Sea Grant Aquaculture Plan

1983-1987

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EXECUTIVE SUMMARY

Policy, Goals and Objectives

The National Sea Grant College Program was established to form a university-based partnership between the federal government, state governments and industry to develop and conserve the nation's marine resources. The National Aquaculture Act of 1980 (Pub. L. 96-362) called for a coordinated national aquacultural program that would involve 13 federal agencies and departments. It assigned responsibility for expanded research, development and related programs to the Secretaries of Agriculture, Commerce and Interior. In a Memorandum of Understanding signed in April 1980 by representatives of the three Departments, responsibility for aquacultural research and development on marine, estuarine, anadromous and Great Lakes species was assigned to the Department of Commerce.

This plan is for aquacultural research, development, advisory and training activities to be conducted during fiscal years 1983-1987 by the National Sea Grant Program within the Department of Commerce. It is an integral part of the national aquaculture plan called for by the Aquaculture Act.

The plan builds on the legislative mandate of the National Sea Grant Program and on nearly 14 years of research accomplishments by Sea Grant researchers and their partners in government and industry. The budget proposed for each of the five years is realistic and represents a logical continuation of the efforts underway in the nation's Sea Grant institutions. Finally, this plan represents the best assessment of problems and opportunities in aquaculture as seen in 1982. It defines policy, sets goals and establishes objectives to help guide decisions in the direction of research efforts and the allocation of resources.

Policy. It is the policy of the National Sea Grant Program to support the legislative mandate of the Aquaculture Act of 1980 by encouraging aquacultural activities and programs to increase aquacultural production, coordinate aquacultural efforts in the United States, conserve and enhance aquatic resources, and create new industries and jobs.

Goal. In accordance with this policy, it is the goal of the National Sea Grant Program to establish a sound scientific basis and disseminate knowledge to ensure the development of a strong national aquacultural industry.

Objective. To accomplish this goal, it is the objective of this plan to define where research, development, education and training should be applied to produce the most rapid progress in stimulating a broadly based and commercially viable aquacultural industry for the nation.

Economic Importance of Aquaculture

Americans consumed about 6 kg (13 lb) of fish and fishery products per capita in 1980. Consumption has slowly but steadily increased during the past several decades and is expected to continue to increase as population grows, as real per capita income increases and as consumer awareness of the nutritional values of fishery products increases.

Most traditional fisheries in United States waters are being harvested at or near maximum sustainable yields. At present, more than 60 percent of the fish products consumed in the United States are imported. In 1980, this represented a trade deficit of more than $2.5 billion, which was 28 percent of the U.S. trade deficit exclusive of petroleum products. As demand increases and fisheries stocks become limited worldwide, these imports will become more expensive and harder to obtain.

An economically viable aquacultural industry would augment the supply of fishery products and decrease reliance on imports. Benefits would include a favorable effect on the balance of trade, increase in domestic business activity and jobs, stabilization of seafood industries and markets, and better use of the nation's aquatic resources. Aquaculture can also augment natural stocks of fishes and shellfishes, which are being diminished by exploitation, pollution and habitat destruction.

The potential of aquaculture has been a topic of intense public discussion for two decades. In spite of this interest, food production by aquaculture is only three percent of U.S. fishery landings or two percent of total consumption of fishery products. Annual aquacultural production in this country is about 100,000 metric tons (220 million pounds). In 1980, aquacultural production had an estimated value of $500 million and a retail value of more than $1 billion.

Present Aquacultural Technology

Public investment in aquacultural research and development has remained small compared to that for land-based agriculture, and the establishment of commercial enterprises has proceeded slowly.

In spite of the relatively low levels of funding, more than a decade of Sea Grant-sponsored aquacultural research has provided the basis for the establishment of evolving aquacultural industries, substantially improving the potential for aquacultural development. For marine or anadromous species, accomplishments include the development of net/pen culture and ocean ranching of fishes in the Pacific Northwest; the establishment of abalone culture in California; the introduction of Malaysian prawn culture in Hawaii and South Carolina; the improvement of raft culture of blue mussels and oysters in New England; the proliferation of oyster hatcheries in the Pacific Northwest and the Atlantic States; and an influential role in establishing shrimp and prawn farms in Central America by U.S. firms. Most of the enterprises that have developed or have reaped direct benefits from the new knowledge are infant industries that still need a wide range of research and extension support.

The following table lists present and potential aquacultural organisms according to their present degree of

Commercial Development Continuum	Organism
Commercial Industry Exists	trout
	baitfish
	penaeid shrimp
	prawns (Hawaii)
	salmon (net/pen rearing; ocean ranching)
	yellow perch
	oyster
Infant Industry	mussels
	abalone
	prawns (continental United States)
	scallops (bay and rock)
Technology Developed to Pilot Scale	seaweeds
	clams
	eels
	bait leech
	striped bass
	channel bass
Technology Partially Developed	scallops (other than bay and rock)
	lobster
	red drum
	sturgeon
	southern flounder
	speckled trout
	red snapper
	pompano
Major Lack of Technology	milkfish
	H_2S bacteria

commercial aquacultural development. "Commercial" aquaculture represents enterprises with established production facilities, profitable markets and continuity of sales. Research needs are similar to those that support established agricultural enterprises. These include product improvement, increased production efficiency, and effective marketing. "Infant industries" may require research on several aspects of production, marketing and creation of an acceptable institutional framework. "Pilot scale" includes promising organisms for which proof of concept is established and basic breakthroughs in production technology have been achieved, but for which refinements are needed to solve scale-up problems and ensure reasonable prospects for economic viability. For species for which technology is "partially developed," one or several crucial problems in the aquacultural technology have not yet been solved. The final group, "major lack of technology," represents those species of high market potential for which many major problems, such as reproduction, larval survival, domestication, strain selection, nutrition and production systems, must still be solved.

Assignment of Resources

Federal funding for the Sea Grant aquacultural program, projected by area of effort for fiscal years 1983 through 1987, is shown in the following table. The areas of effort include the following research thrusts.

Aquacultural systems must be developed to control environmental quality, including monitoring and control of physical, chemical, biological and thermal conditions.

Projected federal funding[1] for Sea Grant aquacultural efforts.

Area of effort	1983	1984	1985	1986	1987
Systems	938	1,023	1,061	1,139	1,227
Genetics	687	695	764	777	857
Nutrition	649	816	683	937	1,017
Diseases	353	361	491	560	616
Policy	266	287	381	534	606
Economics	409	449	435	447	512
Exploratory	108	119	130	144	158
Advisory	527	580	638	701	771
Total	3,937	4,330	4,583	5,239	5,764

[1] Values, in thousands of dollars, were based on 1981 Sea Grant funding and include an annual inflation factor of 10 percent.

They must handle the various species from early life stages through harvest and preparation for marketing.

Genetic studies must be recognized at the outset as long-term commitments to improvement of cultured animals and plants. For genetic studies, at least 10 years of continuous effort are usually required to begin to achieve useful results.

Nutrition and diets must be studied at all phases of the life cycle of aquacultural organisms. This is not only crucial to growth rates, but diet composition must be conducive to maturation and reproduction in captivity. Also important is the most cost-effective protein level and feed conversion ratios.

Studies of diseases will become more important as crowded conditions and continuous operation of commercial aquacultural systems inevitably present substantial disease problems similar to those that haunt poultry and swine growers.

Research in public policy is crucial to understand and recommend improvements in state and national policies and statutes so that aquacultural business attracts entrepreneurs and venture capital. Many states now have laws written to encourage or manage the harvesting of fish in "the wild." Because aquaculture was not envisioned when these laws were written, many of them inadvertently cause hardships and barriers to the establishment of aquacultural enterprises.

Economic studies are needed to improve the efficiency and profitability of commercial aquacultural systems. The potential of markets for species, grown in aquacultural systems in which product quality and regular supplies can be assured, has been assessed for ony a few cases. The market potential is substantial for new and economical food products with desirable human nutritional characteristics.

Resources also must be set aside to encourage exploratory research into species not currently thought of as having aquacultural potential. In a fast-moving, exciting field such as aquaculture, new discoveries prompt new, unexpected ideas that need to be examined if optimal progress is to be achieved.

Finally, advisory services and training are needed to disseminate the results of research and to effect technology transfer to industry and a wide range of other users to reach the goal set by Sea Grant.

To date, funding of research and advisory services in support of the nation's aquacultural industry has been low. However, through the Sea Grant-sponsored research program, substantial progress has been made. Even with continued modest federal funding, but with industry cooperation and assistance, three levels of emphasis in aquacultural research will be pursued.

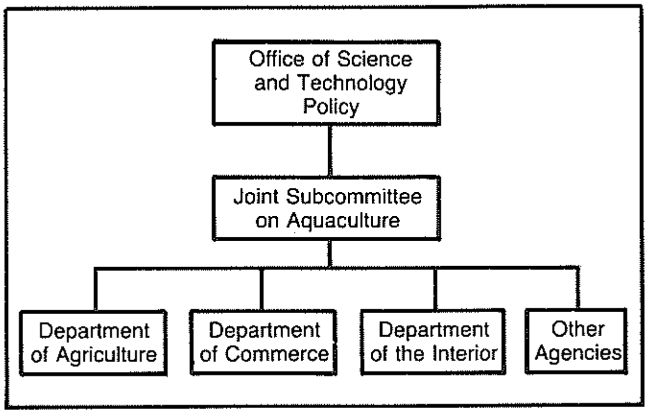
- Primary emphasis will be placed on those species and systems that will directly benefit the developing aquacultural industry during the next 10 years.
- A secondary program of emphasis will be made in systems and species for which the technology and experience do not yet justify commercialization, because there is often a time lag between innovative research and its application in industry.
- Sea Grant will continue to place a third level of emphasis on approaches and species that are most adaptable to these long-term and/or high-risk solutions. Experiences in land-based agriculture have shown that the most important progress in diseases, genetics and nutrition requires an extended program of systematic research. Conversely, some of the most exciting developments from university-based research have resulted from innovative solutions to problems not adequately described by conventional wisdom.

Through this balanced program of resource investment, Sea Grant will move U.S. aquaculture forward in cooperation and in consultation with the evolving industries.

The National Aquaculture Effort

This Sea Grant Aquaculture Plan is an integral part of the national aquaculture effort called for by Aquaculture Act. It must be recognized as a major element of the national effort for two reasons. First, it builds on the solid foundation of 14 years of Sea Grant-sponsored research, which has produced new knowledge, technological advances in aquacultural systems, important patents, useful publications and overall advances in the nation's aquacultural capability.

The second reason that this plan is a major component of the national aquacultural effort is that marine and Great Lakes organisms represent the largest share of the nation's species that are potentially eligible for aquaculture. As the populations of the United States and the world increase, and as freshwater supplies become even scarcer, food grown in salt water will assume an ever-increasing role of importance.



Sea Grant Aquaculture Plan
1983-1987

INTRODUCTION

Domestically, seafood consumption has increased from 4.7 kg (10.3 lb) per person in 1960 to 5.9-6.2 kg (13.0-13.6 lb) in 1979-1980. Fish and shellfish are in such great demand because of their high nutritional value. They are high in protein, low in carbohydrates and fats, and are excellent sources of minerals and water-soluble vitamins.

In the United States most traditional fisheries are being harvested at or near maximum sustainable yields (Reference 104). At present, more than 60 percent of the fishery products consumed in this country are imported to meet the high demand. In 1980, this represented a trade deficit of more than $2.5 billion, which was 10 percent of the total deficit and 28 percent of the deficit exclusive of petroleum products. Aquaculture would improve the balance of trade, increase the stability of seafood industries and markets, and provide more jobs for American workers (104).

