incidence without reducing the physical productivity of a given aquacultural system.

Oysters produce a considerable volume of organic wastes which might prove a suitable cultural medium for sandworms. Although rejected as a species on which to base significant aquacultural industry, the sandworm might well be considered as a complementary product in the production of oysters. Similarly, the waste effluents from salmonid rearing are high in nitrogenous compounds which might stimulate algal growth for oyster culture. In sales, an aquaculturist may well find customers more receptive if more than one species can be supplied. Such complementarity in sales reinforces the case for multiple species systems or horizontal integration with other supplies of food fish to obtain supplies of several species.

These considerations are hypothetical, however, and we can find no germane literature to support the hypothesis that mixed systems are more profitable than single species systems. Consequently, we have somewhat reluctantly abandoned the concept of mixed systems at the present time. Future research may yield results which warrant further consideration of the concept. As an alternative, an aquaculturist may choose to explore the concept in experimental efforts ancillary to production in a single species system.

A related, but distinct, topic concerns the possibility of complementarity between domestic waste effluents and culture of filter feeders such as oysters. The extra-market costs of discharging these effluents have been largely ignored by the public agencies in order that monetary costs to taxpayers be minimized. This attitude is increasingly criticized by a concerned public. It may prove possible to use aquaculture in this context to help solve an environmental problem; however, it may be necessary to develop public/private cost sharing mechanisms to do so. Moreover, it should be recognized that most systems for disposal of domestic wastes have little or no control over fluctuations in the components of their effluents. Such fluctuations could be incompatible with successful aquaculture.

4. Analysis of Selected Species

The American Oyster *(Crassostrea virginica)*

Supply and Demand

Supply. Approximately 85 percent of the total U.S. oyster landings are eastern oysters. In recent years, eastern oyster landings have ranged from 45 million to 50 million pounds, meat weight, valued at $25 million to $30 million.

Forty-five to fifty percent of eastern oyster landings are from the Chesapeake region, slightly less originate in the Gulf of Mexico (Louisiana) and the remaining two to three percent are from other regions including New England.

The average range in market value is $0.55 to $0.60 per pound, meat weight; Gulf oysters average less than $0.40 per pound and Chesapeake oysters average over $0.65 per pound. However, New England oysters, amounting to less than one percent of total landings, have been valued at more than $2.00 per pound. New England and New York oysters have high meat and shell quality, and this quality enables them to command the high prices in Northeast metropolitan markets. These oysters are marketed for the "half-shell trade" which is higher priced than the shucked oyster trade.

Although 13 percent of the total bottom areas currently producing oysters are privately controlled, they produce 50 percent of the oysters marketed (Wallace and Lunz, 1968). Thus both quantity and quality of oysters have been significantly increased by the intervention of man. These results, in addition to the premium prices paid for a quality product in nearby metropolitan areas, augur well for the culturing of eastern oysters.

If an average value of $0.60 per pound is used, about 1.7 million pounds in additional production—a four percent increase in domestic supplies—would be required to generate gross sales of $1 million. This price is conservative in that it reflects the shucked oyster trade rather than the higher priced half-shell trade. Thus, if increased production is profitable at $0.60 per pound, there should be little difficulty in developing markets.

There is a wide discrepancy between current and historical supplies. In 1910 New England production was 2.6×10^7 pounds, or about that of the entire United States in recent years. By 1951 New England production had declined to 1.91×10^6 pounds, or about seven percent of 1910 levels. From 1951 to 1967, production continued to decline, but since 1967, a remarkable recovery has occurred (MacKenzie, 1970). Somewhat less precipitous declines have occurred in oyster production by Middle Atlantic states. The causes of these declines were reviewed by Matthiessen (1970) in his *Review of Oyster Culture and the Oyster Industry in North America* and included: poor sets, misuse of shoreline areas, predation and adverse weather. Another factor involved is public/private control of oyster beds. Management of public beds has traditionally been negligible, except for restrictions on time of harvest, harvesting technology and the catch itself. Virtually no inputs have been supplied, a factor believed by experts to be especially important because failure to return shell results in depletion of the cultch on which new sets are dependent. Predator control has also been absent for public beds.

The intensity of management received by the better private beds (see State of the Art and Production Costs) results in fivefold to tenfold productivity increases. The potential of closed system "factory" production has been explored by Goodrich et al (1968) in an engineering feasibility study, but opinions are mixed on the relative advantages of better management of natural areas as opposed to intensive culture "factory" methods of production. Two things are clear regarding technology: (1) technology exists, or is on the horizon, which will permit considerable expansion in supplies, and (2) the technology possessed by private industry is more advanced than is generally available in the literature, but is often proprietary.

This knowledge could be more widely used in commercial production were it not for the problem of property rights. A prerequisite of intensive management by private industry is the existence of adequate property rights. It is no coincidence that the Long Island Sound/Connecticut coast area is the center of private production and the area in which the most sophisticated management practices are to be found. Historical lease rights are found in that area. Assuming that property rights can be provided, it appears likely that increased production can be effected by private enterprise with the current technology and state of the art.

Demand. Several studies exist which discuss in whole or in part the demand for oysters. These include Working Papers Nos. 10 and 50 by the Department of the Interior, Bureau of Commercial Fisheries, and studies by Sutton and Corrigan (1970) and Purcell and Raunikar (1968).[1]

An analysis of the annual U.S. landings of fresh and frozen oysters (Working Paper No. 10, pp. 15-18) indicates that per capita consumption of oysters is significantly affected by the price of substitutes (clams and scallops), but the effect of oyster prices on per capita consumption is not statistically significant. Purcell and Raunikar, however, found a significant oyster price effect. Income elasticity was found to be negative (Working Paper No. 10). This finding is somewhat suspect, however, in view of the strong secular decline in available supplies. Suttor (1970) found a significant positive relationship between ex-vessel price, deflated by consumer price index, to Chesapeake Bay oystermen, and real per capita disposable income. Data in Working Paper No. 50 indicate (p. 2) no consistent variation pattern in per capita consumption and per capita income. However, the income ranges chosen are rather narrow (from $1 to $3500 with a $3500+ category). Purcell and Raunikar provide (p. 29) the weighted average expenditures per quarter by an Atlanta consumer panel. (See table 4-1.)

The data in this table indicate a low, but positive, income elasticity of demand for fresh and frozen oysters. Furthermore, income elasticity appears to increase with income. It has been contended by many persons in our conversations that the cause of decline in per capita demand has been a shortage of supplies and gradual loss of consumer awareness of oysters. The preceding data on income elasticities are consistent with this contention. The positive income elasticity of demand would indicate that oysters are not an inferior good in consumers' minds and that the cause of decline in consumption lies elsewhere. The availability of supplies is one possibility. It is possible that fear of oyster-borne diseases may have been a contributing factor. It is difficult to confirm or deny this possibility, however. This factor, if it exists, may be overcome by strict quality standards and brand name promotion. Positive income elasticity of demand is encouraging for the prospects of increasing demand, but extensive product promotion will probably be necessary if projected supply increases are to be absorbed without large price decreases.

[1] *The Bureau of Commercial Fisheries has been supplanted by the National Marine Fisheries Service, Department of Commerce.*

Purcell and Raunikar also studied variations in consumption patterns by race, season and family size. They found consumption of oysters to be significantly higher for white households than for nonwhite households. This is the reverse of the findings reported in Working Paper No. 50. The divergence of findings may reflect distinctly different consumption patterns in the South Atlantic states where per capita consumption of oysters is two to three times higher than in most other regions of the country. A comparative study of marketing patterns and methods in the South Atlantic states should reveal information useful for promotion elsewhere in the country.

The two researchers found significantly higher expenditures on oysters in spring and summer. However, due to the methodology used, it is not possible to separate these consumption increases into supply and demand components. The per-capita quantity purchased increased with household size and was greatly influenced by the number of family mem-

Table 4-1. Quarterly expenditures on oysters; dollars per household.

	Dollars per Quarter per Household (Income Elasticity)[1]		
Income Level	**Fresh Oysters**	**Fresh and Frozen Oysters**	**Oysters[2]**
2000	0.28	0.29	0.63
(E_i)	(.21)	(.14)	(.05)
4000	0.34	0.33	0.66
(E_i)	(.29)	(.24)	(.12)
6000	0.39	0.37	0.70
(E_i)	(.23)	(.32)	(.17)
8000	0.42	0.41	0.74
(E_i)	(.29)	(.37)	(.16)
10000	0.45	0.44	0.77
(E_i)	(.33)	(.45)	(.26)
12000	0.48	0.48	0.81

[1] *Income elasticities were computed for the above table as the ratio of percentage changes in expenditures to percentage income change.*

[2] *Includes oysters consumed in other product forms: canned, stew and bisque.*

bers of age 18 or less. Per capita expenditures in dollar terms reached a maximum for three-person households. Maximum observed per capita quantity and expenditures were 0.76 pounds and $0.87 for three-person households.

State of the Art

Methods for culturing the American oyster on a commercial scale have been explored extensively, particularly during the past decade, and certain techniques developed by various investigators and private culturists in North America have been recently reviewed (Matthiessen, 1970). Since the various methods employed reflect to a degree local environmental and economic considerations, the following discussion will focus primarily upon techniques most directly applicable to the New England region.

Reproduction. The most detailed and comprehensive work on oyster culture under controlled conditions has been accomplished at the National Marine Fisheries Service Biological Laboratory in Milford, Connecticut, and this has been reviewed in detail by Loosanoff and Davis (1963). In general, techniques for inducing oysters to reproduce that have been adopted by various research groups and private culturists are patterned after procedures developed at Milford.

The basic procedures are summarized as follows:

> Adult oysters are conditioned for spawning by manipulating the water temperature in the holding tank in such a way as to accelerate the process of gametogenesis. (Conversely, ripened adults may be prevented from spawning, if this is desired, by maintaining temperatures below 18°C.) Depending upon the nature of the water supply and the particular hatchery regime, the adults may or may not be fed cultured food during the conditioning process.
>
> The oysters are induced to spawn by temperature manipulation usually involving a sharp temperature increase to 30°C. (If thermal stimulation by itself does not stimulate spawning, suspensions of oyster gametes added to the spawning trays may trigger the spawning reaction.) (Matthiessen, 1970)

Although oysters which have ripened naturally, i.e., in the natural environment, may by early summer be induced to spawn reasonably easily in the hatchery simply by thermal manipulation, the objective of most commercial operations has been to assure reproduction throughout a good portion of the year. In the late winter or spring, oysters that are not ripe must be further conditioned by artificial means. In late summer or fall, after the normal spawning season, oysters must be reconditioned by similar means, or alternatively ripe adults must be held at temperatures just below that level required for spawning, i.e., approximately 20°C.

Some investigators have obtained their best results by subjecting the oysters to a relatively rapid and steady increase in temperature and by providing large volumes of food during this period. Matthiessen and Toner (1966), working in Massachusetts, found that oysters collected from nature in January, when water temperatures approximated 1°C, could be induced to spawn prolifically as a result of the following procedures: (a) The oysters were held in trays through which seawater circulated at an approximate rate of 48 liters per oyster per day. (b) Water temperature was increased daily by 1°C until it reached 28°C. (c) Algal food (*Cyclotella nana, Skeletonema costatum,* and either *Monochrysis lutheri* or *Isochrysis galbana*) was added at a rate of approximately 10^{10} cells per oyster per day.

Under this regime, satisfactory spawning, initiated by a final temperature rise to 30°C, took place approximately 35 days after the oysters were brought into the laboratory. These investigators believed that the procedure could be hastened by elevating the temperature at the rate of 2°C per day.

Hidu et al (1969), working in Maryland, induced oysters to spawn throughout much of the year by means of thermal manipulation only; provision of supplementary cultured food was found unnecessary. In the early part of the season, the oysters were held in running seawater, at a temperature of 24°C for a period of six weeks. At the end of this period, they were conditioned for spawning.

Rearing of Larvae. The procedure for rearing oyster larvae to the setting stage, or metamorphosis, depends upon a supply of warm seawater free of toxic materials, pathogens and predators, and upon adequate amounts of suitable algal food. Methods of satisfying these criteria vary considerably among various oyster research and production facilities; these have been summarized as follows:

> The (oyster) eggs, once fertilized, are passed through fine sieves to remove unwanted debris, and held in sea water at temperatures of 25 to 30°C. Depending upon the hatchery, this water is usually pre-filtered, and may be treated with antibiotics and exposed to ultra-violet light prior to use. In short, every effort is made to eliminate potential predators, competitors and pathogenic organisms.
>
> Within 24 to 48 hours, the eggs have developed into motile larvae; these are generally transferred to larger tanks (100 gallons or more in capacity) and held at specific densities. Again depending upon the particular hatchery, larval densities may vary from 15 larvae per milliliter of culture water to one larva per two or three milliliters; water temperature may vary from 25 to 30°C, and the water may be changed daily, every other day, or less frequently. The duration of the larval period may vary from 10 to 20 days, depending upon temperature, population density, and abundance and quality of food.
>
> Larval food, in the form of unicellular algae, is usually provided daily. The type of algal food culture, the method by which it is cultured, and the amount fed to the larvae vary from hatchery to hatchery. The favored larval food in certain hatcheries are the small naked flagellates *Monochrysis lutheri* and *Isochrysis galbana*, maintained in limited-volume unialgal cultures under generally aseptic conditions. Alternatively, cultures of mixed and unidentified species may be maintained by clarifying raw seawater by means of centrifuge, thereby removing algal predators and competitors, and obtaining planktonic "blooms" by exposure to sunlight and by addition of inorganic nutrients. Finally, certain hatchery operations have been successful without providing supplementary food; raw seawater is simply passed through a filter of suitable porosity to remove predators and introduced directly into the larval tanks.
>
> When the larvae attain 'setting' size, i.e., when metamorphosis from the motile larval form into the sedentary adult form is initiated, they are transferred to setting tanks. The tanks typically are provided with a layer of oyster shell to which the young oysters attach during metamorphosis. (Recently, methods have been developed whereby the metamorphosing oysters are not allowed to become permanently attached to a substratum, but rather are cultured as single, non-attached oysters.) (Matthiessen, 1970.)

Under this general procedure, private commercial hatcheries on both the Atlantic and Pacific coasts are presently capable of producing considerable numbers of juvenile oysters each year. Some of the techniques developed by private industry apparently are patentable, and specific procedures employed by certain hatcheries have not been disclosed.

Although the rearing of large numbers of oyster larvae through metamorphosis appears to present no major technical difficulties, periodic, heavy, and, in some cases, unexplainable mortalities have occurred. These have been attributed to seasonal incorporation of toxic substances into the seawater supply system, but such substances have not always been defined with certainty. Davis (1969) states that

> Survival and growth of oyster larvae can be drastically reduced by certain metallic salts, insecticides, herbicides, detergents, silt, and even by metabolites of certain natural phytoplankton blooms. Hatcheries must be cautious of locating in areas of heavy domestic or industrial pollution or heavy runoff from intensively pesticide-treated areas, and areas where intensive, possibly toxic natural blooms occur regularly.

The larvae of this species are considerably more tolerant of reduced salinities than the larvae of either the hard clam *(Mercenaria mercenaria)* or bay scallop *(Aequipecten irradiens)*. According to Davis (1969), an oyster hatchery could be located anywhere that the salinity remained about 16.5 o/oo. He has reared larvae to metamorphosis at salinities lower than this. The pH of the water should be kept between 6.75 and 8.75 (Calabrese and Davis, 1966).

Davis (1969) has emphasized the need for extreme cleanliness in the rearing of oyster larvae, citing the fact that the larval and setting tanks in commercial hatcheries are carefully scrubbed with Chlorox and Alconox at each water change to prevent or reduce bacterial contamination.

Rearing of Juveniles. The post-larval (juvenile) oyster, after completing metamorphosis in the hatchery, is usually transferred to the natural environment as soon as ambient water temperatures are high enough to permit growth and to assure a high percentage of survival. Then there is no need to culture the large volumes of food required for rapid growth.

Matthiessen and Toner (1966) found that, in order to sustain a weekly shell growth increment of two to three millimeters among oysters initially averaging 15 millimeters in shell height, 8×10^7 algal food cells were required for each oyster per day. Roughly four weeks were required for newly set oysters to attain a shell height of five millimeters when fed at a rate of 3×10^7 cells per day. Goodrich et al (1968) have estimated that an oyster approaching three inches in size would require 10^9 food cells each day for sustained growth. Clearly, the daily food requirements of large numbers of oysters approaching market size are enormous; it is exceedingly doubtful that such quantities of food could be cultured on an economical basis. As Davis (1969) points out, "It seems much more practical, at present, once the spat have been obtained, to allow the growing oyster to harvest its food from the sea than to grow the enormous quantity of the phytoplankton necessary to feed the oyster from seed to market size."

Ukeles (1965) has described a method of culturing large volumes of algae in outdoor tanks, whereby the cost of providing artificial illumination to promote photosynthesis would be eliminated. In this method, artificial seawater is used as the culture medium to reduce chances of contamination of the cultures. In New England, this approach might be limited by seasonal variations in both temperature and sunlight. If employed on a commercial scale, the cost of the artificial seawater might be substantial.

Claus and Adler (1970), in seeking an alternative for algal food for oysters, have described the use of specially treated living red blood cells as food. Their results indicate highly favorable rates of growth, comparable to those obtained by control groups reared on an algal diet. This experiment lasted for a period of only eight weeks, and, therefore, its application to a large-scale production facility has not been fully demonstrated. It nevertheless represents an interesting possibility for reducing food production costs, since the blood is a waste product of slaughter houses. Reportedly, after inexpensive treatment, the blood may be readily stored under refrigeration.

A recent attempt has also been made to culture juvenile oysters to maturity in artificial growth chambers, in which the requirements for food, oxygen and waste removal are satisfied by a continual flow of untreated seawater (Johnson et al, 1968). The primary advantage of this system is the high survival rate of the oysters resulting from the elimination of natural predators. The practical aspects of expanding this system to a commercial operation have not been fully tested at this time, although pumping and maintenance costs, e.g., control of fouling and oyster waste removal, must be considered.

Food. Methods for culturing algal food for oysters have been summarized by Goodrich et al (1968). As discussed in detail by Davis and Guillard (1958), the following generalizations regarding algal foods can be made: (1) The food cells should be small, preferably less than 15 microns in size; (2) Algae with heavy cellular walls, such as *Chlorella,* do not appear to be readily assimilated by oysters; (3) Oyster larvae, particularly in their early stages, appear to thrive best on a diet of naked flagellates rather than of diatoms, and (4) Certain algal forms, including *Chlorella* and *Prymnesium,* may produce metabolites that are toxic to oysters, particularly to the larvae.

Initially, many of the commercial oyster hatcheries in the Long Island Sound area obtained food simply by clarifying seawater by means of centrifuge to remove zooplankton, large algae and detritus and allow the small phytoplankton remaining in the clarified water to bloom by exposure to light. According to Davis (1960), most hatcheries now maintain certain species under culture as well, in order to insure sufficient food at all seasons. In any event, provision of sufficient food for larvae does not appear to be a problem, since their daily food requirements are relatively low.

Claus and Adler (1970) have given figures on daily food requirements of oysters at different stages of development; these are summarized in table 4-2.

It is evident from the data in table 4-2 that sustaining the rapid growth of oysters approaching marketable size requires such large volumes of food as to cast doubt on the practicality of culturing algae for this purpose. Although some investigators have found that the quality of oyster meats may be substantially improved by providing oysters with certain cereals in fine particulate or colloidal form (Haven, 1965; Dunathan et al, 1969), successful rearing of oysters from spat to marketable size on such a diet has not been reported. It is possible that the use of treated blood cells, as described by Claus and Adler (1970), may be of practical value, although its feasibility on a commercial scale awaits further investigation.

Major Technical Problems. The major technical problem in culturing oysters under controlled conditions is the provision of adequate amounts of suitable food from the post-larval to adult stage. Assuming a dense algal culture to contain 10^7 cells per milliliter, or approximately 4×10^{10} cells per gallon, one gallon of food would satisfy the daily requirements of only 40 rapidly growing oysters that were approaching marketable size.

If the oysters are to be fed simply by pumping untreated seawater through the tanks, and it is assumed that each gallon of seawater contains 4×10^7 food cells, each mature oyster would require 25 gallons of water each day in order to sustain rapid growth.

Culture in the Natural Environment. Commercial oyster operations today rely heavily upon the natural environment for maturation of their crop and, to a large extent, for their supply of seed oysters. According to MacKenzie (1970), there are presently five oyster hatcheries operating in the Long Island Sound area, with a sixth under construction. These hatcheries have been effectively used to assure a more predictable supply of seed oysters each year, as well as to develop desirable genetic strains. They also have been employed as a means of acquiring "cultchless" oysters that, grown as singles, may have improved shape and quality and may reduce the labor in culling. However, the great percentage of oysters that are harvested from this area today derive from natural sets (J. R. Nelson, personal communication), suggesting that such sets, although irregular in occurrence, dwarf hatchery production in terms of volume.

Although oysters reproduce reasonably reliably in certain areas of Maine, New Hampshire and northern Massachusetts, local reproduction has not been sufficient to sustain an industry of much magnitude. Even from Cape Cod southward, where the New England oyster industry is centered for the most part, there are few areas where natural reproduction presently occurs on a thoroughly reliable basis. This is why oyster hatcheries were established in the Long Island Sound region during the past decade. Although such hatcheries offer great opportunity for development of improved oyster strains as well as provide the means for producing single, cultchless oysters, they are expensive to construct and to operate. Moreover, a certain technical proficiency is required. Obviously, if natural sets could be obtained regularly, the commercial importance of hatcheries would be diminished.

The opinion has been expressed (C. MacKenzie, personal communication) that a considerably greater volume of seed could be obtained through natural reproduction, at least in the Long Island Sound area, if certain management techniques were practiced. These would include removal of predators and silt from setting areas, careful monitoring of the larvae, spreading of dock-dried shells (cultch) on the beds at the appropriate time, and systematic control of predators once setting has occurred.

Certain of these practices would not be required if suspension techniques were employed. One private firm in New England, making use of a brackish pond heavily populated with oysters, has obtained intensive sets during eight of the past nine years by suspending strings of shell from rafts at

Table 4-2. Daily food requirements of oysters.

Age of Oysters	Algal Food Cells (Per Oyster Per Day)
larva (2 days old)	1×10^4
larva (12-15 days old)	2×10^4
larva (setting size)	5×10^4
spat	2×10^5
spat (3 weeks old)	3×10^6
spat (8 weeks old)	2.4×10^7
seed oyster	8×10^7
adult oyster (3 inches)	1.1×10^9

the appropriate time. The seed oysters then were sold to private growers, who spread them upon their growing beds. Since the oysters, while in the pond, are never in contact with the bottom, methods for removing bottom-crawling predators or avoiding siltation are not required. The shells used for cultch are dry and clean, and the occurrence of larvae is carefully monitored.

Nevertheless, areas in New England where setting always occurs in significant quantity on an annual basis, particularly north of Cape Cod, are believed to be rare. Unless a private grower has access to such an area, it would seem that a hatchery facility would be required, at least on a stand-by basis, for some production during poor setting years.

MacKenzie (1970) has stated that oyster production has increased more than tenfold in Long Island Sound, off Connecticut, since 1966. He has attributed this dramatic change to vastly improved predator control practices and to the movement of seed oysters away from heavily silted areas at the appropriate time of the year. The use of lime (CaO), at a rate of up to 2,000 pounds per acre, has reduced seed oyster mortality from starfish predation to 5 to 10 percent. Oyster drills have been controlled by suction dredge or application of a hydrocarbon compound, with similar reductions in mortality. The growers have greatly reduced mortalities from siltation by moving the young oysters early in the year, before warming water temperatures stimulate pumping activity. MacKenzie (1970) estimates that, whereas in previous years one bushel of seed oysters could be expected to yield one bushel of market-sized oysters, the current yields may be in excess of ten bushels of adults per bushel of seed.