At present, world aquacultural production represents about 10 percent of the world aquatic food production by fisheries. By 1985 that figure is expected to be 20 percent (110). Worldwide, aquacultural production in the 43 countries that have such industries produce more than 4 million metric tons (almost 9 billion pounds) of fish and fish products. Exclusive of the aquaculture of sport, bait and ornamental organisms and of pearls, this production includes more than 90 species of fish, seven species of shrimp and prawns, six species of crawfish, diverse marine plants, and many species of oysters, clams and other molluscs (104).

During the past decade numerous technological breakthroughs have increased the potential of aquaculture in the United States: the development of net/pen culture and ocean ranching in the Pacific Northwest; the establishment of abalone culture in California; the introduction of Malaysian prawn culture to Hawaii and South Carolina; the improvement of raft culture of blue mussels and oysters in New England; the proliferation of oyster hatcheries in the Pacific Northwest and the Atlantic States; and the establishment of marine shrimp farms in Central America by U.S. firms. Table 1 lists technological development of the aquaculture of species included in the Sea Grant plan.

Annual aquacultural production in this country is about 100,000 metric tons (220 million pounds), about three percent of U.S. fishery landings or two percent of total consumption of fishery products (104). In 1980, aquacultural production had an estimated wholesale value of $500 million and a retail value of more than $1 billion. The National Research Council (105) estimates that aquacultural production in the United States may exceed 250,000 metric tons (551 million pounds) by 1985 and that, with proper support, production could reach 1 million metric tons (2.2 billion pounds) by 2000.

The present level of aquacultural production, then, indicates the potential of aquaculture in the United States. However, the lack of routine technology, high production costs, and inadequate marketing and financial aid programs inhibit development of a profit-making aquacultural industry.

Table 1. Marine and Great Lakes organisms grouped by level of U.S. commercial aquacultural development.

Level of Commercial Development	**Species**
Commercial Industry	trout
	baitfish
Infant Industry	penaeid shrimp
	prawns (Hawaii)
	salmon (net/pen rearing and ocean ranching)
	yellow perch
	oyster (hatchery/nursery production)
	mussels
	abalone
Technology Developed to Pilot Scale	prawns (continental United States)
	scallops (bay and rock)
	seaweeds
	clams
	eels
Technology Partially Developed	bait leech
	striped bass
	channel bass
	scallops (other than bay and rock)
	lobster
	red drum
Major Lack of Technology	sturgeon
	southern flounder
	speckled trout
	red snapper
	pompano
	milkfish
	H_2S bacteria

Basic technology must be improved, specifically in the fields of nutrition, genetics, disease control and culture systems. New marketing strategies may be needed for aquacultural products, and various governmental policies and regulations restrict all phases of aquaculture.

Without public funding of research aimed at removing these restraints, additional industrial involvement in aquacultural development will be impeded.

As with land-based agricultural research, most aquacultural research in the United States has been done at universities. Such research should continue to be based in the universities for several reasons. First, many of the aquacultural enterprises are small or in the start-up phase, and the investment required for research is too large for most firms. Second, solution of many of the problems facing aquaculture requires the diverse expertise available and most easily coordinated at the university level. Finally, when studies are done in universities, the results become public information, leading to their rapid dissemination.

Sea Grant provides a unique opportunity for involvement of both the public and private sectors. The principal objective of the Sea Grant aquacultural program is to make aquaculture commercially viable in the United

States. Another objective is to educate individuals needed to manage and staff these enterprises. In this program, public institutions combine the academic, scientific and technological know-how with the production expertise of industry to rapidly advance the state of the art. This arrangement has been fostered by the Sea Grant Program since its inception in 1966.

COORDINATION WITH THE NATIONAL AQUACULTURE PLAN

The Aquaculture Act of 1980 (100) provided the initiative for all components of the Department of Commerce to work together to develop the U.S. aquacultural industry. Sea Grant has been a leader among federal agencies through close cooperation with industry to achieve that goal. The relationship between the Sea Grant aquaculture program and the national effort called for by the Act is shown in Figure 1. The foci of the program are outlined below. Recommended distribution of research and advisory efforts, assuming continuation of the present type and level of federal program support, are given for fiscal years 1983-1987 in Table 2.

Figure 1. Relationship of the Sea Grant aquaculture plan with the national plan.

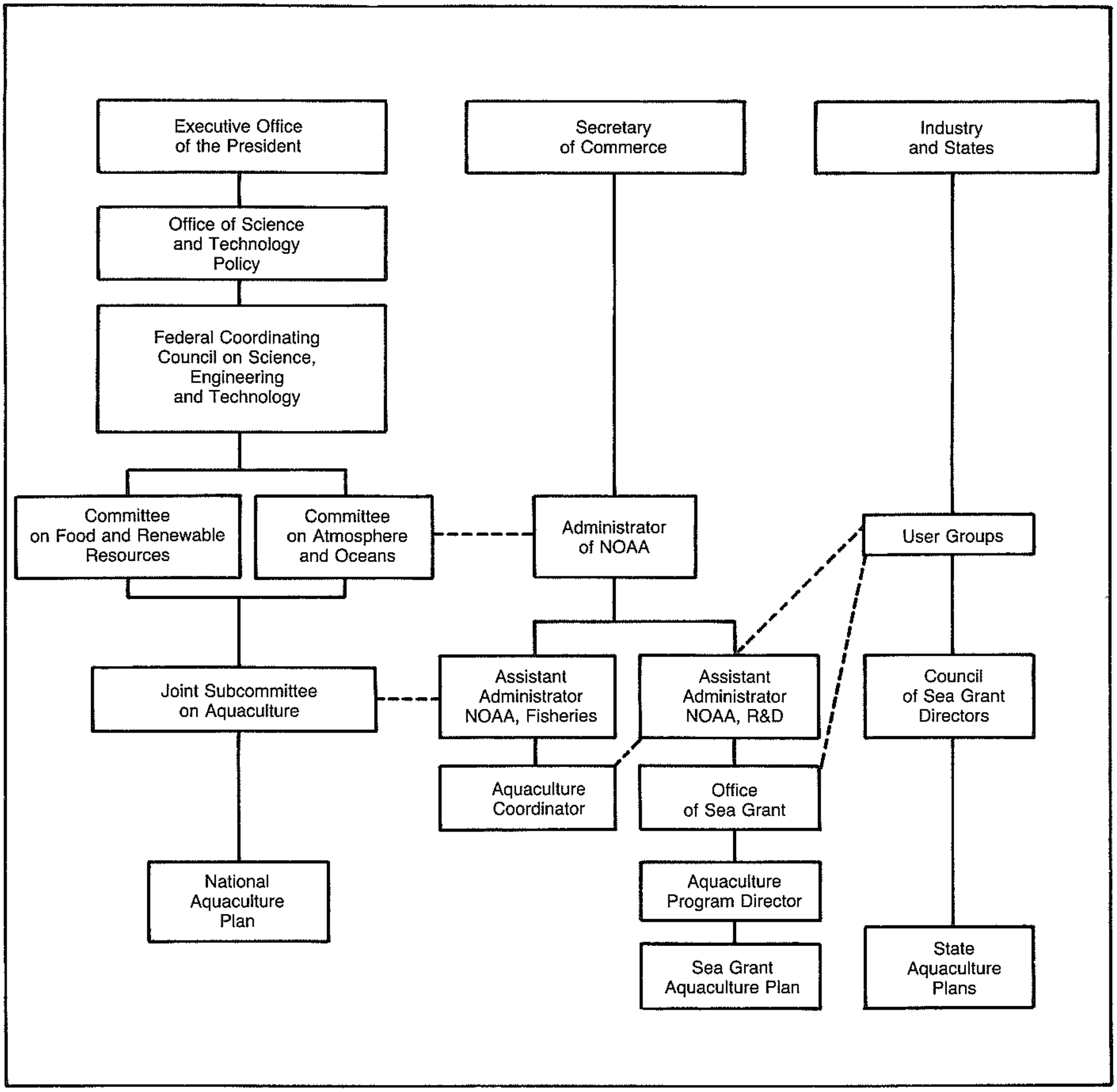


Table 2. Projected federal funding for Sea Grant aquacultural program, by area of effort, FY 1983-1987. Includes advisory services related to aquaculture and exploratory research on "new" aquacultural species. Values are in thousands of dollars, were based on 1981 Sea Grant funding, and include an annual inflation factor of 10 percent.

Area of Effort	1983	1984	1985	1986	1987
Systems	937.6	1,023.4	1,061.3	1,139.4	1,226.6
Genetics	686.9	694.5	763.6	776.8	857.2
Nutrition	649.4	816.0	682.6	936.5	1,017.0
Diseases	353.2	360.9	491.3	559.6	615.6
Policy	266.1	287.4	380.8	534.3	605.9
Economics	408.6	449.4	435.3	447.3	511.5
Exploratory	107.8	118.6	130.4	143.5	157.8
Advisory	526.9	579.6	637.5	701.3	771.4
Total	3,936.5	4,329.8	4,762.8	5,238.7	5,763.0

Research

Research crucial to further national aquacultural development of marine, anadromous, catadromous and Great Lakes species will be supported by Sea Grant during 1983-1987. Areas that will be addressed are:

1. Aquacultural systems development,
2. Genetics and selective breeding,
3. Nutrition,
4. Disease control,
5. Public policy, and
6. Economics and marketing.

Education

As technology for each species improves and aquaculture approaches the level of commercial viability, it will be the responsibility of the Sea Grant College Program, working with industry, to educate aquaculturists by:

1. Assessing present and future needs for personnel, and
2. Designing and implementing programs to educate them.

Advisory (Extension) Services

The results of the Sea Grant research must reach the public so that they can be applied to improve the aquacultural industry. This will be done by:

1. Publications, such as operations manuals and technology updates,
2. Aquacultural extension agents and services, and
3. Demonstration projects.

Sea Grant institutions, working with federal and state agencies and with industry, will strive to remove nontechnological barriers to the development of a strong and prosperous industry by identifying sources of financial support, evaluating and recommending changes in regulations and policies that restrict aquaculture, and promoting product acceptance.

The program will be regularly evaluated to ensure continued progress and improvements, to guarantee high-quality work, to coordinate efforts, to avoid duplication, and to re-evaluate research needs in light of new developments. Sea Grant and industry will revise these research plans periodically, based on advances that will have been made. The progress of the program will be measured by assessing the value of results achieved, by feedback from commercial operations and entrepreneurs, and by peer reviews and site visits.

ACCOMPLISHMENTS TO DATE

The Sea Grant Program has been involved in aquaculture since 1968. During the intervening years, Sea Grant-sponsored university researchers have achieved literally hundreds of accomplishments, usually working cooperatively with public and private aquaculturists. Sea Grant programs have stimulated the initial U.S. commercial ventures for culturing marine shrimp, Malaysian prawns, blue mussels, European oysters, American eels, Manila clams, salmon and red seaweeds. Also, they are responsible for entry into this field by many companies and for the expansion of previous aquacultural activity for production of the American oyster, hard clams, crawfish and abalone. The following list of some of the accomplishments of the Sea Grant aquacultural efforts indicates the type and range of the research successfully completed during the past 14 years.

Aquacultural Systems

1. Development of off-bottom culture techniques for European oysters that have been adapted and adopted by more than 50 commercial growers.
2. Adaptation, development and transfer of pond culture techniques for the Malaysian prawn to private firms in Hawaii, which have expanded their sales from $180,000 in 1976 to $1.7 million in 1981.
3. Growth and harvest of two shrimp crops in one growing season in the continental United States.
4. Development of techniques for off-bottom culture of the blue mussel, which led to the establishment of four private production operations.
5. A 10-fold increase in clam yields by use of protective screens.
6. Design of several successful seawater systems for shellfish grow-out.

Genetics and Selective Breeding

1. Development of cryopreservation techniques for salmonid sperm, an important technique for improving the species through genetic engineering.
2. Production of a strain of salmon that suffers 50-80 percent less mortality when transferred from fresh water to salt water.
3. Development of procedures for mating and spawning several species of marine shrimp in captivity.
4. Development of techniques for production of polyploid shellfish, allowing production of sterile shellfish that will use all available energy for growth rather than for sexual development.

Nutrition

1. Replacement of as much as 50 percent of the fish meal in salmon feeds with yeast or other substitutes without affecting growth rates.
2. Development of a dry salmon feed with equal quality and better storage characteristics than moist feeds.

Diseases

1. Development of a vaccine for salmon, increasing survival by 50 percent.
2. Development of spray and immersion method of immunizing fish with bacterins.
3. Development of osmotic filtration to immunize shrimp against *Vibrio* bacteria.

AREAS OF EFFORT

The following sections describe the areas in which Sea Grant aquacultural research has placed particular emphasis and in which further effort is needed. Descriptions in this part of the plan do not specifically apply to a particular species but are intended to acquaint the reader with terminology and, to some extent, the state of the art of U.S. aquaculture in general. In some cases, more detailed discussions are given in later sections of this plan that address the status of aquacultural science and technology by species or species group.

These sections were written by working groups at a workshop held at Texas A&M University on October 20 and 21, 1981. Members of the working groups are listed in Appendix 2.

Aquacultural Systems

Aquaculture involves the propagation of aquatic animals and plants. A variety of production systems of different levels of technological sophistication is needed to control the environment of cultured species and to aid in efficient handling from early life stages through harvesting and preparation for market. One key to successful propagation is the maintenance of environmental quality, which includes monitoring and control of physical, chemical and biological factors, as well as ecological interactions in aquacultural facilities. Control systems must be cost-effective and provide benefits that justify costs of their design, installation, monitoring and maintenance. Environmental control is needed in laboratory, waste treatment, production (e.g., ponds and raceways) and semi-natural systems. Typically, these systems should not be viewed as discrete elements but as part of an overall aquacultural production continuum.

Production systems and pond dynamics. In production and grow-out systems, interactions with and between target species and coexisting organisms, such as bacteria, phytoplankton, zooplankton and benthic organisms, must be understood to allow design of controls that improve productivity, product quality and reliability. Areas for study include gas exchange, nutrient cycling, phytoplankton and bacterial population dynamics, hydrology, substrate and benthic communities, loading density, and physical factors.

Laboratory systems are research tools used to identify and solve fundamental problems. The degree of environmental control and the level of system monitoring are typically more precise in the laboratory than in production systems once acceptable tolerances are understood.

Hatchery and nursery systems. These systems produce high-value products and can therefore afford extensive control systems. Productivity and reliability of these systems need to be improved. The systems may also be used for studies of nutrition and genetic selection.

Semi-natural systems. Aquaculture that takes place in the natural environment does not lend itself to the same degree of control as that in artificial systems. Rather, such systems must adapt to and control only those parameters necessary for economical operation. Managers of estuarine aquaculture and ocean ranching, for example, must determine carrying capacities of the environment for the organism under culture in order to prevent possible ecological damage when the aquacultured animals are released to enhance natural populations.

Funding projections should be based on the present level of technological needs. Certain systems, such as use of depuration and wastewater, have minimal technological problems and will require more modest funding than other types of systems.

Genetics and Selective Breeding

Aquaculture now raises basically "wild" animals. In wild populations, genetic variation is more extensive than in traditional agricultural populations. This variation must be evaluated before selective breeding and genetic engineering studies can be done. Domestication requires control of maturation and reproduction, and systematic changes in the genetic make-up of the aquacultural population. Aquacultural species also exhibit a number of traits that facilitate genetic manipulation and domestication. These accomplishments require thorough understanding of reproductive mechanisms and of the influence of environmental stimuli, nutritional adjustments and physiological modifications.

Aquatic species also display unique properties, such as indeterminate growth and a greater susceptibility to environmental and demographic influences, which render inappropriate many methods of genetic manipulation developed for terrestrial organisms. Therefore, new experimental protocols and technologies must be developed along with or before genetic/reproductive manipulation to make full use of the advantageous properties. Needs for special studies include comparison of environmentally and genetically caused variations in production; development of effective methods of tagging individuals; and development of techniques for broodstock management. These studies will require a long-term coordinated effort.

Table 3 gives percentages of available funding for genetics studies that will be targeted to studies of specific problems in genetics and selective breeding, by level of technological development. (See also Table 1.)

Nutrition

Diet costs can account for as much as 70 percent of production costs. The goal of aquacultural nutrition research is to develop information about least-cost diet formulation techniques and specialized feeds. The nutritional requirements of most aquacultural species are unknown or poorly understood. Concentrated research on nutrition, feeds and feeding of aquacultural species raised in the United States has been limited to a few salmonids and the channel catfish. However, quantitative nutritional requirements of even these fishes are not all known.

During the initial stages of aquacultural development, nutritional studies focus on acceptable feeds and feeding techniques. Usually moist feeds or semi-moist pelleted, extruded or flaked feeds, formulated for fishes or terrestrial animals, are used. This lets aquaculturists evaluate a variety of cultural factors. However, as production goals increase, the importance of additional information on nutritional requirements increases, and research emphases change.

Nutritional requirements depend on species, strain, sex, stage in the life cycle, feed form and composition, cultural conditions, feeding regimes, and production performance goals. The necessity of and potential for improving aquacultural feeds vary depending on interactions between these factors. Figure 2 shows the types of aquaculture and types of effort necessary for aquacultural nutrition studies for species reared under different cultural conditions.

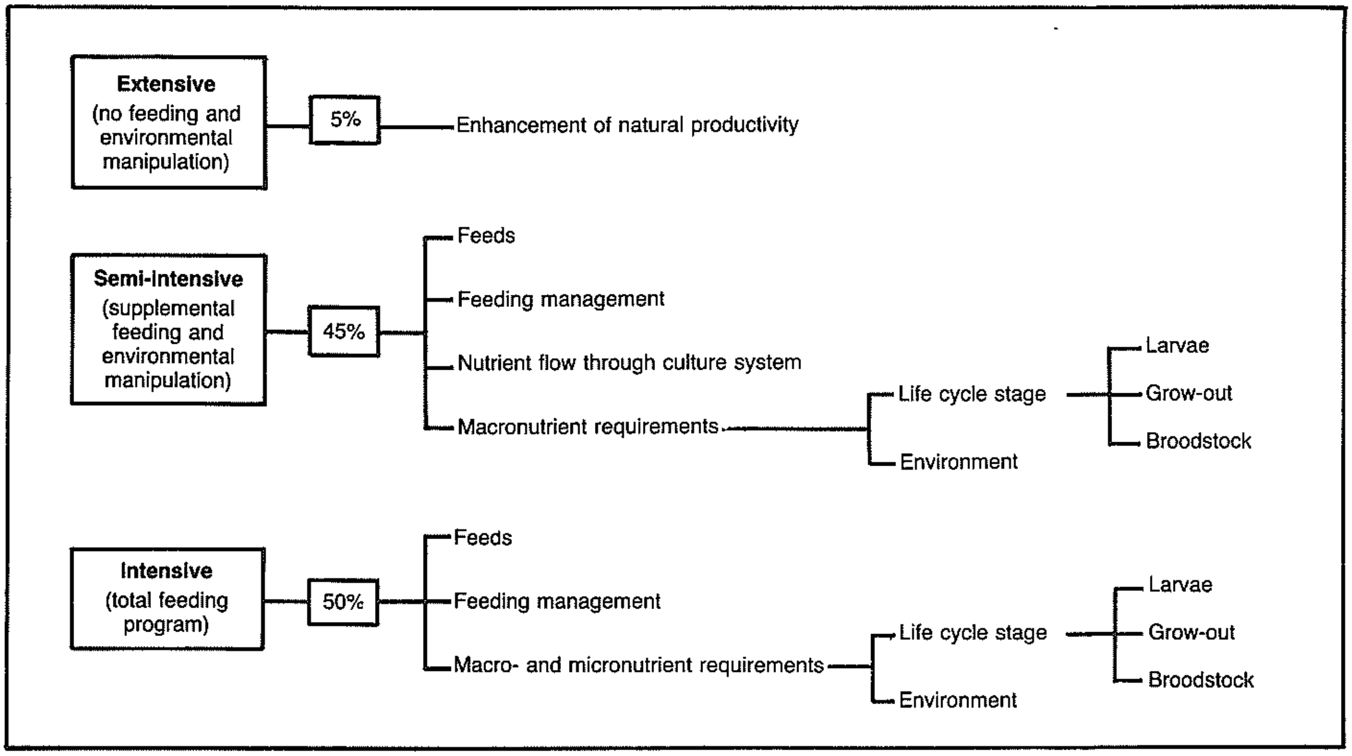
In extensive cultural systems, species are raised at relatively low densities to take advantage of natural prey organisms. Consequently, determining specific nutrient requirements is unnecessary. Instead, research should be directed at methods of environmental management to simulate and maintain trophic levels at which the target species feed.

For more intensive cultural systems, studies of nutritional requirements are necessary. Initially, research should identify acceptable feed types and develop feed management programs. Specific studies of nutritional requirements should follow, based on environmental and life-stage variables.

Table 3. Recommended targeting of funds for research in genetics and selective breeding of aquacultural organisms. Numbers are percentages and are based on a 100 percent level of funding for a species at each level of technological development. See also Table 1, which classifies aquacultural organisms by level of aquacultural technological development.

	Level of Technological Development				
Research Problem	**Major Lack of Technology**	**Technology Partially Developed**	**Technology Developed to Pilot Scale**	**Infant Industry**	**Commercial Industry Exists**
	%	%	%	%	%
Maturation	5	10	17	40	50
Ovulation/spawning	5	10	17	30	30
Fertilization	5	10	16	30	20
Broodstock management	15	25	25	--	--
Stock evaluation	30	30	20	--	--
Selection/breeding	30	15	5	--	--
Genetic engineering	10	--	--	--	--
Total	100	100	100	100	100

Figure 2. Levels of effort and development strategies for aquacultural nutrition studies.



Acceptable feed types and feeding management programs are largely species-dependent. For example, rainbow trout larvae can feed rapidly and efficiently on conventional pelleted feeds. Coolwater fish larvae, however, are much smaller and require food particles smaller than those that current processes can manufacture. Similarly, residence time for conventional feeds for many invertebrates may be so long that water-soluble nutrients leach from the feed. Therefore, development of specialty feeds and feed management programs is crucial to increase feed acceptance and minimize nutrient leaching.

Under semi-intensive culture, some natural food may be available. Supplemental feeding is required to provide macronutrients (i.e., protein and energy), while natural food supplies many micronutrients (i.e., trace minerals and vitamins). Under intensive culture, both macro-and micronutrients must be supplied in feeds because natural food is either scarce or not available. Optimizing feed utilization will require further examination of the effects of life stage and environmental variables on nutritional requirements.

Diseases

All animals are subject to a variety of infectious and non-infectious diseases. Under artificially crowded and stressful conditions characteristic of many aquacultural practices even chronic, low levels of minor diseases can become catastrophic. Furthermore, diseases of aquatic animals usually become apparent suddenly and can result in complete loss of stocks.

Certain management procedures developed for the husbandry of other food animals, and diagnostic and therapeutic principles of human and veterinary medicine, have allowed some progress in aquatic animal health. For example, it is now known that many, if not all, aquatic vertebrates possess an immunological defense system similar in certain respects to that of vertebrates. Certain principles of immunoprophylaxis and serodiagnosis, then, may be used to detect, diagnose and control diseases in aquatic animals.

Many animals offer considerable potential for aquacultural development during the next five years. Although a health problem may be species-specific, certain elements are common to all species. Therefore, Sea Grant aquacultural research during the next five years should include the following elements.