These facts suggest that, if oyster beds are managed properly, losses from predation and siltation may be insignificant. Alternatively, it is possible to employ suspension techniques whereby these problems need not be considered.

Oysters have been cultured by suspension from rafts, on a somewhat limited scale in New England (Shaw, 1968; Matthiessen, 1970). The usefulness of this approach, however, may be severely limited in many areas by moving ice, storms and boat traffic.

One private concern has adopted the use of underwater racks, which are free of surface hazards, but nevertheless maintain the oysters in suspension above the bottom. In addition to the costs of rack construction and handling, additional expenses are incurred in the construction and handling of shell strings suspended from the racks themselves. It is believed, however, that these additional costs will be compensated for by elimination of the need for predator control and avoidance of siltation, as well as by improved growth rates and possibly higher oyster quality.

Production Costs

Culture in a Controlled Environment. Goodrich et al (1968) have synthesized costs for a hypothetical manufacturing plant for rearing oysters. The production subsystems are generally applicable to bivalve mollusks. The plant would produce 200,000 bushels per production cycle. Their published study is detailed and comprehensive. Several systems were included in their plant: (1) an algal culture system, (2) a hatchery system, (3) a growing tank system, and (4) a water supply system. Each of these included one or more subsystems and/or alternatives. The water supply system, for example, included alternative water sources and subsystems for recycling water and for waste disposal. Costs were synthesized for each component of each subsystem and alternative, and these were then used in a cost analysis of critical parameters. Production costs were estimated to range from $8.50 per bushel to $72.00 per bushel. The wide range reflects the range of alternatives and subsystems analyzed, which in turn reflects the uncertainties that surround the critical parameters.

The critical parameters determining feasibility were found to be (1) water requirements for postlarval stages, (2) food requirements, (3) stocking density per unit volume of growing tank, and (4) growth rates (time required to reach market size). The ratio of maximum to minimum flow requirements explored was 36, while the ratio of maximum to minimum food requirements explored was approximately 5.

The importance of food costs is supported by other commercial hatchery operators. E. Fordham (personal communication) has estimated a production cost of $0.02 per gallon of cultured algal food. Half of this cost covers labor expense; the other half covers operating expenses such as heat, light, nutrients, etc. At consumption rates mentioned in the bio-technical discussion, this implies a daily cost for algal culture of about 5×10^{-2} cents per bushel per day.

If unenriched seawater containing 4×10^7 food cells per day were pumped through growing tanks, about 25 gallons per oyster per day would be needed. Electrical costs for large volume (2.0×10^3 gpm) irrigation pumps are about $3.00 per day. On this basis, approximately 100,000 mature oysters, or about 350 bushels, could be reared at a cost of less than $0.01 per bushel per day, pumping costs only. Assuming a six-month growing season, and further assuming that three years would be required for the oyster to reach minimum market size after setting, it is roughly estimated that the pumping cost for raising oysters to maturity in this manner would approximate $0.01 per oyster. This would not include the cost of land, equipment, construction and maintenance. Therefore, although this approach might be considerably more economical than attempting to culture food, it would nevertheless incur expenses that would be avoided by allowing oysters to grow in a completely natural environment.

The ratio of maximum to minimum stocking densities in the Goodrich study was 12. The ratio of maximum to minimum growth rates was two. It was concluded that more fundamental data are needed from which accurate designs can be generated.

Six recommendations were made based on the cost analysis: (1) study and evaluate means of controlling the sex process; (2) establish process conditions required for minimum practical growing period; (3) define the effect on growth rate of water flow, temperature, and type and amount of food; (4) evaluate various conceptual designs for varying stocking density per unit volume; (5) further study continuous algal culture if algal food is required beyond seed size, and (6) study market potential and include an appraisal of the future cost and prices to that of oysters produced by traditional means.

We conclude that at the present time culture in a controlled environment is of questionable economic feasibility for oysters, clams or bay scallops.

Culture in the Natural Environment. Several firms in the Long Island Sound area off Connecticut are culturing oysters, using what may be characterized as extensive techniques. Considerable investment in environmental and predator control has been made at various stages of the life cycle. In contrast, there are no cultural practices on public beds. The level of investment per unit of product appears less than in the intensive system synthesized by Goodrich. The small number of firms and the proprietary knowledge involved preclude release of realistic production cost estimates. Conversations with individuals in the industry and with state personnel suggest that profitable production is possible on leased beds using modern predator control methods and efficient harvesting technology and making seasonal transplants of seed oysters. Furthermore, the persons interviewed seemed to believe that production can at the present time be done more cheaply by extensive culture than by intensive culture systems.

A prerequisite of such a system is a lease tenure of reasonable duration. Present production is done on long-term leases and grants; the latter were granted in perpetuity prior to 1915. While perpetuity may be unnecessarily long, a period of several production cycles would be necessary to warrant capital investment.

In summary, oyster culture appears feasible at present product prices, and expansion on existing leases can be anticipated. Further expansion depends on market considerations and on the availability of leases on the ocean bottom that can be made suitable for oyster culture.

From the preceding discussion, the following conclusions emerge with respect to supply-and-demand prospects in the oyster industry: (1) private producers have the technical knowledge and capacity to greatly increase supplies at existing prices, and (2) the principal difficulties in increasing supplies and developing the industry are legal (acquiring adequate property rights in areas suitable for production) and in marketing (developing markets capable of absorbing increased production at profitable prices).

The Hard Clam *(Mercenaria mercenaria)*

Supply and Demand

Supply. Bureau of Commercial Fisheries Working Paper No. 55 (April 1970) contains basic economic indicators for clams. Since considerable differences exist among species, reference is also made to annual issues of *Fishery Statistics of the United States*, particularly the regional statistics contained therein.

An increase of 3.7×10^7 pounds in clam landings occurred during 1956-1966. About 3.1×10^7 pounds, or 84 percent, of this increase can be accounted for by increased New Jersey landings. Other states made substantial increases in percentage terms but because of the small absolute magnitude of their landings, their impact on the national total was minor. Imports have been of minor importance, averaging about 2×10^6 to 3×10^6 pounds annually. Domestic landings of all clams in the U.S. in 1967 were 7.2×10^7 pounds valued at $\$2.1 \times 10^7$ ex-vessel ($0.29 per pound). Of this total, about 1.6×10^7 pounds, or 23 percent, was comprised of hard clams. On a dollar basis, however, hard clams were valued at $\$1.2 \times 10^7$ or about 58 percent of the total value of all clams, reflecting the higher ex-vessel price of hard clams ($0.74 per pound). Thus the clam market is one of significant volume. The hard clam market, although small compared to the total clam market, is significant.

On a per capita basis, supplies increased by 32 percent from 0.269 pound per capita to 0.355 pound per capita during 1952-1967. Clam imports have been fairly stable, although a shift in the composition of imports has occurred from fresh and frozen to canned. During this same period, hard clam supplies have fluctuated in the range 1.4 to 1.7×10^7 pounds with no evident trend. The major portion of hard clam supplies originates in the New England and Middle Atlantic states. New England's share of U.S. hard clam landings declined from 32 percent in 1952 to 18 percent in 1967, while Middle Atlantic landings rose from 54 percent in 1952 to 63 percent in 1967. This shift reflects an absolute decline and an absolute increase in the landings of New England and Middle Atlantic states respectively.

The maximum sustainable yield (MSY) of hard clams in Atlantic waters has been projected at 3.21×10^8 pounds (Working Paper No. 55, p. 30). Other stocks are believed to exist, and some are known to exist but are not currently exploited. The above MSY estimate is based on increased exploitation and on artificial rearing. If imports are assumed to remain stable and supplies exploited for the U.S. market are restricted to the Northwest and West Central Atlantic stocks, with cultivation the estimated MSY is 2.25×10^8 pounds. This estimate is 14 times larger than 1967 landings, but it includes the effect of increased culture. This effect will materialize only when prices rise sufficiently to attract and warrant commercial culture and adequate bottom lease rights are made available.

There are commercial clam culturists at the present time. Since their knowledge has been gained at considerable personal expense, they are understandably reluctant to supply free information on cultural techniques or production costs. It may be concluded, however, that commercial production is at least marginally feasible and can be expected to attract more producers in the future, provided adequate bottom leases are available. Supplies from public beds do not necessarily increase with market price as is true with most products; this is a consequence of the common property rights associated with public beds. In the absence of definite property rights, no incentive exists for resource conservation. Market forces tend to result in resource depletion and diminution of sustainable flow. Under a common property regime, the supply curve of a fishery will be negatively sloped for excessive levels of fishing effort. This pattern of management is to the advantage of neither harvester nor consumer. Commercial aquaculture, through bottom leases, may permit realization of potential production by better conservation measures and by improving the productivity of the natural resource.

Demand. Price and income elasticities of demand for clams have been estimated to be −0.61 and +0.25, respectively (Working Paper No. 55, p. 14). While not large, income elasticity is positive and has led to a gradual rise in demand over time. This rise has enabled prices to remain relatively stable despite increased per capita consumption. In the case of hard clams, total supplies have been relatively stable; per capita supplies have declined, and prices have risen from $0.42 per pound in 1952 to $0.74 per pound in 1967. This price rise presumably reflects both the decrease in per capita supplies and increased demand resulting from rising per capita incomes. Assuming an annual population growth of 1.5 percent and an annual real per capita income growth of 1.5 percent, annual supply increases of about 1.9 percent could be absorbed with stable prices. At 1967 supply levels, this annual increase would amount to 3.0×10^5 pounds valued at $\$2.2 \times$

10^5. Within five years, the market value of these supply increases would total in excess of $\$10^6$.

The per capita consumption of fresh and frozen clams differs considerably between New England and other regions. Specifically, consumption in New England in 1969 was 0.638 pound per capita which is seven times larger than the next highest (Pacific) consumption region (Working Paper No. 55, p. 9). The third highest region was the Middle Atlantic region with .072 pound per capita. The population concentration coupled with high per capita consumption levels in the New England-Middle Atlantic region implies that most supplies are eventually consumed in these regions. A large population accustomed to consuming clams exists in these regions; promotion efforts in these regions would probably have less consumer resistance to overcome.

State of the Art

Methods for inducing the hard clam to spawn and for rearing the larvae through metamorphosis were described more than 20 years ago by Loosanoff and Davis (1950). Since that time, this species has been cultured in captivity by various investigators in the New England area, including Carriker (1956), Turner and George (1955) and Matthiessen and Toner (1966). In certain respects, this species may be more readily cultured than other species of bivalve mollusks of commercial importance. General procedures are described and reviewed by Loosanoff and Davis (1963).

Reproduction. The hard clam, unlike the oyster, does not resorb its gonads if held for prolonged periods at a temperature below that required to stimulate spawning (Loosanoff and Davis, 1963a). There is no "refractory" period, and adults held at slightly below 20°C may be induced to spawn at virtually any time of the year. Loosanoff and Davis (1950) reported that clams brought in from nature in winter, when water temperatures approximated 0°C, ripened successfully in trays of running seawater in which the temperature was elevated several degrees every three to five days until it reached 20 to 22°C. Carriker (1961) induced clams to spawn in early summer by warming the water to 38°C and by adding suspensions of clam sperm as stimulus. In order to obtain larvae later during the summer, ripened adults collected in mid-June were held at 15°C; satisfactory spawning occurred as late as mid-August when these were exposed to higher temperatures.

Turner and George (1955) took adult clams from Maine, from where they had been shipped in early spring, and induced them to spawn throughout the summer months by exposing them to temperatures of 26°C and adding sperm or egg suspensions to the spawning containers. Temperatures of the Maine waters in which these clams were held never rose sufficiently to stimulate spawning even during summer.

In general, this species appears to respond readily to thermal manipulations and stimulation by suspension of eggs or sperm as a means of inducing spawning. According to Loosanoff and Davis (1963a), a large female is capable of producing as many as 24 million eggs at a single spawning.

Rearing of Larvae. According to Davis (1969), the fertilized eggs of the hard clam are rather sensitive to low salinities and fail to develop in water of salinity below 22 o/oo. The larvae, however, are hardier and "can survive and grow reasonably well at salinities of 17.5 or even 15 o/oo." Loosanoff and Davis (1963b) state that the optimal salinity for egg development is about 27 o/oo; they found that the optimal temperature for rearing larvae lies between 25° and 30°C, and that larvae reared at the latter temperature may begin to set as early as the seventh day after spawning.

Clam larvae appear to be considerably less particular in food requirements than oyster larvae. They have been cultured successfully, from straight-hinge state to metamorphosis, on a variety of food, including certain diatoms, such as *Nitzschia closterium* (or *Phaeodactylum tricornutum*) (Turner and George, 1955) and *Cyclotella nana* (Matthiessen and Toner, 1966); flagellates, including *Monochrysis lutheri* and *Isochrysis galbana* (Davis and Guillard, 1958); green algae, such as *Chlorella obliguus* (Hidu and Ukeles, 1962), and even filtrates of various cereals such as pablum (Carriker, 1961).

Matthiessen and Toner (1966) found that the survival of larvae was highest when these were cultured at densities of five or less per milliliter of culture water, and when the culture water was changed daily. Unlike the oyster, which does not undergo metamorphosis until it has attained nearly 300 microns in size, clam larvae generally metamorphose at a size of 200-215 microns.

Hidu and Tubiash (1963) have found that the growth rate of both clam and oyster larvae may be accelerated by the addition of the antibiotic "Combistrep" (dihydrostreptomycin-streptomycin sulfates) to the culture water at concentrations up to 2,000 parts per million. Evidently this antibiotic promotes the growth of certain forms of bacteria of nutritional value to the larvae, while eliminating certain pathogens detrimental to larvae.

Although clam larvae apparently are less sensitive to pollutants in the water than oyster larvae (Davis, 1969), they are nevertheless susceptible to disease. In addition to infections by fungus, as described by Davis et al (1954), the larvae may also suffer high mortalities as a result of bacillary necrosis (Tubiash et al, 1965). The latter authors conclude, however, that at least short-term control could be reached through use of various antibiotics, including Combistrep, Chloramphenicol and certain others.

Rearing of Juveniles. Although the hard clam is a species that spawns readily in captivity, and the larvae are relatively hardy, little has been reported on the rearing of juveniles under controlled conditions, at least, with respect to food and water flow requirements.

Matthiessen and Toner (1966) described the growth of post-larval (approximately .2 millimeter) clams cultured in trays; more than 50 days were required for these to attain an average size of two millimeters. The clams were fed daily a diet of *Cyclotella nana* in combination with either *Monochrysis lutheri* or *Isochrysis galbana*. The feeding rate was initiated at approximately 10^5 food cells per clam per day and was gradually increased to about 6×10^5 cells per clam per day as they reached two millimeters in size. At the end of an additional two months, during which they were fed on a similar diet at a rate of nearly 10^7 food cells per clam per day, the clams in one group averaged eight millimeters in size.

A considerably faster growth rate was obtained by holding the juveniles in flowing water to which algal food was added continuously; in this case, the clams reached an average size of nine millimeters within approximately two months. Toward the end of this experiment, roughly 46 gallons of algal food were required daily to satisfy the requirements of 10,000 quahogs. The maximum feeding rate approximated 4×10^7 cells per clam per day, and the water flowed through the six-liter containers at a rate of 108 gallons per day. Survival under these conditions, however, was relatively low due to invasion of the culture containers by the ciliate, *Vorticella,* which grew profusely over the tiny clams and smothered most of them.

Because of the voluminous food requirements of juvenile clams, it does not appear to be practical to attempt to provide the usual cultured food for large numbers. On the other hand, tiny clams cannot be transferred from the hatchery and planted directly in nature without the risk of heavy losses from predation (Carriker, 1956). Matthiessen and Toner (1966) attempted to culture three-millimeter juveniles in nature by holding them in sediment-filled buckets, supported on floating trays. At the end of the growing season, these clams averaged only ten millimeters in length, and survival was relatively poor due to algae fouling the surfaces. The practicality of this approach on a large scale is doubtful.

Carriker (1959) found that a relatively high percentage—over 80 percent—of juvenile clams planted in nature would survive if protected by one-fourth-inch mesh fencing. More recently, Castagna et al (1970) have reported more than 80 percent survival of juvenile clams protected by aggregates, e.g., particles of shell, gravel, etc., spread over the planted area. The aggregate material prevents crabs and other predators from dislodging the small clams from the sediment. How the growth rate of small clams may be affected by planting in such material has not been reported.

Food. As indicated earlier, although the hard clam appears to be considerably less selective in its food choice than the oyster, the rearing of large numbers of clams successfully on other than an algal diet has not been reported. Even certain dried algae, apparently satisfactory for clam larvae, do not appear to be a particularly satisfactory diet when fed to juveniles (Hidu and Ukeles, 1962). Furthermore, although clam larvae and juveniles will grow on a diet of readily-cultured algae such as *Chlorella,* their growth rate is not as satisfactory as when they are provided diatoms or flagellates. In addition, metabolites resulting from heavy concentrations of *Chlorella* may be toxic. Therefore, at present, commercial clam rearing facilities probably must rely upon the production of large volumes of living unicellular algae, in the form of diatoms or naked flagellates. Green algae such as *Chlorella* may be used to a limited extent.

Algal food requirements for clams do not present any particular problem until after the larval stage, as is true with the rearing of other bivalve mollusks under controlled conditions. It can be assumed that for sustained growth the food requirements of a larval and ten-millimeter clam differ by several orders of magnitude.

Major Technical Problems. Certainly the major technical problem in rearing hard clams under controlled conditions is the provision of sufficient food for the post-larval stages. Compared with the bay scallop, which may attain a marketable size within a single growing season, the hard clam does not grow rapidly and generally requires a minimum of two years to attain marketable size. During this period, large volumes of food are needed to produce commercial quantities of clams. This species may assimilate and grow upon various unicellular green algae, living or dead, and suggests the possibility for the mass rearing of readily-cultured algae, such as *Chlorella* or *Scenedesmus*. But, unless the juvenile clams exhibited a fast rate of growth under such conditions, it is doubtful that this approach would be economical.

The alternative would be to hold clams in continually flowing seawater, from which they could derive their nutrition directly. However, according to figures from Matthiessen and Toner (1966), post-larval clams one to ten millimeters in size require an average of 4×10^7 food cells per day to sustain a weekly growth increment of one millimeter, even when held at temperatures favorable for growth. This food demand would be expected to increase with increasing size if the same rate of growth were to continue. The culture of juvenile clams to marketable size under such conditions has not been reported in detail.

Culture in the Natural Environment. Because of their food requirements, it would seem far more practical at this point to culture clams in the natural environment, relying upon natural seawater as their primary source of nutrition. Certain factors should be considered if this approach is taken.

According to Turner (1953), the natural continuous range of this species extends from Cape Cod southward; north of Cape Cod, populations tend to be isolated and restricted to areas where local seasonal warming of the water permits spawning. Dow and Wallace (1955) state that in Maine, natural sets are infrequent. The great percentage of hard clams in Maine are limited to the area of Casco Bay.

Even in southern New England, the setting intensity of this species in any given area may be highly variable from year to year. Carriker (1959), working in a salt pond in Long Island Sound which was naturally populated by clams, found relatively few survivors of summer spawning despite the occurrence of larvae. Heavy clam sets frequently do occur in southern New England; however, for any particular area, and with few exceptions, such occurrences are sporadic and unpredictable. Therefore, efforts to culture clams on a commercial scale in New England would appear to have a limited chance of success without a means of guaranteeing successful reproduction each year, such as a hatchery facility.

Since hard clams are relatively sedentary, methods for containment in natural areas would not be required. However, hard clams are highly vulnerable to predation, particularly in the very early juvenile stages. The most serious predators appear to be various species of crabs (Carriker, 1959), which have reportedly destroyed almost the entire population of newly set clams in a given area.

Carriker (1959) found that such predators could be effectively excluded from planted areas by erecting fencing, consisting of one-fourth-inch mesh galvanized wire buried one-half foot beneath the surface of the sediment and extending three and one-half feet above the sediment. Over a period of one year, approximately 80 percent of the planted juvenile clams survived. However, it was found necessary to continually remove those crabs sufficiently small to pass through the mesh. After molting and increasing in size, the crabs were unable to escape. The extent to which fencing may be feasible on a large scale has not been demonstrated.

In the northern portion of its range, the hard clam grows relatively slowly. Although Belding (1931) reported that, in certain areas of southern Massachusetts, this species might attain a length of two inches within two years after setting, it may require anywhere from three to six years in Maine (R. L. Dow, personal communication). Ansell (1969) found that even under temperature conditions considered optimum for growth seasonal variation in phytoplanktonic food abundance seriously limits the growth rate in nature. If hard clam juveniles are densely planted in natural areas, it seems likely that at least three years would be required for maturation of the crop and, in areas of low current flow, possibly longer.

Production Costs

Culture in a Controlled Environment. As noted earlier, the discussion of oyster culture in a controlled environment is generally applicable to bivalve mollusks. It seems unlikely that the costs of culture in a controlled environment are warranted for oysters. It seems even less likely that controlled culture is warranted for clams which are of lower value than oysters and can also be cultured in a natural environment.

Culture in the Natural Environment. We have attempted to ascertain production costs of hard clam culture in a natural environment. Production costs for a hatchery (to assure availability of seed) could be estimated by synthesis from bio-technical data, as was done for oysters (Goodrich et al, 1968). A check on hatchery costs is available since seed are marketed. However, insufficient published information exists about juvenile phases to project accurately the costs of producing clams to a marketable product for consumption. There are commercial producers in existence, but we do not know whether or not these operations are profitable. Probably the degree of profitability is highly variable, depending on particular circumstances. We suspect that operations are of marginal profitability at the present time, but this picture will probably improve with rising prices.

The Bay Scallop *(Aequipecten irradians)*

Supply and Demand

Supply. Supplies of scallops include sea scallops and bay scallops. Domestic landings of sea scallops have been in the range of 10 to 26 $\times 10^6$ pounds per year since 1960, with lower landings predominating since 1964. Imports have been in the range of 7 to 16 $\times 10^6$ pounds per year during this period. Total supplies available for domestic consumption have been about 32 to 36 $\times 10^6$ pounds per year with the exceptions of 1967 and 1968. In those two years, total supplies were about 26 $\times 10^6$ pounds per year. Annual per capita supplies were in the range 0.17 to 0.20 pound per capita except for 1967-1968 when they declined to 0.13 pound per capita. Ex-vessel prices were in the range $0.35 to $0.66 per pound except in 1967-1968 when they rose to $0.76-$1.11 per pound.

Supplies of bay scallops were in the range 1.5 to 3.2 $\times 10^6$ pounds per year valued at $1.1 to $2.1 $\times 10^6$ per year. Ex-vessel prices for New England bay scallops were $0.71 to $1.28 per pound from 1960 to 1963 with prices since 1963 being $1.22 or higher. In 1968, a record price of $1.58 was received. If the bay scallop were viewed in isolation from the total scallop market, the market volume criterion would be rather unfavorable. At 1967 prices, the supply increase associated with $$10^6$ additional sales would be about 75 percent. If the market volume criterion were applied to the total scallop market, the supply increase associated with additional sales of $$10^6$ would be only 3 percent.