1. Greater focus must be placed on the status of legislation, regulations and registration of drugs used to control diseases in aquatic species. An annual update of these matters should be prepared and distributed at professional and scientific meetings.
2. The effects of disease on aquaculture must be quantified. Industry representatives concerned with disease control should include costs of disease prevention and control in budgets of planned production systems.
3. Standard diagnostic methods are needed for important diseases of cultured aquatic animals.
4. Information on histopathology is lacking for many aquacultural organisms. Normal histology also should

be emphasized because it is important in histopathological studies.

5. The role of viral diseases is largely unknown for many aquacultured species. Research in this area must be intensified.
6. Immunoprophylaxis offers considerable potential for control of certain diseases. Optimal conditions for administering protective agents and the dynamics and duration of immune responses in aquatic animals are poorly understood. The applicability of immune mechanisms for controlling diseases of commercially important aquatic invertebrates is largely unknown. Greater research emphasis should be placed on this area and reviewed periodically at professional and scientific meetings.
7. The role of exotic species in disease transmission is poorly understood, and research on the subject should be part of planned introductions. The development of broodstock that would eliminate importing diseases should be emphasized.

Table 4 assigns percentages of available funding for studies of diseases to major groups of aquacultural organisms, by specific research needs.

Public Policy

As it presently exists, public policy poses major constraints to the development of commercial aquaculture in the United States. These constraints arise both from legal requirements themselves and from the nature of the institutions that have developed in response to existing policy. Many such constraints are common, and some are unique to local political jurisdictions.

Sea Grant-funded research can provide information to help governmental bodies formulate, implement and change public policies to reduce constraints and provide a business and regulatory climate more conducive to aquacultural development. Such research is often interdisciplinary.

Where critical disciplines specifically include law, coastal management, natural resources management, planning, public administration, social science and aquacultural science, Sea Grant research will strive to develop workable approaches to remove or reduce constraints to development and expansion of aquaculture in the following problem areas:

1. Water rights conflicts.
2. Ownership, leasing and use of terrestrial and seafloor sites.
3. U.S. Food and Drug Administration regulations restricting the use of drugs and product distribution systems.
4. Issues related to the introduction of exotic species, including disease and pest introduction and ecological damage that may result if these animals escaped.
5. Environmental and human health permitting problems; for example, uncertainties as to predictability, timing and costs.
6. Legal definition and placement of responsibilities for aquaculture within the institutional framework of the states.
7. Possible conflicts between aquaculture and other uses, such as fisheries, agriculture and other competitors for sites.
8. Conflicts related to ocean ranching and other open-water aquaculture (e.g., resource allocation among groups that exploit the Pacific salmon).
9. States' role in planning and developing aquaculture, including land-use planning, assessing natural and technical resources, and determining barriers to aquacultural development.
10. Tariffs and quotas to limit imports that compete with domestic products.
11. Public sector policies that affect financing and investment in aquaculture.

Table 5 lists public policy issues by category and by priority. More funding should be targeted toward those species whose aquaculture is at or near the commercial level of development.

Table 4. Recommended targeting of funds for research in disease control in aquaculture. Numbers are percentages and are based on a 100 percent level of funding, by group of aquacultural species.

	Species Group					
Research Problem	**Molluscs**	**Crustaceans**	**Marine Fishes**	**Anadromous Fishes**	**Great Lakes Fishes**	**Seaweeds**
	%	%	%	%	%	%
Drug registration	10	15	0	15	15	0
Quantifying effects of diseases	10	10	35	10	10	25
Standardization of diagnostic methods	30	30	30	30	30	30
Histopathology	10	10	20	10	10	5
Viral diseases	15	15	15	10	10	10
Immunoprophylaxis	5	10	0	15	10	
Exotic species	20	10	0	10	15	30
Total	100	100	100	100	100	100

Table 5. Priorities of public policy issues that affect aquacultural development. Priority increases from "5" to "1".

1: water rights
submerged lands
2: FDA regulations
planning studies
ocean ranching
3: environmental permitting
legal definition
4: species introductions
competition
financing
5: tariffs and quotas

Economics and Marketing

The development of a commercially viable national aquaculture industry requires that individual enterprises be profitable. The development of a new agricultural or aquacultural enterprise usually requires especially favorable economic conditions to provide enough time to adapt stocks to unique local conditions and to achieve profitable levels of production. Besides being a new business, an aquacultural effort uses new production methods for which husbandry experience and supporting science are inadequate. Poorly developed markets and marketing channels compound the problem. Economic research can be used to assess the general implications of development and to guide production, marketing and investment decisions of the aquaculturist.

Feasibility and Impact Studies. Economic feasibility studies determine regions appropriate for aquacultural production or the prospects for profitable aquaculture in a certain region. Feasibility studies can also reveal barriers to development that could be lessened by changes in public policy. Economic impact studies analyze the benefits and costs to various sectors, communities or regions and provide bases for policy development and public investment. These types of studies usually identify factors retarding development and determine research priorities to reduce cost or increase revenues.

Production. Production costs depend on the costs of resources, such as sites, water, equipment, animals and feeds, and on the knowledge and skills of the aquaculturist in transforming these resources into plant or animal products. For most of the animals listed in Table 1 production is still more an art than a science. Many problems remain in developing methods of systems control, feeding, handling, etc., to optimize survival and growth, but many problems in these areas remain. As science and experience in husbandry techniques provide new information on relationships between resources and production, the opportunity to reduce costs will continue.

Economic simulations of expected costs and returns over time can be used to analyze an aquacultural venture as an investment alternative or for repayment of loans. Such studies can also provide a basis for developing credit systems to facilitate financing of aquaculture.

Marketing. Because marketing channels and prices change constantly, marketing analyses are needed for all aquacultural industries, regardless of their level of technological development. Prices of aquatic products, which affect returns, depend on consumer preferences, incomes, product availability, prices of competing products, and demand. Demand analysis is required to estimate future prices and price trends. The characteristics of the consumer population (size, race, sex, geographic distribution, income, income distribution, etc.) and expected changes in these variables must be examined before the potential for market development and growth can be forecast. Estimates of demand and demand elasticity are less reliable for a new product or one with a limited market than for a product whose market is well established. Follow-up studies are needed as markets develop.

Although the retail market ultimately determines price, the price the aquaculturist receives also depends on factors such as processing, the marketing infrastructure, product handling and types of available transportation. Economic analysis can reveal areas that need improvement, determine what research is needed to improve processing and handling, and improve the marketing infrastructure.

Table 6 suggests funding levels for economic research and related advisory services for each level of technological development given in Table 1.

Table 6. Recommended targeting of funds for research in the economics of aquaculture. Numbers are percentages of total funding for economics studies. See also Table 1, which classifies aquacultural organisms by level of aquacultural technological development.

	Level of Technological Development				
	Major Lack of Technology	**Technology Partially Developed**	**Technology Developed to Pilot Scale**	**Infant Industry**	**Commercial Industry Exists**
	%	%	%	%	%
Feasibility and impact studies	0.8	5.5	8.3	4.4	2.2
Production	0.8	11.2	18.7	10.5	7.1
Marketing	0.0	.9	11.7	9.7	8.2
Total	1.6	17.6	38.7	24.6	17.5

Advisory Services

Sea Grant advisory specialists and agents communicate information resulting from research and provide analyses and education to aquaculturists in many ways. A developing industry needs advisory specialists to analyze short-term problems that increase costs or decrease returns. In addition, advisory personnel can improve decision making by teaching potential aquaculturists the fundamentals of aquacultural techniques and transfering new technological developments to established aquaculturists. Finally, the well-trained agent or specialist provides Sea Grant administrators with feedback that is important in determining research targets and research investment strategies. Funding levels for advisory services related to aquaculture are projected for fiscal years 1983-1987 in Table 1.

SPECIES PLANS

The following sections summarize the aquacultural status and potential of species that have been or are being studied by Sea Grant. They also discuss specific research needed to further develop the aquacultural industry for each species or group. These sections provide details and serve as references for the areas of effort discussed earlier. The species sections were written by working groups, the members of which are listed in Appendix 2.

Molluscs

Oysters

Oyster species commercially important to U.S. fisheries are *Ostrea edulis*, *Crassostrea virginica* and *C. gigas*. Trends in oyster harvest production are illustrated in Table 7. In 1980, U.S. sales were valued at $90 million on 32,000 metric tons (70.8 million pounds) of meat. Imports accounted for 30.6 percent of this total, reflecting diminishing domestic supplies, which has led to a decreasing market size. In the early 1900s, annual domestic production and consumption consistently exceeded more than 45,400 metric tons (100 million pounds), and no oysters were imported. For comparison, domestic production in 1975 is broken down by region and species in Table 8.

Except for a few large commercial operations, the oyster industry has not changed for generations. Harvesting is done by "watermen," individuals or families who remove oysters from public beds and sell them from their boats. This industry depends on the natural setting of larvae. The success of natural sets flucuates widely from year to year, and watermen experience corresponding fluctuations in income. This instability has caused the leaseholder to enter the industry.

Leaseholders own or lease underwater land, on which they deposit old oyster shells before the spawning period. The shells attract larvae and increase their chances of survival. Leaseholders also try to control predators, which are often a major cause of damage to beds.

Leaseholders may harvest oysters at any time, but watermen can enter the market only when public grounds are open. During this season, supplies increase and prices decrease. Leaseholders, however, can harvest their oysters after the season has closed. At this time, supplies have diminished, and the leaseholders can get higher prices.

Leasing has somewhat stabilized oyster supplies, but even leaseholders depend on natural sets. Holders of larger leases have tried to reduce this dependence by producing seedstock in hatcheries, but most hatcheries were constructed before enough research had been done and have been only moderately successful.

On the West Coast, the industry uses the "setters" or eyed-larvae technology developed by the Oregon State University Sea Grant Program. In New England, the industry uses cultchless spat grown in off-bottom culture systems, a technique developed by the University of Maine Sea Grant Program. High-technology hatchery and nursery methods on both coasts could fill the international need for seedstock.

Aquaculture could change the industry from a net importer to a net exporter, converting the $30 million dollar trade deficit into a $100 million dollar surplus. Eventually, the oyster industry could become an intensive, large-scale aquatic farming business.

Table 7. U.S. sales of domestic and imported oysters, 1950 to present. Weights are in thousands of metric tons (55).

Year	Domestic	Imported	Total	Percent Imported
1950	34.7	0.2	34.9	0.5
1955	35.2	0.6	35.8	1.8
1960	27.2	3.0	30.2	9.9
1965	24.8	4.1	28.9	14.2
1970	24.3	7.0	31.3	22.4
1975	24.2	5.6	29.8	18.8
1980	22.3	9.9	32.2	30.7

Table 8. Domestic oyster production by region, 1975. Predominant species is given for each region. Weights are in thousands of metric tons (101).

Region	Weight	Percent
New England (*Ostrea edulis*)	0.3	1.2
Mid-Atlantic (*Crassostrea virginica*)	1.5	6.2
Chesapeake Bay (*C. virginica*)	10.3	42.6
South Atlantic (*C. virginica*)	0.7	2.9
Gulf Coast (*C. virginica*)	8.8	36.4
West Coast (*C. gigas*)	2.6	10.7
Total	24.2	100.0

Resolution of technical barriers alone cannot lead to industrial expansion of oyster aquaculture. Government regulations that protect the environment and the individual or small-businessman also hinder industrial development.

Research Needs

Nurseries. The oyster industry would benefit measurably from a dependable, sufficient supply of high-quality, reasonably priced seedstock. The major problem is rearing oyster spat to the 20-to 30-mm stage in a nursery where food supplies are limited. The solution lies in perfecting techniques for mass algal culture, developing non-algal dietary supplements, and formulating artificial diets. Advances in nutrition, disease resistance and genetics will be vital to the success of nursery-reared oysters planted on natural beds.

Bivalve aquacultural research program. The most efficient, cost-effective means to develop aquaculture of oysters and other bivalves would be a national, coordinated program that would include all commercially desirable bivalve species. This program would combine laboratory and field studies, including research in genetics and selection, nutrition, disease control, mass algal culture, the development of non-algal feeds, and other related systems and technical developments.

Clams

Three species of clams have received the most attention in aquaculture: the hard clam *Mercenaria mercenaria* and the soft clam *Mya arenaria* on the East Coast, and the Manila clam *(Tapes japonica)* on the West Coast. Combined, the annual landing of these species is about 12,200 metric tons (27 million pounds) (102). However, clam aquaculture involves relatively unmonitored releases of seedstock into public and private waters, so estimation of its contribution to the landings is difficult. At present, it is probably less than one percent.

The annual wholesale landed value of the fishery is about $60 million, of which $44 milion comes from *Mercenaria*, $15.3 million from *Mya* (102), and $0.5 million from *Tapes* (27). If standard multipliers are applied, the fishery's true contribution to the economy is about five times those amounts (33).

Hard clams are unusual among fishery products because small clams are more expensive than large ones. This creates an ideal situation for the aquaculturist because the animals reach minimum marketable size and maximum value at the same time.

Clam aquaculture may involve any combination of the hatchery, nursery and grow-out phases. Hatcheries, the most fully developed phase, produce seed clams for sale to public agencies and private firms. Many state and local agencies are experimenting with aquaculture to supplement local clam fisheries (113). At least 10 hatcheries in the country now produce seedstock, and at least that many more are capable of doing so. Each hatchery should be able to produce about 10 million 3- to 5-mm clams per year. Seed clams of that size sell for $6-$20/1,000, but price depends on size, quantity ordered and other factors.

In some cases, seedstock is broadcast over a large area, which makes it difficult to estimate the area under cultivation. For example, one company operates a hatchery that seeds 5,261 ha (13,000 acres) of bay bottom off Long Island (82).

In nurseries, seed clams are cultured intensively during the early, most vulnerable stages. Nursery systems range from intensive protective systems, such as raceways and rafts, to simple forms of bottom cultivation and predator control. In many cases the nursery phase may be eliminated, and seed clams are broadcast onto natural growing areas. Unprotected, this seedstock has very low chances of survival. More intensive nursery culture has proven successful and is becoming economically feasible in some places (23, 88).

Research conducted by industry has emphasized improvement of hatchery efficiency. This research is privately managed, and it is difficult to evaluate its impact on the industry. In general, it emphasizes improvement of algal culture methods, disease control and the design of systems for growing newly set clams.

The industry has also spent considerable effort to improve nursery culture. Several East Coast firms have tested field-and shore-based nurseries, such as gravel beds with mesh covers, bottom boxes and racks, and rafts and raceways receiving pumped water. This work has usually been based on work done by public agencies, often with Sea Grant support. In effect, the industry has been forced to conduct its own demonstration projects. Because this work is proprietary, communication has been limited, and firms have repeated each other's work and mistakes.

With one or two crucial exceptions, the technology for a food-producing clam aquaculture industry has been established. Many barriers to further development are basically the same as those that inhibit the development of aquaculture in general, unique to clam culture only in detail. Sea Grant's research efforts will allow industry to realize its potential with an investment that is less than two percent of the annual wholesale landed value of the clam fishery. If aquaculture can be improved to produce 10 percent of the natural harvest, a reasonable target, Sea Grant's five-year investment would be returned in only one year.

Research Needs

Nurseries. Although the efficiency and reliability of clam hatcheries are still suboptimal, hatcheries theoretically can meet the demand for small seed clams. The most crucial technical constraint is the lack of techniques for efficient, cost-effective handling of commercial quantities of small (0.5- to 3-mm) seedstock. Development of nurseries will require improved understanding of the nutritional and environmental requirements of the animals. Investigations of the components of nursery culture are critical, especially in the areas of nutrition, predation, systems engineering and genetics. These problems are best approached through a coordinated effort of researchers from several disciplines, advisory personnel, and industry.

Demonstration facilities should be developed, associated with commercial firms to reduce costs, to ensure exchange of ideas with industry and to improve the credibility of the work. Nursery culture, the weak link, should be emphasized, but the facilities would deal with problems encountered in all phases of clam aquaculture.

These facilities must have a strong advisory component, in part to ensure that the projects do not simply become the research and development departments of the firms directing them. Furthermore, the projects must coordinate their efforts. Although conditions vary across the industry's geographical range, many problems are common to all such systems. The facilities would become the focus of a coordinated research effort that would include work on nutrition, engineering and disease. Research talent and facilities would be used at institutions most capable of attacking a specific problem, regardless of their location. Constant communication must be maintained among those involved in support research, in the demonstration facility, and in industry.

Some of the research will be applicable to other species. The engineering of nursery systems and work in nutrition and genetics, for example, should be coordinated with similar work on other bivalves.

Legislative and regulatory constraints. The lack of leasible intertidal and subtidal lands is a very strong barrier to clam aquaculture. Multiple-use conflicts, sociopolitical factors and judicial overlaps have precluded leasing programs in most states. Many of the same problems hinder the culture of oysters, scallops, mussels and other species. Consequently, a unified approach to the solution of these types of problems, rather than an effort emphasizing only one species, would be the most effective. Sea Grant should develop model legislation that can be used by the states to improve the legal and political climate for aquaculture, an effort that has begun in a number of states.

Scallops

In the United States, scallop aquaculture is a relatively new field, but the Japanese successfully rear the sea scallop *Patinopecten yessoensis* on a large scale. During 1975, world fisheries harvested 181,600 metric tons (400 million pounds) of scallops (44). In 1976, production in Japan was 154,360 metric tons (340 million pounds), most of which was produced by aquaculture in Mutsu Bay (98).

Pilot efforts have begun commercial culture of the giant scallop *(Pecten maximus)* in England and France (98). In the United States, experimental culture of the bay scallops *Argopecten irradians* and *A. gibbus* and of the rock scallop *Hinnites multirugosus* is now inspiring commercial interest (78). *A. irradians* is being reared on Martha's Vineyard with town government support to allow seeding of nearby beds.

Several other U.S. species have promise for aquaculture but have not received sufficient study. These are the weathervane *(Patinopecten caurinus,* which may be the same species as *P. yessoensis),* pink *(Chlamys rubida),* spiny *(C. hastata)* and sea *(Placopecten magellanicus)* scallops (98). A tropical species *(Spondylus calcifer),* native to the Pacific Coast of Mexico, is also of interest (77).

Aquaculture of the rock scallop can develop into an industry within 10 years if problems with spawning and juvenile production are overcome. Aquaculture of the bay scallop can become viable within five years, but legal impediments to grow-out in suspended systems may restrict its development. Basic studies to lay the groundwork for aquaculture of other scallop species should be well underway by 1990.

A California firm that markets rock scallops receives $1 for each adult reared from naturally set juveniles recovered from harvested oysters. Each yields an average of 50 g (0.11 lb) of meat with a value of about $20/kg ($9/lb) (64). This meat compares favorably to commercially available sea and bay scallops (78) and should command a price high enough to attract major aquacultural development.

Offshore seabottom culture of scallops, by habitat confinement for rock scallops and by seeding leased parcels for free-living species, could constitute a multimillion dollar business. In two years, production of the rock scallop, now farmed on posts at a density of 100/post/m^2, would increase several times if rearing panels were used in deeper water (78).

Offshore scallop culture will not interfere with surface water activities. Fishing would benefit because the installations will attract other organisms. No negative environmental influences would result. Also, a large-scale scallop-farming enterprise would increase jobs and business for seafood processors and marketers, divers, and barge operators.

During the next two years, Sea Grant should support research to refine the aquaculture of the bay and rock scallops, for which technology is most developed. New studies should begin on the weathervane, pink, spiny and sea scallops and on *Spondylus.* The need for advisory programs regarding scallop aquaculture will increase during the latter part of the five-year period.

Research Needs

Induction of spawning. Culture of young from hatchery-produced eggs has had varying degrees of success, depending on species (22, 53, 78, 98). When dependent on gravid females collected from the wild, spawning can be induced only at the peak of the natural spawning seasons (78). In some species, spawning may be induced during only one or two months of the year (78). Conditioning of broodstck to spawning readiness and retention of gravid females at low temperatures can extend the reproductive season for hatchery production (53). These approaches are currently being tested on the rock scallop (76).

Induction of setting. Generally, scallops are hardy as juveniles and adults, are tolerant of moderate variations in temperature and salinity, and grow relatively fast (98, 78). However, attempts to collect spat or recently set juveniles from nature, simply accomplished for *P. yessoensis,* have not been successful for all species. The rock scallop, for example, sets on shell and rock in nature, but effective chemical attractants must still be devised for aquaculture. Bay scallop seedstock has been obtained from artificial collectors but in quantities too small for commercial aquaculture.

Scallops are harvested within three months after setting and are transferred to mesh pens or cages where they grow to cementing maturity (about six months of age for rock scallops). Free-living species remain on these structures until they have grown to market size and are harvested.

Improving post-setting survival. Larval survival varies widely from crop to crop, and mortality of post-setting juveniles is often high (78, 109). In the rock scallop, survival after metamorphosis is excellent (78). Procedures and structures for in-sea rearing of rock scallops from juvenile to adult have been very successful, but effective containment structures are needed for other species. The chief problems are associated with stocking densities and crowding (78, 97).

Grow-out. The sea scallop may be farmed effectively if growth rates can be increased. Grow-out systems for deep (10-50 m) coastal waters must be designed and tested.

Red tide toxins. Toxic levels of *Gonyaulax* (red tide) toxins have been measured in rock scallops from the northern California Coast and have caused one death by paralytic shellfish poisoning (21). The California Department of Public Health (20) prohibits taking scallops, mussels and oysters during the summer. Intensive monitoring programs are needed for safety and to ensure sound marketing.

The mouse bioassay used to determine toxicities is time-consuming and expensive. A less expensive, faster assay is needed that can be used by the industry instead of by health departments.

Mussels

In the United States, four private firms culture the blue mussel, *(Mytilus edulis)*, the only indigenous mussel species cultured commercially. A total of 84 ha (208 acres) is under cultivation, primarily in New England and Washington. The combined annual production from these operations is about 2,600 metric tons (105,000 bushels) whole-shell weight, which has an annual value of about $1.6 million. A few smaller firms have begun mussel culture, but their level of production is relatively insignificant and is not included here.

More than 90 percent of the mussels cultured in the United States are grown in suspended culture systems such as longlines or rafts (58, 84). A Maine firm recently seeded 26.3 ha (63 acres) of subtidal bottom with juvenile mussels. The success of this pilot-scale bottom culture operation will be evaluated in 1982.

Most of the mussels cultured in the United States have been grown with the longline system used extensively in Sweden (59). Firms engaged in mussel aquaculture have tested different types of settlement substrates, seed tubing and flotation systems. Suspended culture techniques consist of ropes hanging from floating arrays (59, 84, 99). Larvae settle on the ropes and grow to market size with little or no manipulation (25, 26, 84, 137). In another method, seed mussels are collected from the wild and transplanted into long mesh tubes suspended from the arrays (58, 99).

Present harvest and post-harvest handling methods are labor-intensive, and mechanized handling methods need improvement (58,59). Adapting the handling and processing machinery developed in Holland to the relatively thin-shelled mussels cultured in the United States has been only moderately successful.

The most significant socioeconomic impact of increased development of mussel aquaculture in the United States will be increased employment. One mussel farm with an annual production of 2,476 metric tons (100,000 bushels) would employ 60-100 people, with a total payroll of about $1 million. Employment involving post-harvest handling and processing would also increase significantly. From 1982 to 1986 approximately 800 new jobs, directly and indirectly related to the aquacultural facilities, would be created if research and development needs are met.