Inclusion of the bay scallop in this chapter has been based on a comparison of the supply increase with total scallop market volume. In choosing the total market as a basis of comparison, we recognize the decline in supplies of sea scallops which has occurred in recent years and the potential substitute role of bay scallop culture in filling this gap. At the same time, we note that natural supplies of sea scallops may recover through a resurgence of historically-exploited stocks and/or exploitation of new stocks of sea and calico scallops. New stocks have been discovered in recent years (National Marine Fisheries Service, Working Paper No. 54, April 1970). The effect of recovery of natural supplies is considered in the following discussion of demand.

Demand. A statistical analysis of bay scallop prices in New York City's Fulton Fish Market was performed. The analysis indicated an own-price elasticity of -2.48 and a cross-price effect of $+2.06$ with sea scallop prices. The latter coefficient indicates a rather strong positive relationship between sea scallop prices and bay scallop prices. Consequently, a resurgence of sea scallop supplies would depress sea scallop prices and also depress bay scallop prices in the New York market. New England markets, especially at the ex-vessel level, might be somewhat insulated from this effect, but a culturist dependent on New York markets would probably experience a pronounced price effect.

The only available estimates of income elasticity are those by Purcell and Raunikar (1968, p. 14), and the National Marine Fisheries Service (Working Paper No. 54, p. 18). The cross-sectional data reported by Purcell and Raunikar suggest low, but positive, income elasticity of demand. The estimated price and income elasticities for sea scallops reported in Working Paper No. 54 are −0.63 and +0.43, respectively. Assuming real per capita income growth of 1.5 percent per annum, annual growth in demand of 0.65 percent could be anticipated at stable prices. Using 1967 supplies and prices as a base, this implies an annual demand growth of about $\$3.88 \times 10^5$. In a period of about three years, cumulative growth in demand would permit absorption of $\$10^6$ increase in supplies at stable prices. These comparisons assume stable natural supplies. As noted earlier, a resurgence of natural supplies of sea scallops could invalidate these comparisons.

State of the Art

As compared to the American oyster *(Crassostrea virginica)* and hard clam *(Mercenaria mercenaria)*, relatively little work has been done in bay scallop culture. However, this species has been induced to spawn and the larvae have been reared successfully through metamorphosis by various investigators (Loosanoff and Davis, 1963; Matthiessen and Toner, 1966; Sastry, 1965; Castagna, personal communication). It also has been reared from the post-larval stage to marketable size under controlled (in the laboratory) conditions as well as in the natural environment.

Reproduction. Methods for inducing a wide variety of bivalve mollusks to reproduce in captivity have been developed and described by Loosanoff and Davis (1963). The basic procedure involves exposing the animals to levels of water temperature sufficient to initiate or accelerate the process of gametogenesis. When the animals have reached sexual maturity, spawning, or the shedding of gametes (eggs and sperm) into the surrounding water, may be induced by further temperature manipulation. In some cases, the ripened animals are exposed to suspensions of eggs and sperm of the same species. Different investigators have used various modifications of this generalized approach.

Loosanoff and Davis (1963) reported that bay scallops were induced to spawn by bringing adults from nature—during February when water temperatures were probably near 0°C—into the laboratory where, after a brief period of acclimation, the scallops were held at 20°C for 23 days. At the termination of this conditioning period, the animals were exposed to water temperatures of 30°C, which triggered the spawning reaction.

Turner and Hanks (1960) obtained scallops from nature during December and January and held these in running seawater (23°C) for a period of three weeks. At the end of this time, histological sections indicated the development of tailed spermatozoa and mature ova, although normal spawning failed to occur. These authors believed that the somewhat erratic results of this experiment and failure of the animals to spawn could be attributed to nutritional deficiencies, since the only food provided was that occurring naturally in the seawater system.

Sastry (1968) also collected his animals from nature during December and initiated reproductive activity by exposure of the animals to 15° and 20°C. At 20°C, animals that were fed 0.0172 to 0.0393 grams (dry weight) of algal food per scallop per day developed eggs of mature size (in excess of 50 microns in diameter) after approximately 30 days. Those held at 15°C failed to develop eggs averaging greater than 20 microns. Animals held at 15°C for ten days, at 20°C for an additional five days, and then exposed to 25°C, spawned normal gametes after two days at the latter temperature. This was approximately half the time required at a stable temperature of 20°C. Control animals which were not fed failed to develop mature sex cells.

Matthiessen and Toner (1966), who obtained scallops from nature in April when water temperatures averaged 7°C, obtained their most satisfactory spawning results by holding the animals at 18°C in continually flowing water, even though 100 days were required at this temperature for the scallops to shed large quantities of eggs and sperm. They recommended that algal food, at densities of 10^4 cells per milliliter, be added daily at a rate of 130 liters for every 12 scallops being conditioned, or approximately 10^{10} food cells per scallop per day.

Castagna (personal communication) has been able to induce scallops to spawn throughout the year. His procedure involves holding the scallops at 18°C for four weeks and at 22°C for an additional two weeks, and then elevating the water temperature rapidly to 28°C. If the scallops fail to spawn as the temperature reaches 28°C, the temperature is lowered to 22°C, a process that frequently stimulates spawning. The scallops obtained sufficient nutrition from food occurring naturally in the flowing seawater system.

All of the above investigators were concerned primarily with the conditioning of scallops "out of season," when gametogenesis and subsequent spawning could be stimulated only by artificial means. It is apparent that methods for temperature manipulation and control are critical, and that in some cases supplementary food provision is also essential. Satisfactory spawning can be reached simply by bringing adults into the laboratory from nature at a time of year when they have ripened naturally (i.e., June and July) and subjecting these to a sharp temperature increase. Although this procedure limits the acquisition of viable gametes to specific times of the year, it eliminates the sometimes costly and laborious process of stimulating gametogenesis artificially.

Rearing of Larvae. Methods of rearing the larvae of bivalve mollusks have been fully described by Loosanoff and Davis (1963), and published work relating to the bay scallop appears to follow their basic procedures. Modifications have included water purification techniques, water change schedule, population densities and the types and concentrations of algal food supplied. However, the two basic requirements for larval culture are (1) a source of warm, contaminant-free water and (2) a supply of algal food generally maintained in the form of unialgal cultures.

With respect to water quality, Matthiessen and Toner (1966) cultured scallop larvae in seawater of salinity of 31 o/oo, that was prefiltered through a one-micron filter; sterilization by ultraviolet light did not appear necessary. The water in the larval containers of 100-liter capacity was aerated, changed daily and maintained at a temperature of approximately 25°C. Both diatoms *(Cyclotella nana* and *Skeletonema costatum)* and a naked flagellate *(Isochrysis galbana)* were maintained in culture as food although *Cyclotella* by itself was found satisfactory during all stages of larval development. Food was added daily to the larval tanks at each water change to provide an initial concentration of 10^5 cells per milliliter. These investigators found the optimum larval density, under these conditions, to be 10 to 20 larvae per milliliter. Certain of the larvae attained setting size, i.e., began to undergo metamorphosis, within one week after initial spawning.

Castagna (personal communication) has maintained larvae at initial densities of 17 per milliliter (straight-hinge); densities at time of metamorphosis were reduced to about three per milliliter. He has found that the diatom *Phaeodactylum tricornutum* is an excellent larval food for this species. He employed an ultraviolet sterilization system, which was not believed to be necessary. Water for the larval tanks was not filtered, but rather was clarified by use of a centrifuge.

For bay scallop larvae, best results were obtained if the salinity of the culture water was relatively high, preferably about 30 o/oo.

Rearing of Juveniles. Little has been published on the rearing of juvenile bay scallops. Castagna (personal communication), working in the relatively moderate climate of southern Virginia, was able to transfer post-larval scallops from the hatchery to semi-natural conditions approximately one week after metamorphosis; the latter involved holding of large numbers of scallops in shallow outdoor trays through which natural, untreated seawater circulated constantly. After a period of several weeks, the scallops were large enough to be transferred to floating trays moored in a lagoon. These trays were approximately 14 square feet in area, and were stocked at densities of 4,000 scallops per tray. Although some trays became heavily fouled, the survival rate was high, and the scallops attained marketable size in approximately one year. Heavy mortalities, however, occurred during ice periods, either as a result of physical damage to the trays, or exposure of the scallops when the trays were pushed above the ice flow.

Matthiessen and Toner (1966), working in southern Massachusetts, obtained best results in terms of growth rate by holding post-larval scallops in eight-liter trays through which seawater, warmed to 28°C, flowed constantly at a rate of approximately 400 liters per day. Each tray held 5,000 scallops, or roughly 24 scallops per square inch of tray surface area. Food, dripped into the tray at a rate of 40 to 100 milliliters per minute, consisted of a combination of *Cyclotella nana* and *Skeletonema costatum* at densities of 1 to 1.65 $\times$ 10^6 cells per milliliter. Under these conditions, the scallops averaged daily growth increments of 85 microns per day and averaged nearly four millimeters in size after one month. Estimated survival during this period was 64 percent.

Matthiessen and Toner (1966) attempted to rear juvenile scallops in nature by maintaining them in fine-mesh screen trays floating in a natural salt pond. These scallops, initially three millimeters in size, increased to an average of five millimeters within a two-week period. Mortality was extremely high, however, as a result of intensive fouling of the screens, and the experiment was discontinued.

Food. The bay scallop appears to subsist primarily upon particles of organic material suspended in the water column in the form of plant cells (phytoplankton) or possibly detritus. Through all stages of its life cycle, including the earliest larval stage, this species can assimilate and thrive upon small diatoms. Three species of diatoms upon which scallops have been successfully reared through the larval and early juvenile periods are *Cyclotella nana*, *Skeletonema costatum* and *Phaeodactylum tricornutum*, which have been cultured in large volumes in commercial and experimental shellfish hatcheries. It is probable that small naked flagellates, e.g., *Monochrysis lutheri* or *Isochrysis galbana*, would be equally suitable. To date, the successful rearing of scallops on other than a living algal diet has not been reported.

We can estimate roughly the amount of algal food required by the bay scallop during certain stages of its life cycle from data provided by Matthiessen and Toner (1966) in table 4-3.

Table 4-3. Daily food requirements of bay scallops.

Stage	Number of Food Cells (Per Individual Scallop Per Day)
larva	10^4
post-larva (early juvenile)	5×10^7
adult	10^{10}

Major Technical Difficulties. These are two: (1) care of the larvae and juveniles and (2) food.

Bay scallop larvae appear to be more sensitive and prone to mass mortalities than the larvae of hard clams and oysters. Recent unpublished evidence appears to indicate that high water quality, i.e., absence of pollutants, is of extreme importance in the rearing of this species in captivity. High mortality rates among some juveniles have been attributed, for lack of other evidence, to toxic substances in the water supply. Unfortunately, the nature of such contaminants is not readily detectable.

The mechanics of handling large numbers of juvenile scallops in captivity have also been found difficult by some workers. This species appears to thrive best in well circulated water, probably since such conditions provide ample oxygen and assure removal of waste products. This requirement may be difficult to satisfy under artificial conditions unless sufficient volumes of water are pumped through the holding tanks to remove all waste material and maintain the tanks in clean condition.

In terms of estimated food requirements, it seems highly doubtful that large numbers of bay scallops could be cultured to maturity in a controlled environment unless foods cheaper than cultured algae can be found. But it is possible that a satisfactory substitute for living algal cells may be developed. Alternatively, the scallops might be transferred to nature shortly after metamorphosis, thereby eliminating food costs.

Culture in the Natural Environment. If bay scallops could be cultured without reliance upon certain artificial techniques described above, major cost considerations such as hatchery construction, operation, and maintenance and algal food culture, would be eliminated. However, other factors would have to be considered.

Even where bay scallops occur naturally, annual reproduction in any given area from year to year is highly unreliable for reasons that are not clear. Marshall (1960) has attributed annual variations in setting intensity to subtle changes in the local hydrographic regime, although such changes have not been defined. In any event, it would seem that regardless of the area in New England selected for culture annual supplies of large quantities of bay scallops will depend upon supplementary hatchery operations as a means for assuring production of juveniles.

Since scallops are reasonably active swimmers, means are needed to retain them within the area selected for culture. Furthermore, they are subject to predation by natural enemies, particularly starfish, which in certain instances may be intensive (Marshall, 1960). Therefore, if cultured in natural areas, methods must be adopted to prevent egress from the culture area and to protect the scallops from predators.

Production Costs

Culture in a Controlled Environment. As noted, earlier, the discussion of oyster culture in a controlled environment is generally applicable to bivalve mollusks. It seems unlikely that the cost of culture in a controlled environment is warranted for either oysters or bay scallops.

Culture in a Natural Environment. As indicated in the State of the Art discussion, published literature on the bay scallop deals with pre-juvenile stages. Survival and growth rates for juveniles after transplanting to a natural environment have reportedly been highly variable for reasons not well understood. Since cost per unit of product is inversely proportional to the rate of juvenile survival, it is impossible to project costs until a reasonably representative survival rate can be defined. With the paucity of data, the most that can be synthesized is an estimate of the minimum survival rate consistent with profitable production. Such an exercise does not seem worthwhile at the present state of knowledge.

One approach, developed by Castagna (personal communication), is that of rearing the scallops to maturity in floating trays although estimates on mortality rates are not available at this time. In areas where fouling by algae, sponges, tunicates, etc., is heavy, continual maintenance would be essential to assure adequate exchange of seawater in the trays. In New England, furthermore, methods of protecting the trays from ice would be necessary.

An alternative method is to culture scallops on the bottom of fenced areas. Marshall (1960) and, earlier, Belding (1931) found, however, that both survival and growth rate were relatively poor under such conditions. The theory was advanced that enclosures tending to reduce circulation were detrimental to scallops. But Castagna (personal communication) has reported excellent growth and up to 70 percent survival among scallops held in pens in the waters of Virginia.

Silver Salmon *(Oncorhynchus kisutch)*

Supply and Demand

The following discussion of supply and demand focuses not only on silver salmon, but on several salmon species of potential interest; the similarity of salmonids in their cultural requirements makes substitution feasible within the same basic rearing facility. Depending on market conditions, it might prove desirable to shift production from one species to another.

Traditionally, salmon and trout have been highly desirable species for food and for sport, and they enjoy a wide market acceptability. Migratory habits and narrow environmental tolerances make them both vulnerable to both dams and pollution in streams. The Atlantic salmon *(Salmo salar)*, formerly abundant from Maryland to Newfoundland, is now all but eliminated from the United States, but there are some trout and salmon privately produced in eastern North America and both species have been cultured in the U.S. for more than a century. Most of this has been in government-owned hatcheries which produce fish for release into natural waters. There is a large amount of technical information and expertise available for the culture of trout and salmon compared to that for other species which we have analyzed. Furthermore, commercial culture and production of rainbow trout *(Salmo giardneri)* is an accomplished fact in Idaho, Washington and Utah.

At least 11 species of salmonid fish are being cultured in hatcheries throughout the country. Since it is technically feasible to raise any of several species, which species to culture depends on demand, supply and cost factors, including: (1) existence of a strong demand demonstrated by the quantity presently being sold and by a high price relative to other species; (2) the potential for increases in natural supplies, and (3) the possibility of profitable production at existing prices.

Supply. Pacific salmon sustain one of the largest fisheries in the United States. Table 4-4 lists the species breakdown for the U.S. and Canada. Annual landings since 1960 have ranged from a low of 2.17×10^8 pounds in 1967 to 3.88×10^8 pounds in 1966. From 1960 to 1963 the U.S. was a net importer of salmon, but since 1964, net exports have been about 40 million pounds per year. Table 4-5 summarizes domestic landings, net imports, inventory changes and apparent domestic consumption of salmon.

Table 4-4. Salmon landings by species 1960-67.

Species	Average 1960-67 (million lbs.)
Chinook *(Oncorhynchus tschawytcha)*	38.0
Silver *(O. kisutch)*	57.0
Sockeye *(O. nerka)*	106.2
Pink *(O. gorbuscha)*	165.2
Chum *(O. keta)*	64.0
Total	410.4

Source: U.S. Department of the Interior, Fish and Wildlife Service, 1967. Fishery statistics of the United States, 1967 and preceding annual issues.

Table 4-5. U.S. supplies of salmon, 1960-1968, in thousands of pounds, round weight.

Year	Landings	Net Imports or Exports[1]	Landings Plus Net Imports	Inventory Change[2]	Apparent Domestic Consumption[3]
1960	235,447	22,751	258,198	448	257,750
1961	310,398	9,300	319,698	1,413	321,285
1962	314,566	5,701	329,267	2,693	317,574
1963	294,177	9,573	303,750	—1,173	285,777
1964	352,246	—48,992	303,254	4,018	299,222
1965	326,806	—40,657	286,149	—45,171	331,320
1966	387,512	—43,658	343,854	47,493	296,361
1967	216,664	—42,855	173,809	—102,663	276,472
1968	310,400	—8,513	301,887	56,159	245,728
average:	290,096				

[1] *Imports minus exports. Minus sign indicates net export.*
[2] *Change between beginning and year-end inventories. Includes fillets and steaks. Beginning 1965 also includes canners' stocks of canned salmon. Beginning 1966 also includes distributors' stocks of canned salmon. Minus sign indicates inventory depletion.*
[3] *Landings plus net imports minus inventory change.*

Source: U.S. Department of the Interior, Bureau of Commercial Fisheries, 1970. Basic economic indicators: salmon —master plan fishery 50-10-48, Working Paper No. 62, p. 33.

Total salmon production is approximately nine times that of trout. The increment of production needed to affect a given percentage in total supplies is, therefore, much smaller for trout than for salmon; this fact is relevant with respect to price fluctuations. Total Canadian and U.S. Pacific salmon landings over 1960-1967 have averaged 4.1×10^8 per year (see table 4-6). Table 4-7 shows landings and values for selected species.

Table 4-6. North American landings of Pacific salmon by species, 1960-1967, in thousands of pounds.

Year	Chinook	Silver	Sockeye	Pink	Chum
1960					
U.S.	24,057	13,665	95,326	52,588	49,811
Canada	9,049	12,801	15,449	16,994	20,304
Total	33,106	26,466	110,775	69,582	70,115
1961					
U.S.	26,962	23,201	103,644	108,452	48,139
Canada	7,945	22,571	26,705	49,658	14,566
Total	34,907	45,722	130,349	158,110	62,705
1962					
U.S.	25,111	27,752	58,049	143,309	60,345
Canada	7,945	24,056	20,084	93,356	18,097
Total	33,056	51,808	78,133	236,665	78,442
1963					
U.S.	27,179	28,131	43,424	156,603	38,840
Canada	9,049	22,952	11,918	59,810	15,449
Total	36,228	51,083	55,342	216,413	54,289
1964					
U.S.	28,732	38,071	57,350	162,325	65,842
Canada	12,139	28,691	22,953	36,416	23,836
Total	40,871	66,762	80,303	198,741	89,676
1965					
U.S.	29,316	38,515	148,119	79,655	31,366
Canada	12,801	36,636	16,332	22,953	6,621
Total	42,117	75,151	164,451	102,608	37,987
1966					
U.S.	27,223	38,755	102,012	163,016	56,506
Canada	15,449	38,623	25,822	73,493	15,449
Total	42,672	77,378	127,834	236,509	71,955
1967					
U.S.	26,181	38,290	66,013	51,721	34,459
Canada	15,449	22,511	37,078	51,644	12,139
Total	41,630	60,801	103,091	103,365	46,598
1960-1967 Averages:					
U.S.	26,845	30,798	84,242	114,709	48,151
Canada	11,228	26,105	22,050	50,541	15,808
Total	38,073	56,903	106,292	165,250	63,959

Source: U.S. Department of the Interior, Bureau of Commercial Fisheries, 1970. Basic economic indicators: salmon —master plan fishery 50-10-48, Working Paper No. 62, pp. 30-31.

Pacific salmon have been cultured and reared on the West Coast since 1872. Eggs are taken from returning adults, fertilized and hatched in tanks and trays in hatcheries located on rivers throughout the Pacific Northwest. All five species of Pacific salmon are cultured, and all are released to the rivers either after six or fourteen months of growth. These hatchery-reared fish go to the sea along with natural spawned fish and return in two to five years to spawn. Between two and ten percent of the hatchery-reared fish return to spawn (Cleaver, 1969). All of the salmon hatcheries are government-owned and all produce fish for release to augment or restore sport and commercial fisheries. There were, at the time of this writing, no commercial salmon production facilities which rear salmon to market size on the West Coast although commercial pilot projects were planned.

World landings of Atlantic salmon *(Salmo salar)* are presented in table 4-8. The world catch of 10,000

Table 4-7. Landings and values of Pacific salmon by species for selected years.

	1964			1967			1968			1969		
	10^6lb.	10^6\$	¢/lb.	10^6lb.	10^6\$	¢/lb.	10^6lb.	10^6\$	¢/lb.	10^6lb.	10^6\$	¢/lb.
Chinook	28.7	11.5	.40	26.2	9.6	.37	24.9	10.4	.42	23.5	9.7	.41
Chum	65.8	5.2	.07	34.5	3.9	.11	61.5	8.4	.14	18.5	2.3	.12
Pink	162.3	17.2	.106	51.7	6.3	.12	148.5	20.5	.14	113.2	15.1	.13
Red or Sockeye	57.3	13.4	.234	66.0	16.1	.24	54.1	15.0	.28	71.3	20.3	.285
Silver or Coho	38.1	8.7	.23	38.3	12.7	.33	38.7	12.1	.31	19.7	7.3	.37

Source: U.S. Department of the Interior, Fish and Wildlife Service, 1964. Fishery statistics of the United States (subsequent years as indicated).

Table 4-8. Landings of Atlantic salmon by principal catching nations, 1938-1967, in thousand metric tons.[1]

Year	Canada	Ireland	Denmark	Norway	Sweden	U.K.	Total Table	Total World
1938	4.0		0.1	1.1	0.2	2.0		
1947	2.7		0.6	0.9	1.2	1.0		
1948	3.0		1.0	0.9	1.3	1.9		
1949	2.9		0.9	0.9	1.1	2.0		
1950	2.7		1.4	0.7	1.4	2.0		
1951	2.3		1.1	0.9	1.1	2.0		
1952	2.3		1.3	1.0	0.8	2.0		
1953	2.1		0.9	1.1	0.4	2.0		
1954	1.8		1.0	1.2	0.5	2.0		
1955	1.2		0.6	1.3	0.3	2.0		
1956	1.2		1.0	1.2	0.6	2.0		
1957	1.4		0.9	1.4	0.4	2.0		
1958	1.6	0.8	0.9	1.2	0.3	2.0	6.8	8.0
1959	1.8		1.0	1.2	0.4	2.0	6.4	9.0
1960	1.6		1.1	1.2	0.4	2.3	6.6	8.0
1961	1.6		1.4	1.6	0.6	1.8	7.0	8.0
1962	1.7		1.3	1.9	0.3	3.2	8.4	10.0
1963	1.8	1.3	1.2	1.8	0.4	2.2	8.7	11.0
1964	2.1	1.4	1.7	1.9	0.6	2.6	10.3	14.0
1965	2.2	1.3	2.0	1.7	0.5	1.8	9.5	12.0
1966	2.4	1.1	1.7	1.6	0.4	1.8	9.0	12.0
1967	2.8	1.5	2.1	1.8	0.5	2.4	11.1	15.0
1968	2.2	1.4	2.5	1.7	0.7	1.6	10.1	13.0

[1] *Data include some chars and trout; one metric ton equals 2,204 pounds.*

Source: Food and Agriculture Organization of the United Nations, 1968. Yearbook of fishery statistics: catches and landings, 1968 (and preceding annual issues).

to 15,000 metric tons per year by the nations listed accounts for 75 to 90 percent of the world total, although this percentage has been declining since 1960. Greenland increased her catch from 127 metric tons in 1961 to 1.588 metric tons in 1967 (see table 4-9). Atlantic salmon supplies in the U.S. are obtained from the Maritime Provinces of Canada. Table 4-10 indicates the origin of Atlantic salmon

Table 4-9. Greenland catch of Atlantic salmon, in metric tons.