If this plan is realized, mussel culture should increase by more than 15,000 metric tons (600,000 bushels) during the next five years, with an estimated value of more than $9 million. Production by the U.S. mussel culture industry could exceed 100,000 metric tons per year in 10 years.

Research Needs

Seedstock availability and regulation of transport. Insufficient quantities of high-quality mussel seedstock from natural populations hinder further development of the mussel culture industry. The feasibility of obtaining seedstock from subtidal populations, which is done in Europe, must be explored.

Also, a program should be initiated to eliminate legal and biological constraints associated with using wild seedstock. At present, seedstock must be approved and certified before it is transported across state lines. On the East Coast, this involves sending samples to the National Marine Fisheries Service Laboratory in Oxford, Maryland, which determines the presence or absence of diseases and parasites. The organisms must come from unpolluted waters, which is irrelevant bacteriologically because the seedstock is not eaten. The certification process takes at least eight weeks, an unreasonable delay because of time and biological limitations. For example, if mussels settle in Virginia in late spring, all mussels may be dead by midsummer if water temperatures exceed 25°C (77°F) (84, 138). Analyses of diseases and parasites conducted on a sample when collected may be meaningless by the time the seedstock is transported.

Mechanization of handling and processing. Handling and processing machinery developed in Holland for bottom-cultured mussels cannot be used on most U.S.-cultured mussels, which have relatively fragile shells. The machinery must be adapted or a substitute developed (washer/graders, debyssing and declumping machinery, etc.) for mussels cultured in this country.

Changes in permitting processes. The difficulty of obtaining a permit for mussel culture varies from one region or state to another. In the Northwest it is the single largest constraint to the expansion of the industry, and it is also a problem in Massachusetts, Connecticut and New York. However, it is only a minor problem in Maine and Rhode Island. Programs to remove legal and social constraints to obtaining these permits would involve the educational and legal efforts of the Sea Grant Marine Advisory Service.

Ecological modeling. Basic studies are required to determine the feasibility of culturing mussels directly on subtidal bottoms in U.S. coastal waters. Gaps in understanding mussel growth under intensive culture make it difficult to estimate the carrying capacity of a given site and, hence, the environmental impacts of a large-scale operation there.

A practical carrying-capacity model applicable to U.S. waters should be developed based on energy flow considerations, following a systems approach that defines aquacultural expectations and limitations.

Predator control. Losses of cultured mussels to predation by sea ducks (primarily eiders and scoters), starfish and certain fishes (primarily the pile perch) are serious problems for the industry, particularly along the Northwest Coast (137). Effective means to reduce predation must be developed.

Red tide toxins. Accumulation within mussels of toxins from dinoflagellate blooms (red tides) restrain further development of mussel aquaculture (85, 139). Considerable research is being conducted on the factors responible for the blooms, and extensive monitoring programs have begun (139). But in many areas, particularly the Northwest, many basic biological studies are still required to explain varying levels of toxins within mussels exposed to the blooms (137). A more rapid, effective assay, perhaps a gas chromatographic method, must be developed to monitor toxin levels.

International information exchange program. A program should be created for the exchange of information and technical expertise between commercial operations in the United States and other nations. Information from this exchange should be made public.

Geographic expansion of the industry. Large numbers of fast-growing, market-sized mussels grow on structures in and near Delaware Bay, an area much farther south than areas where mussels are now cultured. Experiments are necessary to establish the feasibility of suspended culture of mussels in this region, particularly near the mouth of the Bay.

Abalone

Seven species of abalone occur on the West Coast, but only the red *(Haliotis rufescens)* and the green *(H. fulgens)* abalones have been cultured commercially to the adult stage (Cox, 1962). The pink *(H. corrugata)* and the white *(H. sorenseni)* abalones have excellent market potential but have been reared only experimentally (73). The black *(H. cracherodii)*, the flat *(H. walallensis)* and the threaded or pinto *(H. kamtschatkana)* abalones are of limited interest because they are so small (36).

Abalone aquaculture is practiced only in California. For the past 10 years, the four private abalone hatcheries have provided seedstock and juveniles of the red, and recently the green and the pink, abalones to the California Department of Fish and Game (CF&G) and to other groups studying grow-out in artificial, in-sea habitats and seafloor farming on newly leased areas (41). Combined, these hatcheries use no more than 1.6 ha (4 acres). Leased offshore areas for grow-out total about 3.2 ha (8 acres).

Recently, aquaculturally produced abalone has been sold to seafood outlets and restaurants. Annual sales by aquacultural firms have totaled less than 0.9 metric ton (1 ton), but new markets are expected to open during the next year, and sales should increase. The total annual value of marketed cultured abalone, including seedstock, is probably less than $500,000.

In the mid-1960s, when U.S. groups first began abalone culture, little technical information was available, and the industry developed original culture methods (75). Incubation and early larval and postlarval growth occurs in pails. Young are transferred to tanks or raceways for grow-out.

Difficulties at the hatchery stage include induction of spawning, control of gonadal ripening, high larval and postlarval mortality, and determination of optimum conditions for rearing juveniles. Round tank systems with rapid water flow proved to be more efficient (74).

Grow-out has been accomplished offshore and in tanks on land (74). Offshore grow-out has been preferred since around 1970 when costs of large land-based systems became prohibitive. However, increasing costs of construction, installation, maintenance, fuel, dive time and insurance now plague even offshore systems.

Hatcheries have emphasized research and have only recently begun production. Sea Grant research has helped develop effective spawning and larval rearing procedures. Private firms and CF&G have developed their own culture methods. One firm uses methods developed in Japan to rear juveniles, including plastic panels and sheets, vigorous aeration and low water-exchange rates (81). Another group uses bin/raceway culture for the younger stages, from which juveniles are transferred to barrel cages and suspended in protected coastal waters for grow-out (93). This is a promising approach. In another method, juveniles are reared in round tanks with rapid water flow, after which they are transferred to raceways or offshore habitats. For three years the Southern California Edison Company has funded studies of the use of heated effluent for the culture of the thermophilic green abalone (79).

Technological refinements are still needed, and industry feels that it should make these advances itself within the free enterprise system. However, basic biological problems should be tackled by researchers outside industry because such information is of broad interest and application and should be made public.

All economic, social, environmental and other effects of abalone aquaculture would be positive. Increased hatchery efficiency and cost-effective grow-out methods, coupled with market trends, can support an economically sound, profitable aquacultural business. Because of the cooperation between abalone fishermen and processors and the consumer demand for abalone, no displacement of the fishery would result.

Shoreline land for hatcheries will be expensive and hard to find, except in remote areas, and water quality near cities may not be suitable for abalone culture. Therefore, in-sea sites are more attractive for such facilities. If locations are granted in agreement with, and possibly in coordination with, abalone fisheries and other users of the areas, conscientious programs using artificial habitats or seafloor farming will not cause environmental or social problems. The environmental impact of properly designed hatcheries should be minimal.

Research Needs

Ecological studies. The Abalone Resource Enhancement Program, a joint project of Sea Grant and CF&G, is conducting intensive studies of abalone population dynamics and ecology (130). The program compares survival and growth rates of natural and hatchery-produced populations of red and green abalones. This important program should continue. It will provide information crucial to the management of natural populations and explain environmental influences on productivity, suggesting optimum conditions for grow-out in seafloor systems.

General biology. A major constraint to abalone culture is the slow growth rate, only 2-4 cm/year (74). Studies are required to enhance growth rates by hormones, diet, temperature and other factors and to control gonadal maturation. Postlarval attrition, the decrease in postlarval survival between weeks one and eight, is so serious that 10 percent survival after this period is considered good (74). The causes of postlarval attrition must be determined so that mortality rates can be reduced. Growth and survival of all life stages may be improved through genetics. Generation time (the age at first sexual maturity) may be as short as 1.5-2 years, making such studies reasonably approachable.

Economics and marketing. Efficiencies and economics of shore-based and in-sea grow-out systems must be evaluated and compared. In-sea systems will probably be the most successful. Recent sales to two- to three-year-old adults to gourmet seafood outlets have improved marketing prospects for aquacultured abalone, but new methods are needed to process and prepare smaller specimens. Market development, particularly for small (2- to 4-in) abalone, needs attention. Specialty products using smaller abalone soon may facilitate commercial development of abalone culture. Sea Grant supports a three-year study of the economics of the California abalone fishery, which is also important to the development of abalone aquaculture.

Related Studies

Sea Grant will continue to support investigations of the aquaculture of unicellular algae and H_2S-oxidizing bacteria. The aquaculture of these organisms is discussed here because its products will be used as food in other aquaculture, primarily of molluscs.

Unicellular algae are important in a variety of aquacultural activities. They are required as food by bivalve molluscs and crustaceans, at least during part of their life cycles. Interacting with animals, algae maintain stable, productive environments in fish and crustacean ponds through oxygen production, carbon dioxide uptake, and contributions to the food chain. Mass algal cultivation has progressed significantly in the past 20 years, but inability to eliminate unwanted algal species from cultures and to maintain consistent productivity blocks commercial aquacultural development.

The research and development required to allow reliable, inexpensive mass production of algae does not fall into typical categories such as nutrition, genetics, disease, etc., but is more compatibly done in conjunction with studies of species that rely on algae for food. In the past, Sea Grant has supported algal research as part of larger aquacultural schemes, and simultaneous study of both problems is more efficient and productive than separate studies.

Recent studies of the Galapagos spreading center (13, 35, 48) and the East Pacific Rise (112) revealed diverse benthic communities supported by bacterial chemosynthesis based on geothermally generated H_2S (35, 48, 61, 62, 65, 83, 111). This mode of primary production has been proposed as an energy base for commercial aquaculture (61, 62). Analogous to a submarine thermal vent ecosystem, this system would have two stages. The first stage would consist of a continuous-flow bacterial culture reactor in which colorless chemolithotrophic sulfur bacteria use H_2S as the energy source for carbon dioxide fixation. In the second stage, molluscs will be cultured using the bacteria produced in the first stage as food.

Hydrogen sulfide is an abundant by-product of many industries, as a contaminant in natural gas and coal gasification gases, for example. Hydrogen sulfide and its primary combustion product sulfur dioxide are highly toxic and harmful to the environment if released in large quantities. Industrial procedures for the environmentally sound disposal of H_2S involves its oxidation to sulfur or to sulfuric acid, compounds of relatively low commercial value. The energy released during this oxidation is wasted, however. On the other hand, H_2S is readily oxidized by colorless sulfur bacteria for the synthesis of organic matter, converting it into sulfate, a non-toxic, natural component of seawater (68).

Interfacing H_2S-driven bacterial chemosyntheis to aquaculture is a unique application of a previously unexploited energy source for the production of food. However, the feasibility of this new approach needs to be verified experimentally at all trophic levels.

This research is being done in two parts. Conditions for continual production of bacteria are being determined, and the suitability of the resulting biomass as aquacultural feed is being evaluated.

Hydrogen sulfide can be safely, precisely and continuously introduced into mass cultures. Because chemosynthesis based on H_2S does not require light, there are no diurnal, seasonal or weather-related changes in productivity. Uncoupled from light and the concomitant requirement for ponds that use large tracts of land, H_2S-supported primary production takes place in small, enclosed reactors. Considering the increasing costs of land, production in smaller facilities is an important advantage.

Colonization and continuous production of colorless sulfur bacteria can be readily achieved in near-shore marine reactors. Conditions are being determined for optimal bacterial production and maximum nutritional value of the biomass produced. Preliminary studies indicate that the mussel *Mytilus edulis* ingests the bacteria, but quantitative feeding studies must demonstrate growth. Such studies have begun on *Mytilus*, and other shellfish species of commercial value will be investigated. Research will also optimize the nutritional output of the biomass reactors.

Because research to determine the feasibility of H_2S-driven aquaculture has just begun, there is no industry to analyze economically. Consumer species must be tested, and the technology that would allow optimal bacterial growth and high nutritional quality is being perfected. In light of the system's present state of development, the necessary information on H_2S-driven biomass production, the nutritional characteristics of the bacteria produced, and the efficiency of its utilization by consumer species should be known within five years. The economic feasibility of this system will be determined during that time. When the bacterial production stage has been successfully coupled with the culture of consumer species, commercial development of the system should be complete within 10 years.

Crustaceans

Marine Shrimp

The marine shrimp fishery is the most valuable U.S. fishery and has the largest market of any group of shellfish or fishes (70, 102). The producer-level value of the market exceeds $1 billion, which most experts assume is limited only by supply, at least during certain seasons. World and U.S. markets were predicted to increase by 25 and 33 percent, respectively, between 1975 and 1985 (17, 104).

While catch levels have remained relatively stable, demand has increased as the U.S. population and incomes have increased. This increase in demand comes at a time when harvests are at or near maximum sustainable yields (104) and when trawler operating costs have increased drastically. The value of shrimp imported into the United States is almost twice that of the domestic catch. For example, in 1980 the dockside value of imported shrimp was $719 million, while that of U.S. shrimp was $403 million (70, 102). In 1978, fishery imports accounted for 10 percent of the national trade deficit, and shrimp aquaculture could significantly reduce this figure.

Throughout the world, most shrimp aquaculture involves the use of penaeid species, such as *Penaeus japonicus*, native to the North Pacific; *Metapenaeus ensis*, *P. monodon* and *P. merguiensis*, native to the West-Central and South Pacific; *P. stylirostris*, *P. vannamei*, *P. californiensis* and *P. occidentalis*, native to the eastern Pacific; and *P. setiferus*, *P. duorarum*, *P. aztecus* and *P. schmitti*, native to the western Atlantic (71).

Commercial shrimp aquaculture endeavors exist in Central and South America, Southeast Asia, Taiwan and Japan. In the United States, six species are being considered for aquaculture: *P. aztecus*, *P. setiferus*, *P. monodon*, *P. stylirostris*, *P. vannamei* and *P. japonicus*.

Shrimp aquaculture has three phases: maturation and reproduction, for production of seedstock (larvae); hatchery, for production of postlarvae; and grow-out to the adult stage in raceways or ponds. Seedstock produced in the maturation and reproduction phase supplies the hatchery phase, and the postlarvae produced in the hatchery supply the grow-out phase. Aquaculturally produced shrimp are used for food, bait and to augment natural populations.

Postlarvae for grow-out can be collected from bays or estuaries. They may also be produced by gravid females that have been collected from the wild, or from females induced to mature, mate and spawn in captivity. Most foreign firms use animals taken from the wild. Some use a small amount of seedstock produced by aquaculture. Seedstock is experimentally produced in Japan, Central and South America, Taiwan, the Philippines, Indonesia, Tahiti and France. The inability to mature, breed and spawn shrimp in captivity is the main limiting factor.

Dependence on larvae or postlarvae from natural stocks is not satisfactory for aquaculture. The supply is unpredictable and expensive; they are available only during local spawning seasons; non-indigenous species are not available; and genetics and selective breeding studies are not possible.

The preferred alternative is to mature, breed and spawn females in captivity under controlled conditions, resulting in a low-cost, predictable supply of larvae. The larvae are then transferred to a hatchery. Hatchery technology is suboptimal but adequate for about 10 species. Postlarvae raised from mature mated females from either natural or captive populations have been used to augment natural populations in the Inland Sea in Japan and in the Gulf of Arabia (1).

After the larvae have been in the hatchery 16-20 days, they reach the "6- to 10-day-old postlarval" stage. The postlarvae are then transferred to ponds, raceways or circular tanks for grow-out (71). The technology required for grow-out in ponds is adequate for commercial operations in many countries, although it is far from optimal.

As much as 841-2,244 kg/ha (750-2,000 lb/acre) has been produced, with a value of $1,500-$4,000, for a potential profit of $741-$2,471/ha ($300-$1,000/acre) (71). As research improves technology, production will increase and become more consistent. For comparison, in 1980 in Texas, the average value of sorghum was $356/ha ($144/acre); that of cotton was $405/ha ($164/acre); and that of grain, silage and forage corn was $778/ha ($315/acre) (131). Furthermore, in areas with very warm climates, such as South Texas, two shrimp crops have been produced in one year. For intensive culture, annual harvests of 56,090-112,182 kg/ha (50,000-100,000 lb/acre) of 20- to 40-count, heads-on shrimp have been predicted (104). To complete the life cycle in captivity, some adults are held in ponds or raceways and used the following season as broodstock in the maturation and reproduction phase (6, 8).

Feed is the primary technological limitation for intensive grow-out in raceways or tanks, and feed costs and feed conversion ratios are too high. Feed constitutes at least one-third of the cost of shrimp aquaculture. In intensive pond culture, annual use of food ranges from 0.9 to 1.8 metric tons/acre (2-4 tons/acre). At least one-half of the feed can consist of vegetable matter. Surplus grain and grain products, such as rice bran, grain distillery wastes and corn meal, could be made into shrimp feed. Improvements in technology and advances in genetic selection of stocks will allow production of a significant number of shrimp by intensive pond or raceway grow-out.

The ideal land for shrimp grow-out ponds is the strip of coastal land that is too salty for traditional agriculture. Along the Gulf Coast, this strip of land is usually 0.8-1.6 km (0.5-1 mi) wide and at least 0.6-3.0 m (2-10 ft) above mean high water. Therefore, a large amount of land only marginally acceptable for other uses could be used to raise shrimp. Also, large areas far inland have salt water near the surface (e.g., West Texas) and could be used for aquaculture. In most cases, these areas need a new agricultural crop, and shrimp would have an important impact on their economies.

Before 1982, only one shrimp mariculture company in the country used grow-out ponds, and it has never made profit. It has depended on seedstock of *P. vannamei* and *P. stylirostris* from Latin America, supplemented with seedstock obtained from female *P. setiferus* mated in the wild but spawned in captivity.

The state of U.S. shrimp aquaculture is similar to that worldwide. Three species, *P. setiferus, P. stylirostris* and *P. vannamei,* have matured, mated and produced live offspring in captivity (19, 24, 70). However, the technology is not sufficiently developed for commercialization without extremely high risk. In 1982, two pilot shrimp farms opened in South Texas, one began operation in South Carolina, and other groups began applying for the permits needed to operate. The hatchery and grow-out technologies are adequate but suboptimal. Shrimp aquaculture is commercial in Central America and Southeast Asia because the growing season is almost a year long, postlarvae or gravid females may be collected from the wild year-round, and both land and labor are inexpensive.

In the United States, seedstock must be produced in captivity for an industry to be successful. Also, the shrimp growing season for pond culture is at most seven or eight months long, except in Hawaii and the trust territories, which have year-long growing seasons.

Between one and three years of adequately funded research will be required before the maturation and reproduction technology can support a commercial company that produces shrimp for food. A commercial venture for the production of shrimp for bait is closer to reality than one for food because live bait brings a higher price.

Research Needs

The priority areas for shrimp aquacultural research are outlined in Table 9. Most of the categories represent refinements in techniques that have been developed during the past decade. New emphasis is needed in dissemination of technical information resulting from the research, in better coordination of the research program, and in removal of legal and regulatory barriers. These are described below.

Educational and advisory programs. Current research on shrimp aquaculture is too diffuse, too little, and poorly coordinated. More funds are needed. Pilot facilities should be built for research, demonstration, education and training, and greater emphasis should be placed on transmitting information to user groups through marine advisory and extension specialists. At least one center for research and extension functions, with pilot facilities, is needed. Satellite programs in other pertinent research areas would complement the center.

Legal constraints and permitting. In some states, a shrimp aquaculture enterprise may need more than 15 permits to operate. The complexity of the legal and permitting constraints handicaps the development of shrimp aquaculture.

Table 9. Priority research areas for shrimp aquaculture.

Seedstock Production
- nutritional requirements
- environmental requirements
- hormonal basis
- artificial insemination; in vitro fertilization
- facility engineering
- diseases
- cryogenics
- economics

Postlarval Production
- nutritional requirements
- environmental requirements
- facility engineering
- diseases
- economics

Grow-out Production
- nutritional requirements; feeds
- environmental requirements
- facility engineering
- diseases
- economics
- marketing
- seafood technology

Other
- genetics; domestication
- demonstration
- extension and advisory services
- legal and permitting problems
- natural history and biology

Management or regulation of any coastal resource should recognize aquaculture as an important use. The permitting process should be simplified as much as possible. One entity should be recognized as a central source of technical and legal information.

Prawns

In the United States, commercial aquaculture of the prawn *(Macrobrachium rosenbergii)* began in Hawaii and has developed most rapidly there. Small commercial experiments also have been undertaken in Arkansas, California, Colorado, Florida, Louisiana, Massachusetts, Nevada, New Jersey, Oregon, South Carolina, Tennessee and Texas. In addition, several U.S. firms are developing prawn farms in Central and South America and in other countries.

The only reasonably reliable statistics on U.S. prawn production are from Hawaii, and Table 10 shows the growth of prawn farming there during the past decade. The major development of prawn culture there has occurred since 1974 (72, 115). Figures on prawn production by U.S. companies elsewhere are difficult to obtain, and most of the figures in Table 11 are estimates. Nevertheless the U.S. prawn industry now produces almost 277 metric tons (0.5 million pounds) per year, with a wholesale value of more than $2 million.

Prawn culture technology includes three phases: hatchery, nursery and grow-out (116). Only the larval stage (hatchery phase) requires salt water (about 12 o/oo appears optimal). However, nursery production and grow-out are effective in brackish water (124).

Two types of hatcheries have been implemented commercially. The "Anuenue" type was developed in Hawaii (46,47) and is the most widely used method. The hatchery consists of 10- to 30-m^3 rectangular tanks of concrete or fiberglass and typically uses mass-cultivated algae for larval feed. It is relatively low-intensity. Typical stocking densities are 30-50 larvae/liter, and production levels average 5-25 postlarvae/liter.

The "Aquacop" prawn hatchery was developed in Tahiti (4, 5, 7) and uses small (2 m^3 maximum) cylindrical tanks with conical bottoms. The method involves intensive management and often routine application of bactericides. Stocking and production levels are typically much higher than in Anuenue systems, 100-200 larvae/liter and 25-100 postlarvae/liter, respectively (5, 7, 87, 121, 129).

Ling (80) first introduced the nursery phase between the hatchery and grow-out phases. Juveniles that have undergone growth in the nursery phase (called "nursed" juveniles) generally survive better and reach marketable size more rapidly than juveniles placed into grow-out facilities immediately after metamorphosis. In temperate zones nursed juveniles may be required for development of commercial aquaculture of the prawn because the growing season is so short (116, 119, 123-125). Although it is not required, the nursery phase is also useful in the tropics (51).

Intensive nursery systems for use in temperate zones typically involve large indoor tanks or small covered ponds (118). The tanks or ponds contain wooden or plastic frames supporting layers of plastic mesh. The mesh increases the system's carrying capacity by providing more surface area to the prawns and distributing them throughout the water column. Postlarvae are placed into the nurseries at high densities, between 1,000 and 3,000/m^2, and are reared there until conditions are favor-

Table 10. Growth of the prawn industry in Hawaii. Production in metric tons; area in hectares; values in thousands of dollars (34, 51).