Year	High Seas	Inshore	Total
1961	—	127	127
1962	—	244	244
1963	—	466	466
1964	—	1,539	1,539
1965	36	825	861
1966	87	1,251	1,338
1967	395	1,283	1,588

Source: McVey, Robert W., 1969. Fisheries of Greenland, U.S. Bureau of Commercial Fisheries, Foreign Fisheries Leaflet No. 92, p. 17.

Table 4-10. Receipts of Atlantic salmon at Fulton Fish Market by point of origin for selected years, in thousands of pounds.

Year and Point of Origin	Fresh	Frozen	Totals
1966			
New Brunswick	58	1.6	59.6
Nova Scotia	0.3	0.5	0.8
Quebec	5.4	—	5.4
Newfoundland	30.8	1.0	31.8
Totals	94.5	3.1	97.6
1965			
New Brunswick	56.9	—	56.9
Nova Scotia	11.1	3.4	14.5
Quebec	46.6	—	46.6
Newfoundland	38.7	—	38.7
Totals	153.3	3.4	156.7
1962			
Massachusetts	0.5	—	0.5
New Brunswick	15.5	0.6	16.1
Nova Scotia	66.6	3.5	70.1
Quebec	32.8	—	32.8
Newfoundland	22.7	3.8	26.5
Totals	138.1	7.9	146.0
1961			
Totals	95.4	6.2	101.6

Source: U.S. Department of the Interior, Bureau of Commercial Fisheries, 1962. New York City's wholesale fishery trade 1962 (and subsequent annual issues, variously titled).

marketed in New York for selected years, and table 4-11 shows the seasonal distribution of receipts of Atlantic salmon in New York City.

The maximum sustainable yield (MSY) of Pacific salmon in the North Pacific has been estimated at 449,000 short tons. Assuming the relative shares of the U.S., Canada, Japan and the U.S.S.R. do not change, the MSY of stocks available to the U.S. and Canada is about 279,000 short tons (Cleaver, 1969). Canadian and U.S. landings from 1960-1967 have averaged about 208,000 short tons or about 75 percent of the North American share of the MSY. The ratio of average landings to MSY by species is as follows:

Chinook	.84
Silver	.81
Sockeye	.88
Pink	.83
Chum	.91

These ratios suggest some possibilities for increases in natural supplies of Pacific salmon. However, these increases would require improved control of exploitation by both domestic and foreign fishing. Of particular concern has been recent high sea fishing for salmon by South Korean vessels. Korea does not recognize the quotas and agree-

Table 4-11. Seasonal distribution of Atlantic salmon receipts in New York City.

Year and Month	Percent of Heaviest Month	Thousands of Lbs.
1966		
May	18	7
June	92	36
July	100	39
August	33	13
Total		95
1962		
January	2	1
May	29	17
June	97	56
July	100	58
August	12	7
September	2	1
Total		140

Sources: U.S. Department of the Interior, Bureau of Commercial Fisheries, 1962. New York City's wholesale fishery trade 1962, p. 1; 1966. Middle Atlantic fishery trends 1966, p. 5.

ments of the International Salmon Fisheries Commission which have to date made the North Pacific the private fishing ground of the U.S.S.R., the U.S., Canada and Japan. It seems unlikely that significant increases in natural supplies of Pacific salmon can be expected in the near future. Similarly, it appears that catches of Atlantic salmon have leveled off over the past ten years (table 4-8) and that increases in natural supplies will be modest at best. On the basis of relative prices and poor prospects for increases in natural supplies, Chinook *(Oncorhynchus tschawytscha)*, Coho *(O. kisutch)*, and Atlantic salmon *(Salmo salar)* appear to offer good prospects for culture. Of these, Coho offers certain bio-technical advantages. Coho is also desirable because its flesh color is acceptable (see subsequent discussion of demand).

Demand. A survey of New England grocery chain stores indicates that salmon sales are five to ten times greater than trout sales. Salmon are shipped whole, gutted, and freeze-glazed to minimize freezer burn. Red-fleshed fish are consistently preferred. A seasonal peak in demand in New England is associated with July 4 when sales volume by food chains increases by a factor of 10 to 12. Food retailers believe that salmon is a small-volume product, relative to other salt water fish, with a small profit margin, and is slow moving except during July.

Fish brokers indicated a good sales volume for most of their smoked fish products. Deep red flesh coloring received less emphasis for this market. Table 4-12 reports the results of a per capita consumption survey of salmon by region and product form during 1969. The same survey indicated that New England per capita consumption of canned red salmon was about 70 percent higher than consumption of pink salmon and about 50 times higher than that of other salmon.

There seems to be a strong demand for red-fleshed, fresh and frozen salmon in the New England, Middle Atlantic and East South Central regions. Table 4-13 presents estimates of aggregate demand for salmon in these regions assuming 1969 per capita consumption patterns; on this basis, these three regions would have an annual consumption of fresh and frozen salmon of about 14 million pounds.

Ex-vessel prices since 1960 have ranged between $0.16-$0.22 per pound with $0.19 to $0.22 per pound predominating since 1965. Wholesale prices have been about $0.60 to $1.13 per pound. The price relevant to this discussion lies somewhere between ex-vessel and wholesale, between $0.20 and $1.00 per pound. This is the price range in which aquacultural production must operate, a range which will probably continue to rise.

The estimated price and income elasticity of demand for fresh and frozen salmon are −1.297 and 1.624, respectively (Working Paper No. 62, p. 23). Thus, a given percentage change in per capita supplies will change the price by less than that percentage. For example, a one percent increase in supply would decrease price by only .77 percent.

The positive value of income elasticity indicates

Table 4-12. Consumption of fresh and frozen salmon by regions, February 1969-January 1970, in pounds per capita.

New England	.125
Middle Atlantic	.082
East North Central	.078
West North Central	.055
South Atlantic	.071
East South Central	.262
West South Central	.019
Mountain	.228
Pacific	.741

Source: U.S. Department of the Interior, Bureau of Commercial Fisheries, Division of Economic Research, 1970. A survey of fish purchases by socio-economic characteristics —annual report February 1969-January 1970, Working Paper No. 50, April.

Table 4-13. Estimated 1985 regional consumption of fresh and frozen salmon.

	Projected 1985 Population[1] (millions)	1969 Per Capita Consumption of Canned Salmon[2] (lbs.)	Canned to Fresh Ratio	Estimated Fresh & Frozen (millions of lbs.)
New England	13.3	.833	4.0	2.77
Middle Atlantic	42.7	1.421	10.5	5.78
East South Central	14.6	2.746	7.4	5.42

[1] *U.S. Department of Commerce, 1969. Statistical abstract of the United States, pp. 12-13.*

[2] *U.S. Department of the Interior, Bureau of Commercial Fisheries, 1970. Basic economic indicators salmon master plan fishery 50-10-48, Working Paper No. 62, May, p. 18.*

that demand can be expected to increase more rapidly than population, since it can be assumed that per capita income will increase. A given percentage growth in per capita income will cause a 62 percent greater rate of growth in demand. With stable natural supplies, price should rise with increasing demand. Assuming 1.5 percent annual growth rates in population and real per capita income, a four percent growth in quantity demanded can be anticipated. If supplies are stable, this demand increase will result in a three percent rise in prices. Alternatively, aquaculturists can effect four percent annual growth in supplies with stable prices.

The seasonal distribution of supplies of Red King and silver salmon is quite pronounced (table 4-14). Most receipts are during the late spring and summer months. Presumably, marketings during fall and winter would receive substantially higher prices. This appears to be the case with Red King, but price quotations for silver salmon during these months are lacking (table 4-15).

It is concluded that significant demand potentials exist for salmon. In terms of aggregate demand potential, the prospects for salmon appear excellent. Of the various salmon species reviewed, either Red King, Atlantic or silver salmon is suggested as a target species because of consumer acceptability and high prices.

State of the Art

The silver (Coho) salmon has been reared successfully in captivity through its various life stages. Although originally confined to the Pacific Ocean, this species has been successfully introduced to the Great Lakes, and more recently to New Hampshire and Massachusetts. Although current interest in this species in the New England area focuses primarily upon its potential as a sport fish, it nevertheless has certain characteristics that make it potentially suitable for commercial culture (Mahnken et al, 1970). It is regarded by some culturists as the hardiest salmon for rearing under artificial conditions.

Reproduction. As a rule, the silver salmon spends its first year in fresh water, migrating to the sea early in the spring of the year after hatching. Most fish return from the sea to their parent stream two years later, at which time they are sexually mature. Those that return after only one year are referred to as "Jacks." According to Johnson et al (1968), the average ripe female may be expected to yield around 2,700 viable eggs.

Standard procedures for obtaining fertilized eggs have been outlined by Hagen (1953). Adults are

Table 4-14. Seasonal distribution of fresh receipts of Red King and silver salmon at Fulton Fish Market, in thousands of pounds.

Year and Species	Totals	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1969													
Red King	788	—	9	19	50	143	186	174	146	22	34	3	2
Silver	279	—	—	—	—	1	1	45	52	87	61	32	—
1968													
Red King	822	—	10	9	49	181	157	169	126	70	48	3	—
Silver	255	—	—	—	—	—	4	45	60	91	32	11	12
1967													
Red King	735	—	—	15	42	158	166	153	122	54	25	—	—
Silver	380	—	—	—	—	—	—	73	97	112	97	1	—
1966													
Red King	710	—	—	6	42	152	175	129	142	50	14	—	—
Silver	561	—	—	—	—	—	2	81	213	136	126	3	—
1962													
Red King	638	—	2	2	20	110	127	181	101	89	4	2	—
Silver	430	—	—	—	1	—	1	97	104	100	124	2	1

Source: U.S. Department of the Interior, Bureau of Commercial Fisheries, 1962. Middle Atlantic fishery trends 1962 (and subsequent annual issues).

held in tanks or ponds until fully ripe, at which time they are usually anesthetized and stripped of eggs and sperm. (In this process, the female is destroyed, but this species would die after spawning in any event.) The fertilized eggs are transferred to incubator trays, at densities of 7,500 eggs or more per tray. Water of reasonably constant temperature flows continuously through these trays, which are generally arranged in stacks. Water flows through a typical 16-tray stack at the rate of nine gallons per minute (Johnson et al, 1968). James Eagleton (personal communication) recommends a flow rate of three to five gallons per minute per stack. An incubation temperature of 11°C (52°F plus or minus 5°) is usually recommended; prolonged temperatures above 15°C (60°F) and below 5°C (42°F) are not desirable.

Rearing of Juveniles. The eggs held at 52°F may be expected to hatch in about 50 days. According to Anthony Novotny (personal communication), silver salmon eggs and fry can be raised satisfactorily in water with a salinity as high as 10 o/oo. Higher salinities, however, could be detrimental. Brackish water would prevent occurrence of freshwater fungus and other diseases.

Usually the newly hatched salmon, or alevins, are allowed to remain in the trays until their yolk sac is completely absorbed, after which they are transferred to tanks, troughs or holding pools. In most salmon hatcheries, the fry are not fed until the yolk sac has disappeared (Stewart, 1971), because the sac apparently provides sufficient nourishment during this period.

The fish, at this point referred to as fingerlings, are then completely dependent upon outside sources for nutrition. For fingerlings, optimum temperature appears to be in the neighborhood of 13°C (55°F plus or minus 5°). Relatively little feeding takes place at temperatures below 47°F, while the young fish are highly susceptible to disease at temperatures above 60°F.

Silver salmon fingerlings may be immediately fed dry foods. At the Palmer Hatchery in Massachusetts, food types include Ewos, which is manufactured in Sweden, and varieties of Strike and Silvercup, which are produced domestically. In general, best results are obtained when the fish are fed small amounts frequently during the day. In certain hatcheries, a dry mash is used as a starter food, and as the fish grow larger they get the Oregon Moist Pellet or other types of pelletized food. Feeding rate depends greatly upon temperature. During the

Table 4-15. Seasonal pattern of wholesale frozen salmon prices in New York City, in cents per pound.

Years and Species	Average	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1969													
Red King		—	143	138	115	113	107	110	115	123	125	140	—
Silver		—	—	—	—	—	—	93	99	98	98	113	—
1968													
Red King		—	—	—	105	105	100	100	105	110	107	95	—
Silver		—	—	—	—	—	—	88	86	83	83	95	98
1967													
Red King	95	—	—	—	—	90	92	91	96	103	105	—	—
Silver	83	—	—	—	—	—	—	81	83	83	83	—	—
1966													
Red King	88	—	—	118	100	88	89	93	88	90	95	—	—
Silver	77	—	—	—	—	—	—	75	75	78	78	—	—
1962													
Red King		77	75	75	75	73	73	70	73	75	73	70	65
Silver		65	60	60	60	59	60	60	65	63	—	60	59

Note: Prices are mid-point of price range indicated in the data source.

Source: U.S. Department of the Interior, Bureau of Commercial Fisheries, 1969. Middle Atlantic fishery trends 1969 (and preceding annual issues, variously titled).

summer months, when feeding is most active, the young fish may be fed at a rate of four percent of their body weight each day.

During the fingerling stage, or prior to development into smolts, the fish generally have been reared in fresh water. Otto and McInerney (1970) report that this species shows no preference for water with salinity in excess of 14 o/oo prior to smoltification, and they conclude that it could not physiologically tolerate seawater of full strength during most of the pre-smolt period. However, fish held in brackish water approximately of 10 o/oo show greater growth rates, food intakes and conversion efficiencies than those held at salinities of 0, 5, 15, 20 and 25 o/oo. Canagaratram (1959) found that over a ten-week period silver salmon fry initially measuring 3.6 and 4.2 centimeters in length grew significantly faster in water of salinities of 12 o/oo and 18 o/oo, respectively, than did control groups in fresh water. The young of this species appear to be somewhat more tolerant of higher salinities than those of the Atlantic salmon *(Salmo salar)* which, as fry, failed to survive at salinities of 15 o/oo (Saunders and Henderson, 1969a).

Because of the dangers of oxygen reduction, waste metabolite accumulation, and spread of infectious disease, stocking density per unit volume is an important factor in the culture of this species, as it is for other salmonids. Wood (1968) concluded that if densities exceeded four pounds of fish per gallon per minute of water flow, disease could become a serious problem. Graphs indicating optimum population densities under different water flow rates have been prepared by Westers (1970). It would appear that under reasonably favorable conditions of water temperature and flow rate, a stocking density of one pound of fish per cubic foot of water is readily attained. Novotny (personal communication) considers this to be reasonable in areas of moderate tidal flow.

In their natural nursery areas, silver salmon usually become smolts approximately one year after hatching, at which time they descend the streams to the sea. However, Garrison (1965) found that salmon fry released in a tidal estuary became smolts within a period of 90 days, attaining a length of 12 centimeters and a weight of 19.6 grams. More recently, fry weighing approximately 22 grams, when transferred to a saltwater environment, increased in weight to 310 grams within a six-month period (Anon., 1970). Less satisfactory rates of growth were obtained by Baird (1953), although his experiments were perhaps made difficult by low water temperatures. Mosher (personal communication) has provided the following statement regarding the acclimation of silver salmon fry to salt water: "We feel that optimum growth will be achieved if the Coho fry are put into one third salt (10 o/oo) at two grams, and kept at that salinity until they are ten grams. By then, kidney development should be adequate for satisfactory growth in full salt water. Temperature should be 10° to 12°C for best growth."

Joyner (personal communication) states that growth rate appears to vary directly with temperature in the 7.5° to 13.5°C range, but that the incidence of disease increases markedly at temperatures above 12°C in the saltwater environment. Mosher (personal communication) indicates that if fry weighing two grams are transferred directly from fresh water to seawater with a salinity of 30 o/oo, only 50 percent may be expected to survive.

Data from Mahnken et al (1970) indicate that silver salmon hatched early in the year and reared in a freshwater environment may weigh 20 grams by the end of that year. (Based on references cited above, it may be assumed that this period might be shortened somewhat by transferring the fingerlings to brackish water at an earlier stage.) Mahnken et al (1970) indicate that in a saltwater environment an average weight of nearly 500 grams, or slightly over one pound, could be obtained during an additional eight-month period, and that the fish might weigh in excess of 2500 grams, or five pounds, within two and one-half years after hatching. Novotny (personal communication) feels that this species could be reared to a marketable size of slightly less than one pound in a period of approximately one year.

Food. Fish reared on a diet of Oregon Moist Pellets show a conversion of 1.5, i.e., 1.5 pounds of food are required to produce one pound of fish (Mahnken et al, 1970). This conversion efficiency is relatively high; still it is evident that inexpensive foods would be desirable in a commercial operation. Of course a major advantage in pelletized foods is that they may be stored readily in large quantities.

Working with the Atlantic salmon *(Salmo salar),* Gunstrom (1970) obtained a conversion of 1.5 also, but the food, manufactured at the rearing facility, cost only $0.10 per pound to produce. By contrast Oregon Moist Pellets cost about $0.165 per pound. The food, described by Gunstrom, is a mixture of ". . . autolysed, predigested ground-fish, fish meal, various cereal additives, vitamins, and sea food by-products high in carotenoid pigments, such as shrimp offal. The end product is a moist pellet that is eagerly accepted by the fish." Gunstrom anticipates that food costs will be further reduced as the processing becomes more fully automated. This particular facility will require two to three million pounds of food each year.

According to Johnson et al (1968), the Abernathy Pellet, which is similar to the Oregon Moist Pellet in price, is an important food in many of the western states' hatcheries, either as a starter mash or in pelletized form.

Baird (1953) reared silver salmon primarily on a diet of mummichogs *(Fundulus heteroclitus)*, interspersed with alewives and alewife roe, herring, smelts and smelt roe, and liver. Saunders and Henderson (1969a) report that vitamin deficiencies appeared to occur among Atlantic salmon reared on a diet predominantly of herring, attributing this to the relatively high amounts of thiaminase in herring.

Rearing Environments. According to Iversen (1968), the return of salmon released from hatcheries on the Pacific coast to their native streams, approximates one percent even when, in the case of silver salmon, they were released at an age of 14 months. From a commercial point of view, it would appear more practical to attempt to rear the fish in controlled or semi-controlled environments, in which food and maintenance costs might be more than compensated for by high survival.

Burrows and Combs (1968) have described a controlled environment for salmon culture in which water volume requirements are reduced by approximately 95 percent. In it, the water is constantly reconditioned through a system of filters and sterilizers, and daily makeup water is only five percent of total volume. Ammonia is removed by nitrifying bacteria colonizing filter beds, carbon dioxide is removed and oxygen replenished by physical agitation of the water and pathogenic organisms are eliminated through ultra-violet radiation and filtration.

This system has been incorporated into a large salmonid rearing facility in Nova Scotia (Gunstrom, 1970), where trout *(Salmo gairdneri* and *Salvelinus fontinalis)* and Atlantic salmon are being raised to market size in artificial pools. Fry reared in an adjacent hatchery building are transferred to the outdoor pools, where both temperature and salinity are regulated to promote rapid growth. Over 90 percent of the water is re-used, which allows for ". . . conservation of water, removal of organic and nitrogenous wastes, lower heating costs; as a result, easier control of the rearing environment." The fry are adapted to salt water as rapidly as possible. According to Gunstrom, "Sea water supplies trace minerals which are absorbed through their skin and gills. It lowers the disease probability, as the majority of fish diseases encountered at hatcheries are freshwater borne." To date furunculosis, a common disease in freshwater hatcheries, has not been a problem at this facility.

The rearing pools at this facility are for the most part circular. The larger ones—one is planned to be 135 feet in diameter—contain their own filtering system, which consists essentially of a shell and gravel bottom that may be back-flushed periodically. The sludge is then collected by net. Burrows and Chenoweth (1970) have recommended the use of rectangular holding pools which in their opinion offer certain advantages over circular pools: (a.) greater ease and efficiency in the use of automated cleaning devices and (b.) a more efficient circulation pattern, which produces fish with greater stamina and higher survival potential.[1]

A different type of holding system has been described by Mahnken et al (1970); this one uses cages and pens constructed of nylon netting and supported by styrofoam floats. After acclimation to moderate salinities, the fry of silver salmon are transferred to these holding devices, where the salinity approximates 30 o/oo. In this case, tidal flushing through the pens performs various functions: replenishes oxygen, removes carbon dioxide and nitrogenous waste and provides supplementary food in the form of planktonic organisms. Under these conditions, with a tidal flow rate of up to 0.5 knot, fish may be reared to market size at densities of two

[1] *Since this writing, the Nova Scotian facility, has ceased operation.*

pounds per cubic foot of holding space. The combination of tidal currents and favorable water temperatures, which range from 8°C (46°F) to 14°C (57°F) are perhaps the critical features of this operation.

Major Technical Problems. The major technical problems in rearing silver salmon to marketable size on a commercial scale are in the areas of disease, food and feeding and temperature control.

The major problem in intensive fish culture traditionally has been that of detecting disease or its causes, and of controlling epidemics effectively. In recent years, great advances have been made in the understanding and control of disease among salmonids; certain of these have been reviewed by Herman (1970). As he points out, "In their natural environments, fishes suffer from a variety of diseases. Under artificial cultural conditions, these diseases may be magnified many times and result in catastrophic losses. In addition, in fish culture we see diseases which have not been reported in the natural environment."

In his review of various approaches to disease prevention and control, he points out the more important as adequate rate of water flow, moderate population densities, suitable temperatures, diets of high nutritional value, the use of dry foods where possible and the use of antibiotics. Klontz and Anderson (1970) have reported that many species of salmonids can be immunized by antigens of infectious agents, at the same time emphasizing that more work in this area is needed. For silver salmon, Fujihara (1969) has described immunization of juvenile fish against bacterial infection by oral administration. MacLean and Yoder (1970) have reported a kidney disease among salmon in Lake Michigan that they attribute to bacterial infection in fish under physiological stress, which in turn may have resulted from low oxygen concentrations.

Certain diseases, such as furunculosis, are associated with the freshwater environment. However, Mahnken et al (1970) have reported occurrences of freshwater diseases, including furunculosis, among salmon held in salt water; these authors believe that the disease organisms are harbored in the tissues from the time of incubation in fresh water and proliferate when the fish is stressed at the time it is initially introduced into salt water. These authors also describe the occurrence of *Vibrio*, a saltwater disease resulting from bacterial infection, among their populations, but they believe that rapid water circulation and maintenance of temperatures below 14°C (57°F) will reduce infection to a minimum. Nelson et al (1969) have reported that *Vibrio* may be controlled to a degree by oral vaccinations administered in the diet.

As in disease control, important advances have been made in recent years in suitable diets for salmonids. Recently developed foods, such as those described by Westgate (1969), would appear to satisfy most of the nutritional requirements of salmon. However, the costs of both food and feeding remain one of the major expenses in fish culture operations. Lindroth (1963) has estimated that for salmon hatcheries in Sweden over one-third of the total operating cost results solely from the purchase of food.

Feeding is automated in some hatcheries, but not in others where certain preferred foods are moist and have a tendency to clog up food dispensers. At the world's largest salmon hatchery on the Cowlitz River in Washington, feeding is still done by hand (Stewart, 1971), which could become a costly procedure in a commercial operation. Rather than purchasing prepared foods, certain facilities manufacture their own reportedly at lower cost. Since fresh fish is a normal, if not essential, component in the diet of salmon, it is obvious that substantial amounts of low-cost fish must be available. (One facility reportedly requires up to 10^6 pounds of trash fish per year for this purpose.)

Maintenance of proper water temperature is critical in the culture of salmonids. Brett (1952) determined the upper lethal limit of fry of the Genus *Oncorhynchus* to be 25°C (77°F), but recommended that maximum temperatures for intensive culture are roughly 20°F lower than this. Brett also found that even after acclimation to temperatures of 5°C (41°F), the young of silver salmon could not tolerate temperatures of 0°C (32°F) for extended periods (four days).

At Lake Charlotte, Nova Scotia, Sea Pool Fisheries Ltd., a private fish-rearing concern, used boilers, rated at 800 horsepower and delivering 20 million BTUs per hour, to maintain suitable temperatures in the rearing pools nine months of the year (Gunstrom, 1970). In this case, much of the water is recirculated. A portion of the heat is retained, but an estimated ten percent of the annual operating cost is for power and fuel. Johnson et al (1968), in estimating the cost of heating water for a salmon hatchery in Michigan, gave a cost range of $0.45 to $0.51 per pound of smolt produced, depending upon whether gas or oil is used. For the New England area, culture of salmon in inshore areas for extended periods of time would require means for heating the water during the winter. Alternatively, eggs or fry could be started in fresh spring water, the temperature of which generally approximates 10°C (50°F). Saline water could gradually be introduced to maintain an optimal salinity for growth and reduce the incidence of disease. The smolt would be transferred to brackish or salt water in early spring with the assumption that they would attain a marketable size by the fall of that year. Salmon smolt would probably not survive the inshore water temperatures of 0°C or less in New England in winter, although Baird (1953) held salmon successfully at temperatures as low as 4°C (39°F). Such an operation, however, would be limited to northern New England since the summer water temperatures from Cape Cod southward approach the upper lethal limit for this species. Data from Mahnken et al (1970) indicate that this species increases in weight at temperatures ranging from 8° to 14°C (46° to 57°F), but that growth rate decreases at the lower portion of this temperature range. Temperature data calculated by Dow (1969) for Boothbay Harbor, Maine, indicate that in parts of Maine this species can be expected to grow satisfactorily for perhaps five months during the year. Since it has been reported (Anon., 1970) that the silver salmon reared in a marine environment increased in weight from 0.7 ounce to ten ounces in less than six months, it should be possible to produce a marketable product in this period of time in northern New England.

Production Costs

The following discussion of production costs includes an estimate for a hypothetical or model plant, and an analysis of the effect of changes in critical design assumptions on production costs. While the cost estimates were derived from known parameters insofar as possible, they should not be regarded as precise. Costs actually incurred by a commercial enterprise depend on quantitative and qualitative resource characteristics of the production site and the specific system design chosen. Any aquacultural system contains elements which must be tailored to the particular site and environment considered. Site selection and system design should involve engineers and biologists in order that the optimal system be chosen for the particular site involved. The following discussion outlines what costs would be incurred under parameters obtained or extrapolated from the literature (see State of the Art). Until tested under pilot plant conditions, these parameters and the costs which are based upon them should be regarded only as rough approximations.

To obtain an idea of costs, the cost data presented by Shields and Veinot (1969) have been adjusted as described in the following paragraphs.

Food Costs. Shields and Veinot (1969) used a price of $0.16 per pound for food. This appears to be unrealistically high for New England, and a price of $0.12 per pound has been used instead. This price is based on salmon food price quotations F.O.B. Westerly, Rhode Island.

Growth Rates and Plant Utilization. Shields and Veinot use a system with 10^6 pounds capacity at a maximum fish size of 1.1 pound per fish. This weight per fish might be reached by Coho after about eight months of growth in seawater (Mahnken et al, 1970). Mahnken et al also report that an additional ten months of ocean growth will produce fish averaging about five pounds each. Using these growth rates, we assume that a one-pound fish can be grown in eight months, at plant capacity of 10^6 pounds. By removing the fish at a rate equal to their growth over the remaining three months, plant capacity is utilized more fully and a greater annual production is possible. Specifically, 1.622×10^6 pounds could be produced at the facility each year.

Cost of Smolts. Smolts are assumed to be purchased from hatcheries ready for stocking in seawater. Coho smolts are available from Michigan at a cost of $1.60 per pound for fish weighing about .05 pound each. Supplies might also be made available by the state of Massachusetts.

Heating Costs. Since we are assuming fish would be marketed prior to the onset of winter, water heating is necessary only during late winter and early spring. Since water inflow is slight for fish of this size, heating costs would be minor.

Interest Charges. The Shields and Veinot (1969) cost analysis did not include a charge for interest on investment. An interest charge of 15 percent on average value is included.

Summary of Production Costs. Table 4-16 presents the components of production cost as estimated by Shields and Veinot and the adjustments described in the preceding discussion. The combined effect of these adjustments has been a cost increase of about $0.03 per pound. Average costs ($0.89 per pound) would appear prohibitive since it must be assumed that salmon of this size would be sold in trout markets which are generally about $0.50 to $0.60 wholesale.

Effect of Varying Design Assumptions. The costs presented in table 4-16 involve a closed cycle, capital intensive system, used only nine months per year. By adding heating facilities, it is possible to maintain the growth of the fish throughout the year at rates comparable to the summer months. The facility could, therefore, produce an estimated 60 percent more in total pounds per year. Sales would begin in September and the total stock would be liquidated by December to make room for new smolts. Under proper conditions, it might be possible to transfer young fish into low-cost coastal cages for growth in the summer. Cage culture would require that extra smolts be held during the winter and early spring. At this time of year, the capital intensive plant would otherwise be operating at less than full capacity because of the small biomass of smolts. Such a system would make it possible to increase total production at the cost of modest increases in water flows, labor and cages.

To show the effect on production costs of extending the growing cycle in the tank, table 4-17 has been prepared. Additional food costs are proportional to additional biomass. The estimate of heating costs is based on an average water flow for 10^6

Table 4-16. Summary of annual operating cost per pound of round salmon.

	Cost in Cents per Pound of Salmon		
Item	Shields and Veinot	Adjusted Cost	Difference
Feed	31.1	24	— 7.1
Direct labor	6.6	6.6	0
Water	6.8	5.1*	— 1.7
Heat exchange water	2.6	0	— 2.6
Fingerlings/smolt	12.9	12.0	— 0.9
Maintenance	2.6	2.6	0
Overhead	9.0	9.0	0
Depreciation	14.5	14.5	0
Interest @ 15% of average value	0	15.4	+15.4
Totals			
Round weight:	86.1	89.2	+ 3.1
Dressed weight:	101.3	104.9	+ 3.6

* *Scaled down for nine months flow.*

Source: Shields, W. D. and Veinot, J. A., 1969. Strait of Canso fish farm feasibility study, p. 65.

Table 4-17. Comparison of projected costs for 12-month operation using cage culture during summer months to augment production.

	Total Cost (in thousand dollars)		Average Cost (in cents per pound)		Marginal Cost 12-month period (in cents per pound)
	9 months	12 months	9 months	12 months	
Feed	389.0	622.1	24.0	24.0	24.0
Direct labor	106.9	106.9	6.6	4.1	4.1
Water	82.6	132.2	5.1	5.1	5.1
Heat exchange		110.0		4.2	11.3
Fingerlings/smolt	195.0	195.0	12.0	7.5	
Maintenance	42.2	42.2	2.6	1.6	
Overhead	145.8	145.8	9.0	5.6	
Depreciation	73.0	73.0	4.5	2.8	
Interest (15% of average value)	250.0	250.0	15.4	9.6	
Total round weight	1284.5	1677.2	79.2	64.5	44.5

Total Production (in thousands of pounds)—9 months—1620, 12 months—2590.

pounds to be raised 5°C (9.4°F) at a cost of 8×10^{-7} per BTU. Additional water pumping costs are proportional to additional biomass. The marginal cost incurred is about $0.45 per pound of salmon. This lowers average cost from approximately $0.79 to $0.65 per pound. The costs of cage-rearing in a marine environment are not known at this time. However, if operated in conjunction with the capital intensive system just described, the small fish to be transplanted would incur only negligible labor and feed costs. No additional plant capacity would be needed. Of course, some assurance of exclusive right to the water column being used would be desirable, if not a prerequisite.

If both variations were combined, it is possible that average costs could be brought within the range of commercial feasibility.

The American Lobster *(Homarus americanus)*

Supply and Demand

Supply. Current supplies of the American lobster are comprised of landings in New England (principally in Maine), imports from Canada (primarily from the Atlantic Provinces) and minor landings from the Middle Atlantic states. United States landings have been approximately 31 to 36 $\times 10^6$ pounds per year during the past decade. Canadian landings during the period have been about 35 to 50 $\times 10^6$ pounds per year. Combined landings have been about 66 to 84 $\times 10^6$ pounds per year.

The maximum sustainable yield of *Homarus americanus* has been estimated to be 32,000 metric tons or 70.5 $\times 10^6$ pounds for the Northwest Atlantic inshore fishery (Longhurst, 1969). While the precision of this estimate is difficult to judge, it is widely believed that substantial increases in natural supplies for the inshore fishery are unlikely to occur on a sustained basis; obviously increases which result in stock depletion cannot be sustained and would result in subsequent diminution of supplies.

The magnitude of offshore lobster resources is unknown; however, exploitation has begun to a small extent. The rate of development is not possible to predict at this time. If one assumes that exploitation of the offshore resource stabilizes or proceeds very slowly, anticipated growth in demand will lead to rising lobster prices. Conversely, rapid increase in exploitation of offshore stocks could result in stabilization of lobster prices at current levels or lower. The time trend is uncertain. Price trends will reflect demand and supply trends, and are consequently uncertain too. Preliminary evidence at this writing suggests that offshore stocks are more limited than originally thought and that yield increases from offshore stocks will be modest.

Demand. Three aspects of demand are particularly relevant to aquaculture. These include magnitude, time rate of change and seasonal variation. In magnitude of demand, lobsters are one of the most important commercial species both for price and aggregate market volume. A supply increase of 10^6 pounds would represent only a one to two percent increase in supplies available for U.S. consumption.

The time rate of change of demand is influenced by population growth, growth in per capita income and the income elasticity of demand for lobsters. Growth in per capita demand may be anticipated to be proportional to growth in per capita income; this factor of proportionality is the income elasticity of demand. Working Paper No. 53 (April 1970) by the Bureau of Commercial Fisheries reports the income elasticity of demand for lobsters as 2.07. Assuming a 1.5 percent annual growth in per capita real income, the annual growth in per capita demand would be about three percent. This means that about three percent annual growth in per capita supplies would be absorbed with no impact on price. If coupled with a 1.5 percent population growth rate, a 4.6 percent annual growth in aggregate supplies could be absorbed with stable prices. This increase represents more than the minimum annual sales level of $\$10^6$. If per capita supplies from natural stocks remain stable, lobster prices would increase by about 5 percent per year. This projection is based on a price elasticity of –0.6 (Working Paper No. 53). This rate of price increase is useful in projecting the time at which lobster culture might become profitable. Assuming a production cost of $1.55 per pound (see section on production costs) and a 30 percent profit margin, a wholesale price of about $2.00 would be expected to attract capital. This would represent a 33 percent increase over 1968 wholesale prices. At a 5 percent price rise per year, this would occur in six years, or during the mid-1970s. Allowing for a two-year development phase, full-scale production could not be reached before this time, even if construction were begun immediately.

An analysis of receipts and prices at the Fulton Fish Market, New York City, indicates significant seasonal variations in demand. The method of analysis used was a regression of monthly lobster prices over a five-year period against monthly lobster receipts and 12 "dummy" variables, one for each month of the year. The analysis indicated significant increases in demand for the months of February through September with the exception of March and June. By marketing during the February-September period, a controlled culture unit could receive prices above the annual average.

Some data have been published on lobster consumption patterns according to socio-economic characteristics. These data are published by the Bureau of Commercial Fisheries (now re-named the National Marine Fisheries Service) in Working Paper No. 50, *A survey of fish purchases by socio-economic characteristics* (April 1970). These data include a cross-classification of annual per capita lobster consumption by race, religion, income level, occupation, education and region.

The three racial categories included are Negro, Caucasian and other. Per capita consumption by whites exceeded that of blacks by a factor of almost three; however, per capita consumption in the "other" category was almost three times that of whites. Per capita consumption was highest for Catholic respondents, followed by Protestant and Jewish respondents.

Per capita consumption by income category shows a strong income effect with the exception of the $1,000 to $2,000 annual income bracket. Consumption in this bracket was inexplicably high and was exceeded only by consumption in the highest income bracket. Consumption by occupation shows substantially higher consumption by respondents in the two categories of craftsmen and foremen, and clerical and sales. Consumption by respondents with less than four years of high school was more than double that of the next highest category, college graduates. These occupational and educational patterns may in part explain the peculiarly high consumption pattern in the $1,000 to $2,000 income category.

Consumption by region showed, not surprisingly, that per capita consumption in New England was 12 times greater than the next highest region, the South Atlantic. The East South Central and Middle Atlantic states were about tied for third and fourth ranking in per capita consumption.

It is apparent that significant differences exist in consumption levels within racial, ethnic, income, occupational and regional categories. These differences should be considered in designing a marketing program, but information more detailed than in the preceding overview would be necessary.

State of the Art

The American lobster has been cultured through all stages of its life cycle at the Massachusetts State Lobster Hatchery and Research Station in Oak Bluffs (Hughes, 1968). A similar hatchery facility has recently been established on Vancouver Island, Canada (Fisheries Research Board of Canada, Nanaimo, British Columbia). The following account of methodology relates primarily to techniques developed at the Massachusetts facility.

Reproduction. Female lobsters may be sexually mature when they have attained a carapace length of approximately 70 millimeters, although most females mature at a somewhat larger size. Immediately after a female has molted, she is isolated with a male lobster of approximately the same size in a tank of flowing seawater. At this time, she is receptive and attractive to the male. The male fertilizes the female by turning her over on her back and, by means of the first pair of abdominal appendages, inserting a packet of spermatazoa in her seminal receptable. After copulation, the male is removed from the tank, and the female is kept in isolation. She is held in constantly flowing water and fed regularly on a diet of fresh shellfish or fish scraps. The container in which she is held need only be slightly longer on each side than her total length and sufficiently deep, e.g., 50 centimeters, to permit satisfactory extrusion of the eggs.

In southern Massachusetts, where ambient coastal water temperatures range from a minimum near 1°C in winter to a maximum of 25°C in summer, a period of approximately nine to 12 months is required before the eggs are extruded. The number of eggs extruded per female varies directly with size, varying from less than 10,000 in the case of a 75-millimeter (carapace length) female lobster to over 50,000 in the case of a female twice this length. The female lies on her back, with head pointed upward, the flexed tail forming a pocket. The eggs are extruded, fertilized by the sperm retained within the seminal receptacle, and cemented in a cluster to her abdomen.

In the temperature range specified above, another 12-month period may be required before the eggs mature. Hatching usually begins as ambient temperatures reach approximately 20°C and is completed within a period of a few days. The larvae are capable of swimming immediately after hatching and are collected at a plastic-mesh screen installed at the overflow pipe in the hatching tank.

Hughes (1970) has reported that in one case, the period between mating and hatching of the eggs was reduced to approximately 11 months by maintaining the fertilized female at temperatures approximating 20°C.

Rearing of Larvae. The larvae are tranferred from the hatching tank to circular rearing tanks through which seawater is vigorously circulated. Such tanks are preferred as a means of preventing the cannibalistic larvae from congregating. The larvae may be held at densities of 50 per liter, but percentage survival increases with decreasing population density. They subsist on finely-ground clam meat or brine shrimp, the latter being preferable because it is less likely to foul the container. In a new hatchery in British Columbia, 70 percent survival of the larvae from first to fourth stage has been reported (Wilder, 1970).

The larval period is considered to terminate after the third molt after hatching, at which time the lobster has a well developed pair of claws that extend anteriorly. Since they normally seek the bottom at this time, the lobsters are either transferred to individual containers or placed in large containers in which shelter is provided in the form of shells, rocks, etc. The duration of the larval period depends upon ambient temperatures, terminating within a period of nine days after hatching at a mean temperature of 22°C, but lasting as long as 32 days at 14°C.

Kensler (1970) cultured larvae at 27°C and, accidentally, at 31°C without appreciable mortalities. At 25°C, lobster larvae reached the fourth stage in nine days.

Rearing of Juveniles. The juvenile stage is considered to be that period between the third larval molt and attainment of sexual maturity.

Because of their cannibalistic tendencies and their vulnerability to other lobsters immediately after molting, lobsters have been reared to maturity only in isolated tanks or containers, through which water flows continuously or is recycled through suitable filters. Under conditions prevailing at the Massachusetts rearing facility, where the lobsters are held in small compartments at ambient water temperatures, the juvenile period extends for approximately five years. During this time, they are fed fresh fish, fish scraps, and shellfish. At optimum salinity and oxygen concentration, i.e., 30 o/oo and 6.4 milligrams of oxygen per liter, lobsters fail to survive at temperatures exceeding 32°C (McLeese, 1956).

Recent experiments at the Massachusetts facility indicate that the entire growth period of the lobster from fertilized egg to marketable size may be shortened considerably by appropriate temperature manipulation. (As indicated above, an 8°C elevation in temperature may reduce the larval period by a factor of nearly four.) The period required for development of extruded eggs, for example, may be appreciably reduced by maintaining water temperatures at 20°C, without subsequent ill effects to the larvae. Similarly, molting frequency among juveniles has been markedly accelerated simply by holding them at higher-than-normal temperatures. Since growth proceeds in stepwise fashion with each molt, it seems that, assuming adequate food, the growth rate can be accelerated by increasing metabolic rate through temperature manipulation.

As an example, a group of lobsters that hatched during the summer of 1968 at the Massachusetts facility were held at temperatures ranging from 20°C to 26°C, beginning November 1, 1969. By October, 1970, these lobsters had an average carapace length of 68 millimeters and an average weight of 243 grams compared with a control group of the same age but held at ambient temperatures, that averaged 43 millimeters in carapace length and 63 grams in weight. These data indicate that it should be possible to rear newly-hatched larvae to a marketable size of nearly one pound within a two- to three-year period if water temperature is regulated. Experiments here have indicated that lobsters may be held successfully in water that is seldom renewed, other than to maintain the appropriate salinity, but that is aerated and recirculated constantly through glass wool filters.

Food. Perhaps the major economic factor to be considered in rearing lobsters is supplying adequate food. It has been estimated (Hughes and Matthiessen, 1962) that approximately 15 pounds, wet weight, of food is required to produce a one-pound lobster. More recently, however, Hughes (1970) has estimated that a more realistic conversion would be four to one, wet-weight basis. These calculations were based upon feeding pre-weighed amounts of food to individual lobsters in isolated containers. Included were clams *(Mya arenaria)*, scallops *(Aequipecten irradians)*, snails *(Littorina littorea)*, mussels *(Mytilus edulis)*, quahogs *(Mercenaria mercenaria)* and starfish *(Asterias forbesi)*. The lobsters were weighed at the beginning and end of consecutive feeding intervals. (The casts of these lobsters were also consumed shortly after molting.)

It would appear from this that the food cost in the rearing of lobsters in captivity to marketable size would not be prohibitive, assuming the ready availability of such low-cost foods as mussels, starfish and snails. Another alternative would depend on accessibility to fish processing and filleting plants where, in some cases, bags of frozen fish scraps may be sold for as little as $15.00 per ton.

Some success has also been achieved with artificial foods, although the present data are fragmentary. Gels obtained from seaweed extracts, i.e., carrageenens, have been employed as a vehicle for various nutritious substances, including fish flour, fish meal, and cat food; lobsters supplied these diets have molted normally. Trout food in pellet form, containing various proteins, vitamins, minerals and trace elements, also has been fed to lobsters, but conversion figures are not available at present.

Major Technical Problems. At the present time, the major technical problems that might limit the profitable culture of lobsters through all stages of their life cycle are cannibalism, disease and the volume and rate of water circulation per individual lobster.

The problem of cannibalism is most serious during the larval and early juvenile stages when it is impractical to hold and feed large numbers of tiny lobsters in individual containers. The feeding and maintenance of large numbers of larger lobsters in individual containers, although not dissimilar in concept to modern poultry-raising techniques, also borders on the impractical in view of the relatively slow maturation and, hence, production rate of lobsters.

The following notes on a report by D. J. Scarrat (Fisheries Research Board of Canada, 1970) are of interest.

> Analysis of stomach contents indicates that lobster diet is rich in calcium (Fisheries Research Board of Canada, 1970). The suggestion was advanced that cannibalism in holding conditions might be associated with a high calcium requirement, and the problem might be avoided if a calcium-rich diet is provided. This was supported by the report that cannibalism was no problem among lobsters that were fed regularly on whole shrimp (D. E. Aiken), or whole soft-shell clams (M. W. Gilgan). A calcium-rich prepared food has been developed, consisting of a gelled mixture (50 percent solids, 50 percent water) of spiny lobster carapace, squid, *Ulva*, and *Enteromorpha* (G. O. Schumann). The mixture is high in vitamins, can be stored in frozen form, and leaves little tank residue.

Lobsters held under crowded conditions may at times experience high mortalities. Aside from more obvious and easily remedied influences (such as inadequate oxygen supply), influx of copper ions from the circulating system, air leaks at the suction end of the circulating system, decomposition of excessive organic matter and the presence of insecticides, lobsters are also susceptible to bacterial diseases about which relatively little is known. Possibly the most serious of these is gaffkemia, often referred to as "red-tail" (Rabin and Hughes, 1968), the cause of which is known to be the bacterium *Gaffyka homari*.

Finally, the fundamental requirements of a lobster for space and rate of water circulation in a closed system should be considered. It has been found in holding experiments, for example, that a minimum volume of two gallons of water should be provided for each pound of lobster. If, for the purpose of maximizing rate of growth, lobsters are held at 21°C, the ratio of rate of water flow (gallons per minute) to pounds of lobsters is approximately 1:30 (Goggins, 1967). At 10°C, the ratio improves to 1 gallon to 55 pounds of lobsters. In other words, the population density may be almost doubled at the lower temperature, but rate of growth would be sharply reduced.

Culture in the Natural Environment. The previous sections discussed some of the methods and problems associated with the culture of lobsters under artificial conditions. An alternative approach would be to make use of natural areas, subject to some degree of environmental control. The cost of rearing facilities, water renewal, temperature control systems, and possibly food might be eliminated or, at least, reduced.

Once an appropriate area has been selected for culture, lobster populations might be established either by releasing them from a lobster hatching facility or by attracting natural populations to culture areas and sub-legal-sized ones to holding cages.

Methods for hatching and rearing larval lobsters have been described in the previous section. Since 1950, the Massachusetts State Lobster Hatchery has reared larval lobsters each year for release in various areas of the Commonwealth. Annual production has averaged 250,000 fourth-stage lobsters. Unfortunately, it has not been possible to release large quantities of these lobsters in any one particular area, and evidence that the release of larvae into the natural environment significantly improves local lobster fisheries is lacking. Certainly it is possible that mortalities among the hatchery-reared lobsters may be high, or that the lobsters may eventually wander from the area in which they were originally planted. In any event, there is some question as to whether the risk inherent in this approach is economically justifiable in terms of a commercial operation unless the area selected for culture is subject to some degree of environmental control.

Some evidence has been presented that both larval and juvenile lobsters occurring naturally in the environment might be attracted to, and concentrated in, selected culture areas. Ingle and Witham (1968) have described a method for collecting post-larval spiny lobsters *(Panulirus argus)*, simply by suspending a particular type of artificial substrate, resembling natural clumps of algae, in areas where both larval and post-larval stages occur. The results, however, were reportedly erratic. Dow (1969) has reported an influx of American lobsters into artificially-created habitats consisting of rocks and cement blocks. However, a question still remains on the reliability of this approach in terms of the numbers that might be attracted and induced to remain.

Scarrat (1970) has described what amounts to a lobster-holding operation recently initiated in Scotland in which lobsters are captured and held in underwater cages installed on the bottom of the sea until the most favorable market conditions prevail. The cages measure 36 feet x 36 feet x 18 feet deep and are stocked with 4,000 lobsters each. Twice weekly, skin-divers supply the lobsters food in the form of trash fish. Apparently the shellfish also find supplementary nutrition in the form of epiphytes growing upon the sides of the cages. Data on the survival of the lobsters and on the economic viability of this operation are not available.

If lobsters are cultured in the natural environment, means must be provided for preventing egress of the lobsters from the selected area, for preventing loss through natural predation and for providing supplementary food if the area is densely populated. It is conceivable that a fenced-off area of bottom supplied with stone, rubble or cinder block, in which the lobsters might take refuge from enemies and to which food is regularly provided, might satisfy these problems. Data on the survival of lobsters held for extended periods under such conditions are not available, since lobster pound operations are generally short-term and involve holding of marketable-size lobsters only. The fact that uncertainties exist in this approach is indicated by a report by Dow (1969). Of a group of fourth-stage lobsters introduced into an abandoned lobster pound, only an estimated ten percent survived to the following year, although in this case no effort was made to control predators other than by placing screening on the face of the pound.

The major deterrent to the commercial culture of lobsters under natural conditions in New England is the five years required for newly hatched lobsters to attain legal marketable size. During this period, they may be vulnerable to such factors as predation, cannibalism and disease, which over a five-year period might appreciably reduce the eventual harvest. However, as Dow (personal communication) points out, this rate of growth does not compare unfavorably with that for certain other species in Maine waters, including the clam, oyster, sea scallop and northern shrimp.

Dow (1969) has described a possible approach to this problem, suggesting the use of the heated effluent from electric generating plants to help accelerate growth rate in a natural area. Lobsters are initially attracted to the area by the provision of artificial shelter, e.g., rocks, cement blocks, etc. It may be possible to regulate the surrounding water temperature as well as retain the lobsters within the area by incorporation of "encapsulating" structures. At the present time, it is too early to evaluate either the economics or the technical feasibility of this approach.

As compared with the culture of lobsters under totally artificial environments like tanks or artificial pools culture in natural areas (other than in cages) will be complicated by the process of capture. This might be particularly true if they are provided with shelter designed to protect them from their enemies, since they might then be all the more difficult to capture at the time of harvest.

Production Costs

The following discussion of production costs for lobsters is adapted from an unpublished preliminary study by Kramer, Chin, and Mayo, Consulting Engineers, Seattle, Washington. Heating costs have been modified as discussed below.

Water Heating. The Kramer, Chin, and Mayo (1969) preliminary study is based on seasonal temperatures in Puget Sound. Using seasonal water temperature patterns of Martha's Vineyard, approximately 172 degree-months additional heat would be required. This contrasts with 141 for Puget Sound, and implies a 22 percent higher cost factor for heating water. Heat for the building could be supplied by energy losses from pump engines and/or electrical generating facilities.

The magnitude of heating costs depends upon the cost of heat energy, on the units of water to be heated and on the proposed temperature increase. Accordingly, we have revised the Kramer, Chin, and Mayo estimate of heating cost to reflect probable heating costs in southern New England.

The flow rate of new water used by Kramer, Chin, and Mayo is 1.44×10^6 gallons per day (GPD). At a density of 8.7 pounds per gallon this implies an annual flow of 4.57×10^9 pounds of water to be warmed. On a per unit basis, this annual flow is about 9.15×10^2 pounds of water per pound of lobster per year.

For Martha's Vineyard, each pound of annual water flow must be raised an average of 8°C (14.3°F). With a specific heat of 0.94 and an annual per unit flow of 9.15×10^2, this temperature rise implies the expenditure of 12.3×10^4 BTUs per pound of lobster.

The cost of a BTU depends on the energy source and its cost. If Bunker C oil were used at a price of \$0.12 per gallon and an energy content of 1.5×10^5 BTU per gallon, each BTU would cost about $\$8.0 \times 10^{-7}$. At 12.3×10^4 BTU per pound of lobster for heating water, this implies a cost of \$0.098 per pound of lobster for water heating.[2]

Bearing in mind the preceding modifications, we present a cost summary in table 4-18.

Effects of Varying Critical Parameters. We investigated the possibility of avoiding transfer of lobsters by building all full-sized cages. A cost reduction of three man years (of \$29,000) per year, or about six cents per pound of lobster, could be achieved. However, an additional capital outlay of $\$1.9 \times 10^6$ would be required, based on 60 percent survival through the first year. The annual costs on this outlay would be about ten times the reduction in labor costs. Unless capital costs could be substantially reduced, lengthening the production

Table 4-18. Cost summary for lobster culture in a controlled environment.[1]

Item	Total Annual Cost (in thousand dollars)	Average Cost (in cents per pound)
Capital cost (10 years @ 8%)	402	80.4
Manpower	134	26.8
Feed	173	34.6
Heat and pumping	59	11.8
M and O @ 2% capital cost	54	10.8
Miscellaneous	13	2.6
Totals	835	167

[1] *Modified from Kramer, Chin and Mayo, 1969. Production scale is 5×10^6 pounds per year.*

[2] *This cost has increased with the recent "energy crisis." Appropriate adjustment for the cost per BTU is left to the reader.*

cycle incurs greater fixed costs per unit of product than it could save in labor. However, based on personal communications with R. Mayo, it is believed that their capital costs are excessive. Reduced labor costs might well justify the construction of full-sized individual cages.

We investigated the effect of reducing heat requirements by operating at lower temperatures for a longer production cycle. Production costs exclusive of heat input amount to about 7.86×10^5 per year at a production scale of 5×10^6 pounds per year. If the production period were extended to four years, these costs would rise by one third to 10.5×10^5 per year, an increase of 2.64×10^6 for an equivalent annual production. The saving in heat input, even if all heat input were eliminated, would be only 4.9×10^4. In fact, however, all the heat supplement could not be eliminated unless the production period were lengthened to five years. We conclude that lengthening the production cycle is not warranted by the savings in heating costs.

Two other possibilities exist for reducing the projected heating cost of $0.10 per pound of lobster. One way is to more completely close the system to lessen the injection of water from ambient sources. As noted in the biological review, salinity control, aeration, and recirculation through glass wool filters are adequate for holding lobsters. The effectiveness of such a system for growth over a long period and for a commercial-scale operation is not known. Another possibility is to select a site with warmer water. This might be possible by using the thermal enrichment provided by power plants. The maximum summer temperature of thermally-enriched waters should not exceed 32°C (89°F) at which lobsters fail to survive (McLeese, 1956).

The largest single cost item is in annual capital cost. Of the total capital investment exclusive of the water supply system, about 45 percent is the cost of individual holding cages for two- and three-year-old lobsters. Thus, elimination of holding cages potentially reduces the capital costs by 45 percent, or about $0.34 per pound. (This might be done by using elongated troughs partitioned into individual compartments by screens.) If a cannibalism control mechanism could be developed (through specialized diets, for example) it would clearly lower costs to the range of commercial feasibility. Additionally, it would be of great value to the present industry in reducing the costs of lobster pounds. Whether a cannibalism control mechanism, genetic, dietary, chemical, or mechanical, could be developed is speculative at this time and warrants further experimentation.

Food cost is second only to capital cost in relative importance. Availability of a suitable food at $0.05 per pound instead of $0.06 could reduce production costs by as much as $0.05 per pound of lobster. As noted in the earlier bio-technical review, frozen fish scraps from fish processing/filleting plants are sometimes available at $15.00 per ton. Also noted earlier (Hughes, 1970) was a conversion ratio of approximately four to one in experiments in individual cages. This ratio instead of the five to one used would reduce food costs by 20 percent. At a food price of $0.05 per pound this implies a $0.05 per pound reduction in the cost of production.

The discussion of production cost has assumed a market size of one pound. This generally equals or exceeds minimum legal size restrictions on possession of lobsters. The market acceptability of smaller lobsters is not known since no observations exist. However, the fact that "chicken" lobsters sell at premium prices suggests no consumer aversion to smaller lobsters. The possibility exists, therefore, that a smaller-sized lobster could be marketed if acceptable under the law. Production of smaller-sized lobsters would reduce inventory costs and mortality risks. By appropriate phasing, it should also permit some reduction in heating costs.

Summary of Production Cost Analysis, Supply and Demand Aspects. Commercial lobster culture at current average ex-vessel prices does not appear feasible. However, at wholesale and off-season prices, production is approaching commercial feasibility, although the profit margin is low. This situation appears certain to improve with time in view of the strong income elasticity of demand for lobsters ($E_t = 2.1$) and limited potential for increases in natural supplies.

Certain variables in the projected budget could improve the prospects for commercial feasibility. Most notably these include (a) development of techniques, genetic, chemical, or mechanical, to eliminate cannibalism and the necessity for individual cages; (b) development of lower cost feed sources and/or improvements in feed conversion efficiency; (c) availability of low cost sources of thermal energy to raise water temperatures; (d) more complete closing of the system to reduce the need for injection of new water which requires heating, and (e) marketing of lobsters at sub-legal size.

The importance of water temperature in production costs suggests that efforts at commercial production should seriously consider sites south of Cape Cod or sites where thermal enrichment raises water temperatures. In the latter case, considerable attention to water quality factors would be imperative.

The growth stage for which knowledge is least developed is the juvenile stage (fourth stage through legal size). There is a need for more experimental information during this stage on survival rates, low-cost acceptable foods, growth rates in relation to temperature and methods by which cannibalism can be eliminated.

5. Environmental and Institutional Considerations

Certain technical and economic considerations relevant to commercial aquaculture in New England have been discussed in preceding sections. The purpose of this section is to review various environmental and institutional factors that must be considered.

The complexity of these factors is evident when it is realized that the land-water interface, the probable site of aquafarming, is the nation's most sought-after terrain; moreover, such competition can pose a threat to the maintenance of high quality water, to access to the shoreline, and to assertion of exclusive fishing (culture) rights, all of which are vital to the aquafarmer. Conversely, an aquafarm may be regarded as a form of pollution if, for example, fish and/or shellfish processing facilities are involved or if aesthetically unpleasing appurtenances like rafts, pilings or floating cages are installed.

The aquaculturist must locate the proper site for his operations, acquire some form of exclusive fishing rights and assure himself of the continued functioning of his operation. He is faced with a spectrum of problems that are particularly acute along the relatively highly developed New England shoreline. These problems are reviewed below.

Multiple Use

It is valuable to delineate those uses that presently exist in estuaries and embayments and that are potentially competitive with aquaculture, and to indicate their growth potential so that levels of competition for the sites can be inferred. A more complete study of the multiple use problem is contained in the *National Estuary Study*, U.S. Department of the Interior, Vol. 5, Appendix F, 1970. The estuarine uses have been classified therein as (a) water transportation, (b) extractive industries, (c) water utilization and discharge, (d) urbanization, (e) recreation and education, and (f) commercial fisheries.

Water Transportation

Ship Building. Recent actions by the federal government indicate that a considerable expansion will take place in the merchant marine fleet over the next several years. The Merchant Marine Act of 1970 (P.L. 91-469) is designed to provide the shipping industry with a large modern fleet. Plans include building 300 new ships over the next ten years while modernizing shipyards.

Port Operations. Land-based facilities will be expanded and modernized to handle the off-loading requirements of the new ships.

Harbor and Channel Construction. Many of our existing harbor facilities are becoming obsolete because deeper draft vessels are being built. Studies indicate that modernizing existing facilities is only one answer. Alternatives exist for developing new ports in less congested areas, rehabilitating centralized or other selected ports and building offshore multi-purpose terminals.

Extractive Industries

Petroleum Mining. Although offshore exploration has been carried on off the New England coast, no test drilling has been done yet. Whether a viable offshore industry will exist on the New England coast is not known. However, the industry predicts intensified activity over the next decade. The current "energy crisis" greatly increases the probability of drilling off New England.

Hard Mineral Mining. Presently, the only hard mineral mining is done by dredging and is limited to sulfur, sand, gravel and oyster shell. Sand and gravel dredging results in one billion tons per year for the country, but is currently economical only when supplies are near use sites. The uses of this resource are for aggregate in concrete structures and highways, and for beach replenishment; therefore, large projects of these types will indicate potential mining sites. Oyster shell dredging is mainly a southern industry with its northerly extent in New Jersey. Sulfur production is limited to Louisiana and Texas. Metal mining does not appear to be a near-term potential industry for coastal New England.

Solution Mining. Salt, magnesium and its compounds, and bromine are the present products of this industry. Sodium chloride is the most important product of this industry as approximately 30 percent of world demand is met from this source. Ninety percent of this country's magnesium and 50 percent of the bromine come from solution mining. Texas is the major location of the industry. Desalination plants, a source of brine, may change the picture somewhat because these plants are being designed to use heat from nuclear power plants.

Water Utilization and Discharge

Electric Power Plants. It is projected that electrical power generated by coastal power plants will increase dramatically. Specifically, power generation by coastal power plants is forecast to be 5.79×10^{11} watts by 1980 versus 2.33×10^{11} watts in 1966 (*National Estuarine Study*, vol. IV, 1969). In 1967, there were 19 such plants in operation along the New England coastline. Since this time, several more plants, or units, have gone into operation or are under construction and others are in the planning stage. Public concern with air pollution will augur well for nuclear vs. fossil fuel construction, but because present nuclear plants are somewhat less efficient, more thermal addition may be expected per megawatt of power generated. Even though steam-electric systems may provide a valuable tool for aquaculture in New England and elsewhere, the long-term effects of plant operations upon the ecology of bays and estuaries is the subject of continuing research and debate. Furthermore, nuclear plants require substantial acreage for buffer zones against operational hazards.

Desalination Plants. Present design concepts combine desalination with nuclear power plants so that pumping and heating costs can be shared. These plants are likely to be built in areas of short and/or poor water supply and increasing urbanization so the New England states are unlikely candidates.

Waste Disposal. During the next five years, some $8 to 10 billion have been proposed for waste treatment operations; $1.5 billion of this for New England alone. Reclamation of primary treatment waste water looks promising in lieu of discharging it into estuaries. Los Angeles County estimates reclamation costs at $0.02 to $0.03 per 1,000 gallons.

Other Pollutant Discharges. Organics, metallic chemicals, insecticides, pesticides, detergents and agricultural and mining run-off may be present in the receiving waters of an estuary.

Urbanization

Housing. In a 1967 report to the House Committee on Merchant Marine and Fisheries, the Bureau of Sport Fisheries and Wildlife, U.S. Department of the Interior, predicted that by 1975 housing developments will become the leading cause of the loss of estuarine areas through dredge and fill operations to create waterfront sites. The creation of artificial islands in estuaries also is being contemplated.

Industry. Those industries requiring bulk raw materials or large volumes of water for processing are expected to acquire estuarine property.

Transportation. The major user in this classification, other than waterborne systems, is air transportation. The extension and creation of additional airport facilities, especially to handle jumbo jets, has necessitated landfill operations and stimulated the investigation of artificial islands.

Recreation and Education

Activities listed under this heading generally do not represent a conflict with aquaculture on the basis of ecological damage to an area. Potential conflicts develop largely on the basis of area use and aesthetics.

Sport Fishing. According to 1965 data, some eight million Americans spent $800 million dollars on this sport. Estuaries and coastal areas received the greatest attention as the predominant species caught are estuarine-dependent.

Wildlife. In 1965, it was estimated that over 1.5 million waterfowl hunters in the nation spent $87 million dollars on this sport. In addition, approximately ten million non-hunters participated in bird-watching and wildlife photography.

Swimming, Surfing and Skin Diving. Approximately $1.5 billion were spent nationally on water sports, implying that those areas with high water quality and beaches receive the greatest interest.

Boating. Recreational boating generates approximately $650 million per year in business in the country. Approximately 25 percent of all boating activity is in coastal water.

Education and Research. Increasing concern with the country's coastal waters has caused the planning and building of research facilities, public and private, on estuarine shores. The President's Commission on Marine Science, Engineering, and Resources recommended expenditures of $30 million per year for education and research on estuaries and coastal waters.

Commercial Fishing

Approximately 85 percent of the value of the U.S. fishery catch has been attributed to the continental shelf region, while over 60 percent, or some $300 million, has been attributed directly to estuarine-dependent species. The needs on which these species depend range from permanent habitat to food sources, spawning areas and passages from fresh to saline water. For the country as a whole, government projections of edible fish and shellfish are six billion pounds by 1975, over eight billion by 1985, and over 13 billion by 2000. New preservation and packaging techniques are expected to increase markets. Growing affluence is expected to increase demand for luxury products. Most of the projected improvement in fishing technology is seen as affecting the fleets, rather than indicating expansion in shoreside facilities. Aquaculture is the main sector of commercial fishing that has been projected to require extended fixed estuarine facilities.

Use Compatibilities

The preceding discussion of estuary users indicates little of the interactions to be expected among the users. The existence of one type of user may preclude or enhance the operations of another type. A precise evaluation of the effect of one or more users on others depends on the particular estuary's land and water characteristics and on the particular user types. The *National Estuary Study* (Vol. 5, Appendix F, Chapter III, p. 62) points out, "The need to accommodate the various interests involved will require highly sensitive multiple use estuary planning and allocation of potential reserves for aquaculture industries."

Generalizations can be made about the compatibility of the various estuary users and summarized in tabular form. Qualitative ratings, such as those shown in table 5-1 (*National Estuary Study*) are always open to debate; however, in a generalized form, they can serve as a "caveat" to the potential aquaculturist.

Land Site Availability

Potential Availability

In determining which areas of the New England coast are suitable for aquafarming operations, it is of value to investigate those areas classified as "recreational" shoreline by the President's Commission on Marine Science, Engineering, and Resources (Vol. I, Chapter III, p. 18). In arriving at this classification, those areas devoted to housing, port facilities, industry, etc. were excluded so that only relatively undeveloped coastline was considered as potential for recreation. Table 5-2 sets forth the potential coastline by state, type of terrain and ownership.

From these data, it is apparent that of the total detailed coastline of New England, which is 6,130 miles long, only 60 percent, or approximately 3,600 miles, remains for further recreational consideration. Of this, some 70 percent, or 2,600 miles, of detailed coast, is in Maine and is to a great extent bluff or rocky shore. The bluff classification for New England (3,023 miles) has been estimated to contain beaches over approximately one-half its extent. In addition, some 381 miles are separately classified as beach. As a result, some 1,900 miles of shoreline, made up of beach (381) and bluff with beach (1,511) is of significant interest to those planning recreational facilities for our population over the next decades. It seems unwise, then, to consider the part of the coast having beaches as potential sites for aquafarming operations, at least at this time. An additional point which supports this observation is that much of the beach extent is on relatively open coast, exposed to surf and storms. On the other hand, many of the beaches, especially in southern New England, are barrier bars with

Table 5-1. Estuarine user compatibility with aquaculture.

General Classification	Sub-classification	Compatibility Rating
Water transportation	vessels construction	medium
	channel construction	very low
	shoreside construction	low
Extractive industries	petroleum mining	very low
	solution mining	high
	bottom mining	very low
Water use and discharge	power generation	low
	desalination	very low
	sewage disposal	very low
Urbanization	housing	high
	commercial industry	high
	airport, highway	high
Recreation/education	sport fishing	low
	swimming, diving	high
	boating	medium
	research facilities	high

brackish lagoons and salt ponds located behind the beach. These areas should certainly enter consideration for locating aquaculture operations.

Destruction and Alteration

Considering the previous discussion on the part of the coast classified as beach, a multiple use problem was implied by the potential recreational use of these segments of the coast. A similar problem exists for the marsh classification. Fishery scientists, resource managers and conservationists are increasingly concerned with the intertidal salt marshes of this country. The result has been legislation including the Coastal Wetlands Preservation Bill, Marshlands Zoning Law and Green Acres Program. The increasing tempo of public concern, and the ensuing legislation, are certain to accelerate the marshland acquisition programs already underway in New England.

If conservation of marshlands is deemed in the public interest, there is a little doubt that these areas of high productivity are in dire need of protection from dredging and filling operations and deteriorating water quality. The resulting legislation, however, can have the characteristics of a double-edged sword for the aquafarmer in that the preservation of the marsh and estuary is assured by prohibiting commercial development, including aquafarming! Therefore, unless the legislation is sufficiently flexible, the coastal aquafarmer may find himself in the position of being unable to use these nutrient-rich waters or locate his operation in appropriately protected waters contiguous to the wetlands. There is need for a sensitive and well-considered zoning or allocation plan so that uses that do not detract from the area may be permitted to operate in it.

If conservation of the coastal zone is desired by the public, there must be an accelerated protection or acquisition program. Table 5-3 has been adopted from the data in *Wildlife Wetlands and Shellfish Areas of the Atlantic Coast Zone* by G. P. Spinner, American Geographical Society, Folio 18, New York City, and from the U.S. Fish and Wildlife *Report to the House Committee on Merchant Marine and Fisheries* 1967. Causes for the physical destruction of wetlands in coastal New England were compiled by the Bureau of Sport Fisheries and Wildlife, Department of the Interior, Region 5, Boston, and were presented in a series of reports (*Coastal Wetlands Inventory*) in June, 1965. Table 5-4 is a compilation of these reports which covered the ten-year period 1954-64. The data is presented as a percent of total wetland loss for each state, attributable to specific causes. In these reports are data on the availability of wetlands in each county of the state as of 1964, and an estimate of the vulnerability of each county's wetlands. This information can be used by the potential aquaculturist to focus on particular regions of each state and to afford him an estimate of the level of intensity of the multiple use problem. It is noted that discrepancies exist between tables 5-3 and 5-5, especially regarding the wetlands of Maine. The June, 1965, report of the Bureau of Sport Fisheries and Wildlife, on the wetlands of Maine points out that of some 96,400

Table 5-2. Shoreline analysis.

						Ownership		
			Terrain			Public		
State	Total Detailed Shoreline[1]	Available for Recreation[2]	Beach	Bluff	Marsh	Recreation	Restricted	Private
Conn.	618 mi.	162	72	61	29	9	—	153
R. I.	384 mi.	183	39	145	4	8	10	170
Mass.	1519 mi.	649	240	288	121	12	6	631[3]
N. H.	131 mi.	25	7	9	9	3	—	22
Maine	3478 mi.	2612	23	2520	69	34	—	2573
Total	6130 mi.	3631[4]	381	3023	232	66	16	3549

[1] *1939-40 Coastal Geodetic Service Study, ref. p. 492, in Fisheries Statistics of the United States, 1963, in 100 ft. unit.*
[2] *Detailed measurements in unit measure of 100 ft.*
[3] *Pre-national seashore on Cape Cod.*
[4] *Totals include rounding errors.*

acres, approximately 80,800 acres were in mudflats and other terrain types laid bare at low tide. However, adjusting for this classification does not account for the discrepancy; it appears to originate from differences in the definition of the word "wetland." A comparison of the two investigations does, however, show the rate of destruction of habitat of interest to the aquafarmer and indicates the location of potential sites.

Conservation Plans

The following paragraphs set forth by state the various programs for salt marsh acquisition and can serve as a guide for the potential aquafarmer. This information was extracted from the *National Estuary Study*, U.S. Department of the Interior, Vol. 7.

Connecticut. The state had 26,500 acres of tidal marsh in 1914; less than 14,800 remained in 1969. Of these, 4,200 are owned by the state Board of Fish and Game. Plans call for the acquisition of an additional 7,100 acres in the next several years, assuming sufficient funds are available. The remaining 3,500 acres or less will belong to local governments or conservation organizations or be in private ownership.

Rhode Island. About 900 acres of salt marsh are owned by the state; more will be acquired as funds become available to the Department of Natural Resources. A Green Acres Bond Issue to provide funds for acquisition was defeated recently.

Massachusetts. The state can obtain land by condemnation. A wetlands protective area in one town was recently established covering 3,300 acres. The legislature appropriated an additional $500,000 for access to inland and coastal waters.

New Hampshire. Most of the acquisition is done by the Society for the Protection of New Hampshire Forests and the state Audubon Society. Public

Table 5-3. Record of estuary and wetlands destruction (10-year period, 1954-64).[1]

	American Geographical Society				U. S. Fisheries and Wildlife Service		
State	**Total Estuary Area (in acres)**	**Important Habitat (in acres)**	**Lost to Dredge and Fill (in acres)**	**Net Estuary (in acres)**	**Coastal Wetlands (in acres)**	**Wetlands Destroyed (in acres)**	**Net Wetlands (in acres)**
Conn.	31,600	20,300	2,100	18,200	14,744	3,200	11,544
R. I.	94,700	14,700	900	13,800	2,200	150	2,050
Mass.	207,000	31,000	2,000	29,000	45,895	1,200	44,695
N.H.	12,400	10,000	1,000	9,000	6,060	150	5,910
Maine	39,400	15,300	1,000	14,300	29,182	300	28,882
Total				84,300			93,081

[1] *A. G. S. investigation defines estuary as area between headlands and important habitat as that part of area less than six feet in depth. (Tables 5-5 and 5-6 contain conflicting data from other investigations.)*

Sources: (1.) Spinner, G. P., 1969. Wildlife wetlands and shellfish areas of the Atlantic coast zone, American Geographical Society, Folio 18, New York; (2.) U.S. Sport Fisheries and Wildlife Report to the House of Representatives Committee on Merchant Marine and Fisheries, 1967.

Table 5-4. Causes of wetland losses (percent of state total).

State	Housing	Disposal	Misc. Fill[1]	Transportation and Industry	Recreation	Erosion	Marinas, Channels
Conn.	5	14	48	24	3	—	6
R. I.	4	11	8	61	—	—	16
Mass.	35	22	16	11	6	6	4
N. H.	33	4	—	29	—	—	34
Maine	—	—	50	—	—	—	50
Long Island	34	1	20	22	17	—	6

[1] *Misc. fill classification used when ultimate use of filled area was unknown.*

Source: U.S. Department of the Interior, Bureau of Sport Fisheries and Wildlife, 1965. Coastal wetlands inventory.

ownership of wetlands totals about 500 acres of coastal marsh and 2,000 of inland wetlands. A wetland acquisition priority list totals 17,925 acres.

Maine. Both the Inland Fisheries and Game Department and the State Parks Commission have coastal land acquisition programs, and the State Parks Commission owns 22 miles of waterfront. The federal Bureau of Sport Fisheries and Wildlife is acquiring about 4,000 acres of salt marsh as a National Wildlife Refuge and to date has acquired

Table 5-5. 1964 wetlands acreage and vulnerability, by county.

State/County	Vulnerability[1] 1	2	3	County Total	State Total
Conn.:					
Fairfield	987	33	100	1,120	
New Haven	4,335	702	1,023	6,060	
Middlesex	1,922	1,563	985	4,470	
New London	613	1,026	1,550	3,189	
					14,839
R.I.:					
Bristol	—	724	21	745	
Newport	74	454	156	694	
Washington	358	240	165	805	
					2,192
Mass.:					
Barnstable	1,512	8,032	3,609	13,153	
Bristol	—	2,623	—	2,623	
Dukes	—	—	400	400	
Essex	880	14,370	2,300	17,550	
Nantucket	—	—	720	720	
Plymouth	136	5,465	—	5,601	
Suffolk	20	550	—	570	
					40,617
N.H.:					
Rockingham	350	200	8,880	9,430	
Strafford	—	—	350	350	
					9,780
Maine:					
Cumberland	—	—	20,875	20,875	
Hancock	—	1,900	12,440	14,340	
Knox	—	—	2,720	2,720	
Lincoln	—	—	3,090	3,090	
Penobscot	—	—	630	630	
Sagadahoc	—	—	8,620	8,620	
Waldo	—	—	2,500	2,500	
Washington	—	12,700	24,530	37,230	
York	—	—	6,345	6,345	
					96,350

[1] *Vulnerability Classification: (1) a wetland in which a known agent is adversely affecting the area or is expected to do so within five years; (2) a wetland in which no known agent is adversely affecting the area, but where a possibility exists, and (3) a wetland for which no loss is anticipated.*

Source: U.S Department of the Interior, Bureau of Sport Fisheries and Wildlife, Region 5, 1965. Coastal wetlands inventory, Boston.

1,316 acres. The Nature Conservancy acquired several areas of islands to add to seacoast holdings.

Site Selection Aids

The Water Quality Office, Environmental Protection Agency, Needham, Massachusetts (Edward Wong), has recently produced the first of an atlas set for the coastal states of New England. The ***Shellfish Atlas of Connecticut*** (February 1970), is a series of 15 large charts covering the coastline of the state. The charts show location of wetlands, regions where different species of shellfish are harvested and the location of prohibited or shellfish closure areas. Food and Drug Administration, New England Technical Services Unit, Construction Battalion Center, Davisville, Rhode Island (Robert A. Campbell) has produced coastal charts delineating shellfishing areas by species and closure areas. Their prime responsibility is to regulate sanitary shellfish in interstate commerce and to evaluate and aid related work by state agencies. These investigations are potentially valuable planning tools for a prospective aquaculturist and can also be used as base maps for entering data on zoning regulations and information from the state planning and development departments on future commercial, residential and recreational developments in each area. The prohibited shellfish areas or regions of water pollution are current evaluations but do not specify the degree of pollution or the type. In addition, they do not take into account a state's goals for water quality improvement. These all must be considered by the potential aquafarmer and can be entered on these base charts.

The preceding section on estuarine and wetlands loss or physical destruction of potential sites does not include information on regional deterioration of water quality and its effects on the productivity of the remaining area. The extent and magnitude of destructive biological effects will depend on the end use of the filled land, treatment facilities, and the size and circulation of the remaining estuary-wetlands system.

Water Quality

General Discussion

A viable aquaculture industry in New England will depend to a great extent upon the availability of clean water, whether the species being cultured are being held under natural conditions or artificially in tanks or pools. Because of economic considerations, probably most aquaculture production will be harvested or reach market size in natural areas, namely, bays, estuaries and salt ponds. Many of these areas, though otherwise potentially suitable, are closed, or perhaps will be closed, to food production because of pollution. Even hatchery operations or controlled environment systems are vulnerable to increasing levels of water pollution, if the major source of water is derived from the natural environment.

There has been much confusion about the use of the word "pollution." A working definition, given by Dr. Clarence M. Tarzwell, senior research adviser, National Marine Water Quality Laboratory, Environmental Protection Agency, West Kingston, Rhode Island, is "the addition of any material or any change in the quality or character of a water that interferes with, lessens, or destroys a desired use." There is a decided emphasis on "use," and under this definition a pollutant is any material or change which damages use. Therefore, if a material or change in quality does not interfere with any desired use, it is not pollution. "Pollutant" is a term that is also very loosely used. Certain materials, such as trace elements, and certain fertilizing materials, such as nitrates and phosphates are needed for satisfactory growth. There are also certain other physical parameters such as temperature and the presence of specific amounts of dissolved gases and metallic salts which are required for good biologic growth. However, when the temperature is too high or too low and when the gases or salts occur in too great or too little concentrations they become harmful.

There is a great need for knowledgeable planning for the coastal zone of New England, which includes the need for knowledge of the range from optimal to least acceptable of water quality requirements for the species selected for aquafarming. These needs are discussed later in this section; the following is concerned with the present status of water quality in this region.

Regional Problems

The magnitude of the coastal water quality problem of each of the New England states can be learned from reports issued by the individual states in accordance with the Water Quality Act of 1965, which was one of two recent amendments to the Federal Water Pollution Control Act (FWPCA). The Water Quality Act requires that standards for interstate waters be set by the states, and then be approved as federal standards by the Secretary of the Interior. The standards identify uses of the waters, including agricultural, municipal, industrial, recreational, fishery and wildlife. They indicate the water quality necessary to support each use, and include plans to implement and enforce this quality. If the state-federal relationship is effective in carrying out the provisions of the Water Pollution Control Act, a powerful instrument will have been fashioned for the coastal zone system. At any rate, the individual state's reports are valuable aids in planning the location of aquafarming industries.

The magnitude of the domestic sewage problem in coastal waters can be evaluated by comparing those areas closed to shellfishing due to health standards with those areas known historically to produce shellfish. The data in table 5-6 are adapted from the *National Register of Shellfish Production Areas* (1966, L. S. Houser and F. J. Silva, Shellfish Sanitation Branch, U.S. Department of Health, Education and Welfare) and recent work by the Food and Drug Administration, Davisville, Rhode Island (R. Campbell), and the Water Quality Office, Environmental Protection Agency, Needham, Mass. (E. Wong).

The magnitude of the industrial waste problem in the states becomes apparent. Only the gross discharge is shown in table 5-7; however, plant locations and types of discharge can be obtained from the state departments of health or natural resources, or subdivisions thereof. To put the total 1963 New England industrial waste discharge (1,300 million gallons per day) in perspective, one can imagine a ribbon of waste water one foot deep and five feet wide extending along the 6,000-mile detailed coastline of New England being discharged *every day* by industry. This water use does not include the 150 gallons per day per capita estimated for domestic water use.

Charts and definitive descriptions of waters closed

Table 5-6. Analysis of shellfish production areas (acres in thousands).

State	Open Acreage	Acreage: Closed (conditional, full)	Acreage: Total	% Closed
Conn.	50	43	93	46
R.I.	88	28	116	24
Mass.	25	17	42	40
Maine	280	70	350	20
Total	443	158	601	26

Sources: (1) Houser, L. S. and F. S. Silva, 1966. National register of shellfish production areas. Shellfish Sanitation Branch, Department of Health, Education and Welfare, Washington, D.C.; (2) Campbell, R., 1970. Food and Drug Administration, Davisville, Rhode Island, and (3) Wong, E., 1970. Water Quality Office, Environmental Protection Agency, Needham, Massachusetts.

Table 5-7. Industrial waste discharge by coastal state, 1963, in millions of gallons per day.

	Total Waste Discharge		Treated		Untreated		% Treated
State	No. of Plants	Volume	No. of Plants	Volume	No. of Plants	Volume	
Conn.	209	319	65	25	144	294	8
R.I.	67	44	11	8	56	36	18
Mass.	304	395	78	44	226	351	11
Maine	64	447	21	55	43	392	12
N.H.	40	96	12	14	28	82	15

Sources: Conn. Department of Health, R.I. Department of Natural Resources, Mass. Department of Natural Resources, Maine Department of Natural Resources and N.H. Department of Health.

to shellfishing are available from each state. These demonstrate vividly the domestic pollution situation in each region, as only the highest quality water, "SA," can be harvested for raw shellfish consumption without depuration. These charts present only a partial picture of the situation in that the particular pollutant is not identified but only the resultant classification is listed if any one of the standards is not met. In most cases, the classification is based almost entirely on coliform count. Therefore, although the sewage may be very fertile in nitrogen and phosphate compounds and beneficial to shellfish growth, shellfish may not be taken from these areas because the sewage also contains coliform bacteria.

Not only the extent of waste treatment by industry and municipalities should be considered, but also the adequacy or intensiveness of treatment by those organizations which do process their waste water must be evaluated. There are indications that even secondary treatment of domestic sewage is inadequate. In many areas, the volume of sewage and other organic wastes has increased to such an extent that the ability of the receiving waters to break down these materials has been exceeded. In areas of dense population, even the effluents from secondary treatment plants can overwhelm a water body. While such plants may remove 85 percent of the biological oxygen demand (BOD), this fact is misleading. The size of the total effluent flow must also be considered in determining the quantity of residual BOD emission. Further, secondary treatment plants as presently operated remove only a portion of the waste materials and merely change the form of the remainder. As a result, large quantities of nutrients are discharged (Tarzwell, 1966). An example of this flow of plant nutrients due to man's activities is given in table 5-8 for the state of Connecticut (Frink, 1970).

In addition to the flow of plant nutrients from sewage treatment plants, the chlorination process necessary to eliminate pathogenic organisms has been shown to be detrimental to aquatic life. A study of the Little Patuxent River, extending over a ten-year period, can serve as an example. Chu-Fa Tsai, National Resources Institute, University of Maryland (Chesapeake Science) found that near the sewage outfall there was more than a 25 percent reduction in species and 80 percent reduction in individuals. Further downstream, in organically enriched areas, the number of species was fairly constant but the composition of the species "changed significantly." Tsai concluded it was the chlorinated sewage that caused the lowered fish populations near the outfall rather than reduced dissolved oxygen or pH or other physical change in the stream. A final example of the inadequacy of some treatment procedures is indicated in a report of the Council on Economic Priorities, Washington, D.C. (Dec. 1970), in which the paper industry's pollution problems were investigated. It is reported that the 24 paper companies used over two billion gallons of water per day, nearly two-thirds of which was discharged after inadequate treatment that did not meet federal standards. One-third of the waste water was discharged directly with no treatment.

Examples like the preceding ones are plentiful. The main point is that both extensive and intensive waste treatment are of concern to the aquafarmer. Documentation stating that all effluent in a particular estuary has been treated is not sufficient information for him to consider locating his operations there. From this point of view, an ideal tool to solve his plant location problem would be a system through which he could supply his criteria, such as water quality requirements, physical characteristics, etc., and receive in return recommended locations.

Table 5-8. Estimates of major plant nutrients in annual waste materials from various sources in Connecticut.

Source	Waste Material (in tons)	Nitrogen (in tons)	Phosphate (in tons)
People—3,000,000	1,500,000	13,500	4,500
Cows—100,000	1,500,000	7,500	1,600
Broilers—12,000,000	240,000	3,600	840
Layers—4,000,000	80,000	1,200	280
Dairy and poultry feed	444,000	13,300	3,100
Dairy farm fertilizer	26,100	2,500	1,300
Other agricultural fertilizer	29,100	2,100	1,000
Non-agricultural fertilizer	25,600	2,800	1,400
Protein produced in Connecticut	—	3,800	—
Protein imported into Connecticut	—	14,000	—
Automobile exhaust	—	38,000	—
Industrial fumes	—	44,000	—

Source: Frink, C. R., 1970. Plant nutrients and animal waste disposal. Circular No. 237, Connecticut Agricultural Experiment Station, New Haven, Connecticut.

In a rudimentary form, the optimal system exists as an accomplishment of the National Estuarine Pollution Study. The *National Estuarine Inventory* is its title and is the result of the assignment under Section 5(g) (2) of the Clean Waters Restoration Act of 1966, "In conducting the . . . study, the Secretary shall assemble, coordinate, and organize all existing information on the Nation's estuaries and estuarine zones. . . .

"The *Inventory* is a compilation of the available information on the coastal zones of the United States. It includes a broad spectrum of information ranging from the economic and ecological values of each estuarine system through the impact of man's use on each system to the needs for waste treatment to enhance water quality." (Extracted from the Preface to the *Handbook of Descriptors of the National Estuarine Inventory.*) There are almost 100 Estuarine Register Areas covering the New England coast from Maine through Connecticut. At the present time, the completeness and quality of the data available are reportedly highly variable. For some regions the data are acceptable; for others some of the data are relatively complete. Some data are missing or incomplete. As a result, the present-day practical value of the *National Estuarine Inventory* is open to question. The point, however, is that a tool of great potential value for coastal zone planning in general and for aquafarming site selection in particular exists. It requires supplemental work by an aquaculturist on site since the data are inadequate for investment decisions.

Species Requirements

Certain physical and chemical characteristics of coastal water have been shown to influence growth, survival, reproduction, meat quality, etc. of the species selected for aquaculture. Much work has been done on determining optimum temperatures, salinities, oxygen levels, nutrient concentrations, etc. for the various species. The main business of the aquafarmer is to provide these characteristics in the proper magnitude at the proper stages of the life cycle of the particular species. He may often be presented with business decisions regarding the cost-effectiveness or marginal value of supplying the optimums, so may be forced to operate under less than ideal circumstances.

Considering the preceding optimizing decisions as positive ones, the aquafarmer can also be faced with a series of negative decisions. The latter decisions cover concentration levels that hinder growth or reproduction, cause mortality, taint the meat, etc. The aquafarmer must know the maximum acceptable concentrations of such characteristics of coastal water as organochloride and organophosphorous pesticides, heavy metals, sulfides, hydrocarbons, etc. The ubiquity of many of these compounds has been established. However, the variability of their concentration at a particular location is not well known except in rare instances nor has the maximum acceptable concentration been established for marine species.

Relatively few of the many substances recognized as potentially toxic pollutants of the marine environment have been studied sufficiently to define their maximum allowable concentrations nor have their potential synergistic effects been fully evaluated. Many determinations have been made of the concentration of toxicants which kill half the test organisms; however, few studies have been made to determine the maximum concentration of toxicants which are not harmful with continuous exposure.

Water pollution is an area of work critical to the success of an aquafarming industry and one that must not be overlooked in planning site locations for this industry. It is important to know the water quality requirements for the species selected for cultivation. Without this information and the parallel requirements for monitoring and control, open system aquafarming in New England may be subjected to "mysterious" mass mortality, infertility problems and tainted flesh, which would result in a high level of economic risk and would impede the development of the industry.

Until more precise data are determined for a particular species' water quality requirements, the following general standards have been proposed by the Subcommittee for Fish, Other Aquatic Life, and Wildlife of the National Technical Advisory Committee on Water Quality Criteria, Federal Water Pollution Control Administration, April 1968.

Salinity. No water diversion activity should be allowed which causes more than ten percent change in isohaline patterns.

Currents. No water diversion activity should be allowed that alters current flow to adversely affect existing biological and sedimentological situations.

pH. No materials should be introduced that change the normal range of pH by more than 0.1 pH or extend the range outside 6.7 or 8.5.

Temperature. Normal monthly means of maximum daily temperatures should not be raised more than 2.2°C (4°F) during October through June and .8°C (1.5°F) during July through September. The rate of temperature increase should not exceed .55°C (1°F) per hour except when due to natural causes.

Dissolved Oxygen. The dissolved oxygen (DO) levels in surface coastal waters should be greater than 5.0 milligrams per liter except when natural phenomena depress this value. The DO levels in estuaries and tidal tributaries should not be less than 4.0 milligrams per liter except for natural phenomena.

Oil. No petroleum products should be discharged such that (1) visible film, sheen or odor results; (2) tainting fish or edible invertebrates results; (3) oil sludge forms on shore or bottom, or (4) effective toxicants are produced.

Turbidity, Color. No changes should be allowed in turbidity or color unless they are demonstrated to be harmless.

Settleable and Floating Substances. No materials should be allowed that contain settleable solids or substances that may precipitate out in quantities that adversely affect the biota.

Tainting Substances. Substances that taint or produce off-flavors in fish and edible invertebrates should not be present in concentrations discernible by bioassay or organoleptic tests.

Radionuclides. No radionuclide, or mixture of same, should be present at concentrations greater than specified by U.S. Public Health Service Drinking Water Standards and Radiation Protection Guides of the Federal Radiation Council.

Plant and Nuisance Growths. No water diversion activity should be allowed that adversely affects biota or promotes nuisance organisms. No artificial enrichment should be allowed that causes major quantitative or qualitative alteration in the flora, or any nuisance that can be attributed directly to nutrient excess or imbalance. Naturally-occurring atomic ratio of NO_3—N to PO_4—P should be maintained. Similarly, the ratio of inorganic phosphorus to total phosphorus should be maintained.

Toxic Substances. Including substances of unknown toxicity, all substances containing foreign materials should be considered harmful and not permissible until bioassay tests have shown otherwise. For pesticides for which limits have been determined, the manual gives two groups, A and B, according to toxicity; the 48-hour TL_m are given and an application factor of 1/100 is recommended. For industrial and other toxic wastes, there are three pertinent points: (a) safe concentrations of metals, ammonia, cyanide, and sulfide should be determined by the use of application factors to 96-hour TL_m values as determined by flow-through bioassays. Application factors should be 1/100 for metals, 1/20 for ammonia, 1/10 for cyanide, and 1/20 for sulfide; (b) fluoride concentrations should not exceed that of drinking water, and (c) detergents and wastes from tar, gas, coke, petrochemicals, pulp and paper, hospitals, etc. should be subjected to frequent bioassay using flow-through techniques. For persistent toxicants, an application factor of 1/100 is suggested, while for unstable or biodegradable types, 1/20 is suggested.

Summary

This section has indicated that present and projected water quality should be a major consideration in determining sites for aquafarming operations. The fact that waste treatment is in existence in a particular area is insufficient evidence that water quality is acceptable for aquafarming.

Maximum acceptable concentrations of expected pollutants need to be determined for the species to be cultured; these should be regarded as the water quality requirements for the aquafarming operation. From the requirements of the various users, or "borrowers" of water, standards can be derived. Coupled with enforcement procedures, the quality of a region's water can be kept from deterioration. Implied here, however, is the setting of priorities for a water body as well as the interplay of politics and economics. Since aquafarming does not exist as a powerful user or borrower of water, its economic and political position is not strong. Until its economic strength is demonstrated and because of its high water quality requirements, aquafarming should be allocated space by coastal zone planners in recreational, wildlife or conservation areas. This observation coupled with information on the salt marsh acquisition programs of the states and private groups, set forth in the section on land site availability, suggest that the potential aquafarming industry might attempt classification as a "conforming use" in these preserves.

Legislation

This section is divided into two major parts. The first is concerned with existing legislation which could be altered to facilitate development of an aquaculture industry, and the second, with new legislation and the exercising of legislative techniques needed to protect a developing aquaculture industry.

Existing Legislation as Impediments

Most existing coastal marine fishery regulations have resulted from a combination of attempts at conservation, competition among fishermen for limited supplies of particular species, and competition between sport and commercial fishermen for certain species. Numerous state and local laws and regulations were designed to protect established small-boat fishermen by restricting the use of efficient devices. Other regulations, making up the maze of state fishery laws, were adopted over the years, for reasons long forgotten. Many towns and counties in New England have ordinances pertaining to local fisheries. These legislative devices, designed in a time when less knowledge concerning those natural resources was available and for a "cottage" industry, are understandably not appropriate in many cases to developments of today.

In reviewing the problem areas of existing state and municipal laws, it is instructive to have in mind a model, even in general form, of an aquafarming operation. The operation may be a continuous one in which the product is being shipped throughout the year. Being a continuous or even a batch operation means there is a spectrum of ages and sizes of the product under control or in possession of the operation throughout the year. There will be females that are ripe, berried, or in spawn; there will be post-larval forms and juveniles in confinement; there may be a large ranging or fattening area in an estuary for the final stages of preparing the product before market. The operator will want to harvest his crop with the most efficient equipment available and whenever it is "ripe." He will have invested a substantial sum in fixed assets, plant and equipment, and may require exclusive control in areas where his assets are producing. With this model in mind, the following paragraphs are presented to point out the problem areas in existing state laws.

Leasing. Maximum term on a shellfish lease can be from five to ten years and at the discretion of local government. In some states, leasing provisions cover just oysters and in others, shellfish in general. Some states have area per lessee limitations; and residency requirements exist in most states. In some states, productive areas are not available for lease, leaving only the marginal and non-producing areas. Navigation rights are withheld by some, so exclusivity is not included. Regulations are geared to bottom harvesting as opposed to water column culture.

Gear. Power boats are prohibited in clam and oyster areas in some states, as are power dredges and hydraulics. Permitted equipment may be specified as hand-operated dredges, rakes, forks, or tongs. Dimensions of harvesting equipment may be limited. Dragging, skin-diving and dipnetting for lobster are prohibited in some state waters.

Size/Age. In all states, size limitations exist relating to clams, oysters and lobsters in possession of the operator. Possession of bay scallops lacking an annular ring is prohibited.

Sex. Possession of egg-bearing lobsters is prohibited. Taking of female crabs may be prohibited.

Quantity. Daily quantity limitations on shellfish exist in most states or towns, which may vary with the type of harvesting gear.

Time. Harvesting is limited to daylight hours in some states. Limitations to certain days of the week and certain months also exist.

The specific local regulations for a species of interest in a selected location can be culled from the state's laws and the town's ordinances. The main point is that an aquafarming operation may by its very nature break a myriad of local regulations as they are presently constituted. Steps to ameliorate this situation in the form of an aquafarming bill have been proposed to legislatures in several states.

Enforcement of land use regulations by the states and localities can have inhibitory effects on aquafarming. There is no doubt that in our society, market values have been emphasized to the detriment of extra-market ones such as recreational, ecological, aesthetic, and psychological values (Report, Commission on Marine Sciences, Engineering & Resources, Vol. 1, Chapter III, p. 124). In the sphere of land-use regulation, when market and extra-market values come into conflict, the market value has most often been paramount and cost-benefit analysis is of limited usefulness as a quantitative technique for handling recreational, ecological, or other qualitative values. Bending to market pressures has a profound impact on effectiveness of land-use regulatory techniques. Zoning traditionally is the responsibility of local governments, and historically they have failed to protect the extra-market values —scenic beauty, recreational values, and preservation of wildlife—against market interests producing jobs and increasing the tax base. For this reason, responsibility for zoning the coastal areas should be at a governmental level above the municipal (*ibid.*, p. 152).

Since coastal areas are natural phenomena, it may be advisable to let the extent of the natural configuration dictate the governmental organizations with the prime planning and regulatory responsibility, rather than the reverse. At the least, various levels of government should be involved. This does not mean that the state should not supply leadership or guidance; rather it means that local backing might be obtained more effectively by including local interests in the planning process. Additionally, it may be advisable to consider how critical the particular area is in allocating responsibility. In some cases, the state may have responsibility, in others an intramunicipal group may have it or in others, a municipal group. *Maine Law Affecting Marine Resources*, vols. 1-4 (University of Maine, 1970), *Report of the Governor's Committee on the Coastal Zone* (Rhode Island Department of Natural Resources, 1970), and *State Coastal Management Legislation* (New England River Basin Commission) are examples of investigations of state natural resources regulations.

New Action by the Public Sector

If creation by legislative action of a comprehensive aquaculture law is desired, then legislation and regulation are required in three general areas: (a) regulations acknowledging the existence of aquafarming as an industry different from commercial fishing; (b) regulations on land use in the coastal zone that allocates space to aquafarming, and (c) regulations regarding coastal zone water quality that insure the existence of standards appropriate to an aquafarming industry.

Development of aquafarming as an industry in the coastal New England states could be facilitated by legislation in the various states which would permit leasing and licensing of coastal lands and waters. Such legislation might include, among its provisions, the following: (a) definition of aquafarming and, perhaps, samples species to be farmed; (b) acknowledgement of lessor responsibilities regarding water quality; (c) definition of lessor's power to grant, and revoke, leases and licenses with provisions included for explicit definition of lease duration conditions at an administrative level; (d) methods for applying, advertising for, assigning, renewing, transferring, etc. leases; (e) rights to be conferred or withheld, such as navigation, recreational fishing rights, access, etc.; (f) rental and fee structures; (g) safety provisions and requirements, such as markers for rafts, racks, etc.; (h) offenses and subsequent penalties, and (i) relation of aquafarming laws to existing fisheries laws.

Areas of coastal waters that are made available to the aquafarming industry must be allocated as the result of a reasonable planning process. Coastal zoning, land acquisition and lease-back arrangements, and purchase of easements, permits, etc., are tools that may be employed following the development of planning at the appropriate governmental level. Planning activity which relies on the marine research activities of private and state groups and agencies within the region should be undertaken to provide the necessary basis for zoning coastal water areas.

Questions of aquacultural lease rights are inextricably linked with broader issues of coastal zone use. If location of aquacultural facilities is promoted on an indiscriminate basis, unnecessary conflicts with other uses of the coastal zone are almost inevitable. Conflicts which might occur include those between aquaculture and either recreation, minerals extraction, harbor and channel improvement, thermo-electric generating plants, municipal/industrial waste effluents or wildlife ecology.

As indicated in table 5-1, the coastal land uses most compatible with aquaculture include urban transit, certain types of industry, recreation and education. Although not explicitly listed as a "use" of coastal lands, one might also list "open spaces" or "green belt" zones. Such zones are by definition distinct from wilderness preservation areas; certain conforming uses may be permitted, for example, agriculture or selective cut forestry. It would seem that inclusion of aquaculture as a conforming use need not unduly strain the concept of open spaces zoning. Regulations regarding land use and water quality must acknowledge the critical requirements of an aquafarming industry for water quality and exclusive control over the bottom and water column. Since this industry does not presently exert a strong economic force, conservation and open-space legislation and acquisition plans might incorporate aquafarming as an acceptable use in those allocated areas. The land and water acquired under these plans can be made available to aquafarming through lease-back agreements, permits, licensing, etc.

There is an alternate approach to zoning which should be considered. Since aquaculture is in its infancy, the need for a general law may be questioned. The alternate approach would be to authorize acquisition or long-term lease by a state agency of one or more coastal areas which are suited to aquaculture and which would have minimum conflicts with other uses. These areas could then be leased to private firms for the purpose of aquacultural production. Public access to information obtained by the lessee could be required, if the lease and/or production facilities involve public assistance. This approach has the following advantages at the present time: it would (a) focus attention on identification of a suitable area or areas; (b) provide information on the feasibility of aquaculture prior to writing comprehensive legislation; (c) provide detailed information which could be useful in any subsequent legislation; (d) make acquacultural knowledge gained by the lessee public information; (e) tend to make potential conflicts and opposition specific to the site chosen, and by careful site selection, potential conflicts could be minimized; (f) allow for a redirection of coastal zone use by letting leases expire if at some future time aquaculture were deemed to be no longer the best use of the site, and (g) under existing administrative authority, allow for exemption from minimum size regulations and harvesting technology restrictions for a bona fide aquaculturist(s) operating on the selected site(s). Somewhat of a precedent for this type of "exclusive use" of naturally productive areas is already established in Massachusetts. Under Section 17(7) of Chapter 130 of the General Laws Relating to Marine Fish and Fisheries, the Director of Marine Fisheries may "occupy, use and control" ponds, estuaries, creeks or other arms of the sea within the coastal waters for experimental purposes. This power has been exercised over two salt-water ponds in Massachusetts.

6. Summary and Recommendations

Summary

Selected Species

At the present time, those species appearing to have the greatest potential for commercial culture in New England are the American oyster, hard clam, bay scallop, American lobster and silver (Coho) salmon. The first four are indigenous to the New England area, while experimental introductions have demonstrated the ability of the silver salmon to thrive in this region. Furthermore, a technology exists for culturing these five species through all stages of their life cycles to marketable size. Finally, market demand for each of these species appears to be strong and to be capable of absorbing significant increases in production particularly if production were scheduled—through culture techniques—to take advantage of seasonal variations in price.

Controlled versus Natural Environments

With respect to the culture of the American oyster, hard clam and bay scallop, the unpredictable nature of annual reproduction in most parts of New England would appear to make a hatchery operation necessary at least on a supplementary basis. However, it does not appear to be economically feasible at present to attempt to culture these species to maturity in a controlled environment. It seems far more practical, in view of the difficulties and expense involved in providing adequate amounts of algal food, to make maximum use of the natural environment at as early a stage in their development as possible. This approach is feasible with these three species since (a) they may derive their food directly from the surrounding water, i.e. at no cost, and (b) they are relatively sedentary and limited in their ability to escape from the selected culture area.

In the case of the American lobster and silver salmon, methods of guaranteeing replenishment of stocks each year through hatchery operation would also be required. In addition, however, since both species are fugitive and since they cannot derive their food from the surrounding water as readily and sufficiently as can the three bivalve mollusks, methods of controlled and intensive rearing throughout the growth period are essential. It would seem most practical to hold these species in confined areas subject to a high degree of environmental control in order to provide maximum protection from predators and to supply food on a regular basis to accelerate their rate of growth.

Technical Problems

Although these five species have been cultured successfully, there are technical problems, particularly ones involving that period between the post-larval stage and attainment of market size, that have not been fully resolved and that are of considerable importance in a commercial operation. In the case of the three bivalve mollusks, high mortalities among juveniles after transfer from the hatchery to the natural environment appear to be the rule rather than the exception as a result of predation or other causes. For lobster and salmon, losses resulting from nutritional deficiencies, cannibalism, disease and other factors associated with intensive culture may be expected. For these two species in particular, there still remains a gap between the successful rearing on an experimental scale and the profitable rearing on a commercial scale; pilot demonstrations would be of great value.

Legal and Political Climate

In addition to certain technical difficulties, private culture in New England faces other problems. It is clear that neither the political nor social climate for assertion of exclusive culture rights in natural areas is particularly favorable; yet securing such rights is imperative for the culture of bivalve mollusks. The coastal waters continue to serve as convenient receptacles for industrial and domestic wastes. Thus, sewage pollution limits the areas available to the culturist, and pollution by oil, pesticides or certain heavy metals, may poison his crop or, at least, reduce its marketability.

In order to compete successfully with other industries, activities, and forms of use—or misuse—of the coastal environment, aquaculture must demonstrate its long-term viability and its social and economic benefits in relation to these other activities. Major reasons for its failure to do so up to the present have included an inadequate technology combined with the existence of unfavorable state and local statutes and other regulations. With improved technology at hand, aquaculture should now be given the opportunity to demonstrate its value to coastal communities.

Public action could take the form of comprehensive aquacultural legislation or of sub-leases by the states of a limited number of specific sites. Such leases could be restricted to aquacultural production and could carry specific exemptions or waivers from inappropriate state and local regulations.

Recommendations

Pilot Plants

1. *The economic feasibility of culturing both lobsters and salmonids should be explored on a production scale. The scale of the pilot operation should be sufficiently large to permit accurate evaluation of the economics of an expanded, i.e., commercial, operation.*

An experimental lobster production unit should focus upon (a) maintenance of optimum water temperatures for accelerated development and growth rates initiated when adult females are initially fertilized; (b) evaluation of "natural" foods, i.e., fish and shrimp scraps, shellfish, starfish, etc., and "synthetic" foods, i.e. trout pellets and other formulations, in terms of ease of procurement, storage, cost, conversion efficiencies, etc.; (c) survival rates as influenced by cannibalism, water quality, etc., and (d) overall operational costs, in terms of heat, electricity, maintenance, etc.

The size of the pilot production facility should be scaled to a minimum annual production of 1,000 pounds of market-sized lobsters per year; it should be designed to hold lobsters in individual compartments after the third larval molt. Water, maintained at room temperature, might be constantly recirculated through compartmentalized troughs equipped with filters to remove organic debris. "Makeup" water, added at a rate of ten percent or less of total volume per day, could be initially warmed by means of a heat exchanger. Circulation through the troughs should be accomplished by means of submersible pumps to eliminate the danger of gas disease. Carbon dioxide would be removed, and oxygen renewed, by cascading, supplemented by aerating devices if required. Because of the catastrophic consequences resulting from possible power failure, the facility should be provided with an automatic emergency electric generating system.

This investigation could be undertaken at a state or federal marine laboratory in the New England area, where an adequate seawater supply system is already installed. Additional equipment, if not already available, would include larval tanks and rearing compartments; heat exchangers; recirculating pumps; air compressor and auxiliary (standby) generator; freezer space for storage, and basic laboratory equipment. A minimum of two men would be required to operate and maintain the rearing facility, under the supervision of a qualified biologist. Additional personnel would be required during hatching periods.

An experimental salmonid production unit should consider (a) tolerance of this species to seasonal variations in temperature; (b) optimum rearing densities with respect to temperature and water flow rates; (c) evaluation of different salmonid species to determine those most adaptable to the New England environment; (d) disease prevention, particularly at those temperatures that promote most rapid growth rates; (e) analysis of various inexpensive sources of nutrition, and (f) evaluation of production costs.

The pilot facility should be designed to produce a minimum of 150,000 pounds of fish each year. (It is assumed that the fish will have attained a marketable size at 12 months of age.) It is recommended that the rearing facilities designed and tested by the National Marine Fisheries Service (Mahnken et al, 1970) be investigated during the latter stages of maturation; floating pens located in tidal channels or estuaries are used. Fish displaying most favorable growth characteristics should be retained as future parent stock; others could be test-marketed or released in selected areas.

Use could be made of existing state or federal hatchery facilities for provision of fertilized eggs, and the initial rearing of fry. As a means of disease control and of promoting favorable growth rate in the early stages, some fertilized eggs and fry should be maintained at coastal facilities where the salinity of the water could be regulated and held at approximately 7 o/oo. The fish, which hatch in winter, could be transferred to coastal sites and held at ocean salinities by late spring. It is recommended that the cage culture phase of production be undertaken at a coastal facility north of Cape Cod, where (a) tidal amplitude, and hence tidal circulation, is greatest, and (b) summer water temperatures do not exceed the tolerance level of this species.

Assuming a production figure of 150,000 pounds and a stocking density of one pound per cubic foot of water, the maximum total holding area that would be required for one-year-old fish would approximate 100 x 100 x 15 feet deep. It would be imperative that the holding pens be situated in areas of strong tidal flow, and that the fish be raised to a marketable size prior to ice formation.

Assuming that fertilized eggs or fry could be obtained from existing hatcheries, the cost of the marine rearing facility—the floating pens—should be rather small. Ideally, these would be moored near an existing laboratory facility, where the feasibility of holding eggs and fry at varying salinities could be tested, symptoms of disease could be analyzed, and different food types might be evaluated. Food could be dispensed automatically into the pens. It is estimated that two men under the supervision of a qualified biologist could maintain the rearing facility.

Using Domestic Wastes

2. *The feasibility of utilizing areas presently polluted by domestic wastes for the culture of organisms of economic value should be explored. Emphasis should be placed upon methods of rearing the juvenile stages of bivalve mollusks to maturity.*

There are extensive coastal areas of New England that are biologically productive, but that have limited usefulness as a result of pollution by domestic wastes. These should be put to more constructive use. At the same time, certain technical aspects and problems associated with commercial culture could be explored.

Experimental use of such areas for intensive aquaculture would accomplish the following: (a) explore the technical and economic feasibility of aquaculture in a variety of locations under a variety of conditions without infringing upon public fishing rights; (b) make significant economic use of presently wasted areas by the eventual transfer of cultured organisms to clean (harvestable) areas, and (c) convert organic material that is presently useless and, in certain respects, an environmental liability in its present form to animal flesh of high economic value.

A program involving the use of polluted areas for aquaculture should be under the control of state agencies and supervised by state personnel. These agencies should be funded appropriately in order to manage selected areas intensively on a scale that may demonstrate the economic viability of similar projects in other areas, both polluted and clean.

Initial experiments should be concerned with the rearing of bivalve mollusks. The mollusks are sedentary and are readily containable within the experimental area, and normally thrive upon the phytoplankton populations whose growth is stimulated by nutrients associated with domestic pollution. The experiments should also be designed to resolve certain of the problems involved in the rearing of juvenile bivalves to maturity, i.e. stimulation of rapid growth rates at low cost, under conditions that might insure a high rate of survival. The program should involve a "multiple species" concept, whereby more than one, and perhaps several, species could be cultured in the same area. Particular consideration should be given to the American oyster, hard clam and bay scallop.

The most favorable areas for such experimentation would be sheltered coves with adequate tidal exchange. Juveniles would be obtained preferably from hatcheries or alternatively from natural setting areas. Methods of rearing the juveniles to maturity would include (a) the use of raft-suspended trays or cages during the initial growth stages, followed by (b) the use of suitable sub-tidal bottom that is fenced to prevent intrusion of predators and escape of the juveniles as they develop to marketable size. Aside from the expense involved in obtaining adequate numbers of juveniles for experimentation, the only significant cost involved in this operation would be that of maintaining the trays and fenced areas free of predators and fouling organisms. Growth and survival rates should be carefully monitored, and the costs should be evaluated in relation to production.

Simultaneously, data could be obtained on the survival, growth and condition of both oysters and mussels cultured in the same area. Juvenile oysters could be collected on strings of shell, either from hatcheries or from natural setting areas. Mussels might readily be obtained by collecting natural sets on ropes as practiced in both France and Spain (Ryther and Bardach, 1968). The cultch strings could then be suspended from the rafts of floating trays employed for the culture of juvenile clams and bay scallops.

Polluted coastal areas could provide highly suitable "testing grounds" for commercial aquacultural endeavors. If commercially significant yields can be obtained from these areas, even though such yields are not immediately usable, it would demonstrate the potential value of coastal areas for aquaculture. Simultaneously, testing grounds would provide valuable practical information that could be applied to future commercial endeavors without interfering with existing fisheries.

Water Quality Tolerances

3. *The tolerance of the American oyster, hard clam, bay scallop, American lobster and silver salmon, during all stages of their life cycles, to industrial wastes discharged into coastal areas should be intensively studied.*

As indicated in chapter 5 of this report, pollution by industrial wastes poses an extremely serious threat to aquaculture and its further development in New England. If mass mortalities occur—as they frequently do—in hatcheries or if cultured animals are condemned as a result of contamination, the financial losses may preclude continuation of the enterprise. Aquaculture is a difficult business under most favorable conditions; if its future is to be taken seriously, then the sources and/or causes of industrial pollution and its short- and long-term effects upon aquatic organisms must be taken equally seriously.

From an aquaculturist's point of view, accelerated research in the following areas would be most useful, assuming pollution in various forms to be a fact of life for the foreseeable future: (a) the tolerance of the oyster, hard clam, bay scallop, lobster and salmon to various concentrations of heavy metals, hydrocarbons and other substances suspected of having negative effects upon the aquatic environment, with respect to survival, rate of growth, ability to reproduce, and viability of offspring; (b) the rates at which these substances can be eliminated from the contaminated organism under varying environmental conditions; (c) the effect of these potentially toxic substances upon food-chain organisms, i.e. phytoplankton, benthic invertebrates, and forage fish, and (d) the degree of persistence of these substances in localized areas.

It is likely that some of these studies are presently being undertaken to determine the practicality of initiating private aquacultural projects at least in certain areas of New England. The need for specific answers is urgent.

Leasing

4. *Specific coastal areas of high quality for culture should be made available under long-term leases to qualified private concerns for culture purposes.*

As indicated earlier, private aquaculture enterprises in New England are inhibited by various legal restrictions and social constaints. It is believed that such constraints persist because aquaculture has so far failed to demonstrate its social and economic superiority over other forms of water use. Conversely, the opportunity for private aquaculture to demonstrate its value has often been impeded by the very nature of these constraints, i.e. the inability to acquire suitable areas for private culture. Under these circumstances, it is difficult to attract private investment for an enterprise that already is regarded as speculative.

This dilemma might be resolved by allowing a private corporation with suitable technical and administrative qualifications to select an area for private culture. The area would be leased to the corporation by the state for a period of not less than five years and no more than ten. During this period, it would be the objective of the corporation to produce aquatic species of market value for a profit. This form of arrangement with a private corporation should contain the following terms:

A. The details of the project—species to be cultured, methodology, projected figures of production, etc.—should be submitted to the appropriate state authorities for review and approval. An approximate timetable for various levels of production would be included.

B. The corporation would submit to these authorities a complete review and description of progress to date at regular, prespecified intervals.

C. At regular intervals, the complete facilities and culture areas of the corporation should be open to the public. At such times, progress, failures and their causes, and improvements in technology would be publicly reviewed. Financial data relating to capital expenses, operational costs, sales, etc. should also be available to the public.

D. At the end of the lease period, the progress and accomplishments of the corporation would be reviewed by the state authorities. At this time, and based upon evidence of significant accomplishments, the area could be made available for renewal of lease. Notice of renewal or non-renewal should be given one or two years prior to the date of lease expiration to avoid the undesirable effects of lease insecurity from impinging on plant maintenance.

This approach would provide an opportunity to demonstrate the feasibility and value of commercial aquaculture under favorable, rather than marginal, environmental and legal conditions, particularly before such areas have been preempted for other uses or have been ecologically damaged. In return, the corporation should be prepared to share the information acquired as a means of stimulating or assisting aquaculture in other areas. Because a profit incentive is involved, maximum emphasis would probably be placed upon sustained production, which is the only true measure of the project's viability.

We recommend that opportunity for this form of arrangement be initiated in each of the coastal New England states. We further recommend that the total area made available for leasing in each state not exceed 1,000 acres. Finally, as a means of attracting participation by private enterprise, we recommend that financial assistance in the form of matching funds be provided, a logical source being the New England Regional Commission.

From a corporation's point of view, a critical factor in such an arrangement would be the selection of an appropriate area. Certainly, the objective would be to select an area that is favorable from the standpoint of size, depth, accessibility, availability of utilities, salinity regime, circulation, and absence of pollution, and yet where right of exclusive use would result in minimum infringement upon existing uses and public interest. In Massachusetts, for example, appropriate areas might be those tidal ponds where, under Section 17 (a), Chapter 130, public fishing rights are presently excluded. State authorities would be in a position to guide in the selection.

Equipped with the dual advantages of optimum rearing conditions and a degree of financial support, a private corporation would be in a unique position to explore a broader approach to aquaculture than is generally feasible, particularly from a financial standpoint. A program might be developed that would include the culture of several species simultaneously, selected in a manner to reduce the total cost of operation. As an example, the viscera and offal of processed bay scallops and salmon could be used directly as food for lobsters, thereby reducing what would amount to be the major cost in the rearing of the latter species. Wastes from salmon holding facilities, such as nitrogenous compounds, might be diverted to stimulate growth of phytoplanktonic cultures, which in turn could be employed as food for bivalve mollusks. Shell from shucked scallops could be used as cultch for oysters or as components in the filtering systems.

The success of such an arrangement would depend in great measure upon flexibility and freedom from certain existing legal restrictions. It should not be required, for example, that all members, stockholders, etc., of the corporation be residents of the town, or even of the state, in which the project is undertaken. Since the species cultured represents a considerable private investment of effort and capital and since their possession or harvesting would have no effect upon natural stocks, existing restrictions upon possession and harvesting should not apply. These include minimum size laws; restrictions on possession of female lobsters' bearing of eggs externally; regulations regarding seasonal harvesting; requirements for annular growth rings on bay scallops, and other laws that may have a certain justification on conservation grounds in a public fishery, but have little justification when applied to populations that are privately reared and controlled.

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