Year	Production	Number of firms	Area Cultivated	Wholesale Value
1972	1.95	1	0.61	15
1973	2.00	1	0.61	15.3
1974	4.99	7	2.02	38.5
1975	18.28	11	10.52	140.9
1976	19.64	13	10.52	151.6
1977	24.90	15	13.36	206
1978	49.99	20	43.30	420
1979	95.26	21	111.29	753
1980	136.08	24	125.46	1,200
1981	119.75	21	116.15	1,100

Table 11. Approximate present annual level of industrial prawn culture by U.S. firms. Production in metric tons; area in hectares; value in thousands of dollars.

Region	Production	Number of Farmers/Firms	Area Cultivated	Wholesale Value
Hawaii	136	21-27	=120	1,200[1]
Continental	≥4.54	15-20	≥20[2]	30[3]
United States	17.7[4]	1	intensive	351[5]
Abroad	72.6	≥4	≥30	560
Total	230.8	41-49	170	2,141

[1] Based on wholesale price of $8.81/kg ($4/lb) of whole animals.

[2] Includes 12 ha of extensive ponds; does not include 40.5 ha of ponds under construction.

[3] Based on wholesale price of $6.61/kg ($3/lb) of whole animals.

[4] Based on projections provided by one intensive culture firm.

[5] Based on wholesale price of $19.82/kg ($9/lb) of whole animals as projected by intensive culture firm.

able for stocking them into outdoor ponds (117, 118). Such systems require a source of heat and are good candidates for use of heated industrial effluents and geothermal waters. In the tropics, small outdoor ponds can be used as nurseries, with stocking densities of 70-170 postlarvae/m^2 (51).

Two general types of pond grow-out are practiced: continuous production and batch culture. Continuous culture is used only in the tropics, where postlarvae are stocked into ponds shortly after metamorphosis (86). Stocking density is usually 16 postlarvae/m^2 of bottom. After seven to nine months, prawns are selectively harvested with a long, large-mesh (1.7- to 2-in) seine equipped with a bag. The prawns are removed from the bag, culled by hand, and the small ones returned to the pond. This harvest method is only 50-76 percent efficient (86), but it yields prawns of a relatively uniform size (all larger than 35-40 g). Selective seining is conducted biweekly or monthly, depending on conditions and production. The ponds are restocked with postlarvae at regular intervals. Production is more or less continuous, although it fluctuates considerably. Overall survival from stocking to harvest is about 50 percent, but survival of subsequent stockings may be only 25-35 percent (51).

Batch culture is better suited to temperate zones, where the growing season is short (116). Stocking density is lower than in continuous culture, only about 6-10 postlarvae/m^2 (125). The ponds are stocked once at the beginning of the growing season and harvested by draining the pond when water temperatures are too low for growth (less than 20°C). This method is highly efficient and requires less labor than continuous seining. Also, survival is at least 70 percent. However, the prawns must be size-graded for the market. The batch-harvest method is also being tested in the tropics.

Although little detailed information is available concerning research and development by the prawn aquaculture industry, the major emphases have been in the following areas:

1. Implementing and evaluating pilot production projects,
2. Improving management of water quality, water exchange rates and algae in ponds,
3. Improving feed formulation, binding, presentation, and distribution,
4. Improving hatchery production and reliability,
5. Industrialization and mechanization, and
6. Improving stocking densities and management practices, including polyculture, for pond culture.

As this list indicates, and as John Corbin (34), manager of Hawaii's Aquaculture Development Program, stated, "...industry's efforts are focused on immediate problems which have the possibility of short-term resolution. Long-term research efforts, with pay-off timetables of 5-20 years, are not part of the private sector's research strategy or budgets at this time." However, the Hawaii Prawn Producers Association has organized a research and development committee to review public and private prawn research and communicate the most important research needs to public institutions. Annual industrial expenditures for prawn research and development, excluding pilot projects, is between several hundred thousand and $1 million.

Development of prawn aquaculture should have positive economic, social and environmental impacts. Prawn aquaculture should reduce U.S. reliance on imported shrimp, increase domestic revenues, provide products for export and create new jobs. With adequate public support of research and development, 759 ha (1,875 acres) should be under prawn aquaculture in Hawaii alone by 1985. This will create about 190 jobs at the facilities and 320 jobs in processing, marketing and related areas. Wholesale revenues of more than $26 million are predicted. If the industry grows at a similar rate in the continental United States and elsewhere, and considering retail revenues, processing and supply sectors, etc., prawn aquaculture could have a $100 million annual impact on the U.S. economy by the middle or latter part of this decade. This would provide an excellent return for the annual investment in public funds.

Positive social effects of prawn farming include protection of agricultural lands from urban encroachment, productive uses of lands marginally suitable for agriculture, and the creation of satisfying jobs, many in an agrarian setting. At present, prawn farming is relatively low-technology, requiring relatively high amounts of labor. The commitment of a considerable amount of water resources is also a positive effect because prawn aquaculture is virtually non-polluting. Instead, because it requires good water, it may protect water quality, a positive effect of aquaculture in general. Also, prawn farming can use brackish waters, which generally have few uses.

Research Needs

Seedstock availability. There is a supply/demand block on development of the prawn aquaculture industry. Private farms, especially small, family-oriented businesses, cannot diversify into prawn farming until supplies of low-cost seedstock are regularly available. Private investors cannot afford to open hatcheries until the demand for seedstock warrants the investment. At present, no more than four private hatcheries in the United States sell postlarvae, and only one nursery supplies juveniles.

Hatcheries. Improved understanding of hatchery practices and of nutritional and environmental requirements of larvae is necessary to increase the reliability and productivity of hatcheries. Development of small-scale, closed or semi-closed hatcheries for medium-sized farms would improve their profitability.

Grow-out. Research is needed to optimize management and production strategies, to develop intensive nurseries, to document water quality effects and develop water management strategies, to decrease the variability in growth rates, and to manipulate prawn behavior. Research is also needed to develop and demonstrate mechanical harvesting methods.

Alternate heating methods. Research is needed to determine low-cost means to heat water in aquacultural facilities, including the use of heated industrial effluents and geothermal water. This would improve the possibility of establishing prawn aquaculture in colder regions.

Nutrition and diets. Feed usually represents the largest portion of the cost of operating a prawn farm. Present knowledge of the prawn's nutritional requirements is rudimentary, so available feeds are suboptimal. Research is urgently needed to develop more nutritious and inexpensive feeds and to improve methods of delivery. Also, currently available feeds need evaluation under production conditions.

Genetics and selective breeding. The prawn is still a wild animal — it has not been domesticated. Long-term efforts should be funded to improve economically important morphological, physiological and behavioral characteristics through genetic manipulation by selective breeding, hybridization and induction of polyploidy.

Economics and marketing. Market development is one of the most significant problems facing the prawn culture industry. Two major problems must be overcome: the poor image and resulting price of prawns caused by low-quality Asian imports and the lack of product recognition. Research and development should be initiated to determine how imported prawns are marketed and used, to identify domestic and export markets for processed whole prawns of different sizes, to substitute smaller prawns (whole and tails) for marine shrimp tails at comparable prices, to conduct market surveys with different kinds of prawn products, and to develop educational and promotional programs to increase the demand for cultured prawns. In addition, methods must be devised to improve mechanical handling and sorting of products, packaging, quality, consistency, and shelf-life.

Heavy demand has resulted in the development of major lobster fisheries with an estimated annual production of almost 181,600 metric tons (400 million pounds) (103). Annual consumption of the American lobster (*Homarus americanus*) in the United States is 22,680 metric tons (50 million pounds), of which 9,072 metric tons (20 million pounds) are imported. Various projections indicate that by 1985 another 18,144 metric tons (40 million pounds) of lobster will be needed to meet domestic demand.

Lobsters

Analysis of catch statistics shows that these fisheries are harvested at or near maximum sustainable yields (16), an especially severe problem for the American lobster, whose populations are on the verge of a major decline. Since 1955, annual U.S. landings have been fairly constant at approximately 13,620 metric tons (30 million pounds), but fishing efforts have quadrupled (40). This reduction in catch per unit effort indicates that the fishery is being maximally exploited and that intensification of harvests will probably have a negative impact. At least 90 percent of the lobsters at legal size are caught each year (29), and most of the females that are trapped have never reproduced. Therefore, a relatively small natural perturbation could cause an economically catastrophic decline in the fishery.

Awareness of the limits of the fishery has stimulated strong commercial interest in lobster aquaculture. Lobster has a high income elasticity, and per capita income influences demand. However, projected aquacultural production of lobsters should not significantly affect prices (50). Therefore, lobster aquaculture does not compete with the fishery but is a new, unique marine industry with expanded employment opportunities. In addition, the biological information resulting from research on lobster aquaculture may be important to rational management of the lobster fishery.

The basic technology for lobster aquaculture is available, but a number of problems hinder rapid commercialization. An economically viable production facility will require a multimillion dollar investment, so uncertainties of the reliability of the present technology must be resolved before an industry will make this commitment.

Sea Grant research and efforts by Canadian scientists and private firms have developed the technology of lobster aquaculture to the degree that commercialization is feasible during this decade. However, research is needed to improve the reliability of aquaculture in such areas as feed formulation, control mechanisms for timing reproduction, and improved understanding of growth physiology. Research in genetic improvement leading to domestication and disease control has long-term significance to commercial lobster aquaculture and has been supported by Sea Grant in the past.

If these problems are appropriately addressed by a combination of academic and commercial interests, U.S. aquaculture could produce at least 4,540 metric tons (10 million pounds) of lobsters annually by 1990. Critical to reaching this goal is the initiation of large-scale production during the next few years.

Research Needs

Reproduction. Recent research has demonstrated that photoperiod is a major factor in regulating egg extrusion, but further work is needed to refine control of the reproductive cycle. Work is in progress on domestication of the lobster through development of hybrids (56), and a long-term research commitment is necessary. At present, failures at crucial stages of the reproductive cycle hamper effective selective breeding programs. Hormonal control and the interaction of growth and reproductive processes with each other and with environmental factors must be understood before domestication is possible. Specific dietary research is needed to develop appropriate rations for broodstock. Research must aim at clarifying the role of lipids and lipid-soluble vitamins in the reproductive physiology of lobsters. Research to develop techniques for fertilization and incubation would remove the constraint of maternal care, decreasing the time needed to domesticate the lobster.

Nutrition. Lobsters can be reared commercially with a variety of fresh and frozen organisms for food, but uncertain supplies and the difficulty of developing automated feeding systems for such feeds make feed formulation a prime requisite for industrialization. Before this critical advance can be made, nutrient requirements must be defined. Rapid progress in this area depends on solving the problem of the delivery of water-soluble nutrients. At present, reasonable growth rates are obtained only if diets include feeds in which vitamins are naturally bound (32). The delineation of specific nutrient requirements using such complex feeds is difficult and time-consuming. Therefore, until reliable systems for the delivery of water-soluble nutrients are developed, progress in lobster nutrition will be slow. The rapid leaching of water-soluble nutrients, particularly vitamins, is a problem in all crustacean nutrition research, and its solution should be given high priority. Effective use of funding dictates that such research be conducted between all Sea Grant-funded investigations of crustacean aquaculture.

Growth physiology. Individual holding will probably remain a requirement of lobster aquaculture and is a major part of the large initial capital investment. Container size affects growth of the American lobster, but the reason is not entirely known. Recent research indicates that larger lobsters inhibit the growth of smaller lobsters downstream, compounding the problem. More research is needed on the relationship between growth and such culture parameters as space, water flow rates, dissolved oxygen and water depth to minimize investments relative to individual containers and space, and to enhance the economic feasibility of lobster aquaculture. Hormonal control of growth should be studied because of its potential economic benefits.

Disease control. Control of diseases in production systems is crucial. Shell erosion, a chronic problem, will become more critical as desirable broodstock is held for longer periods. Shell erosion also influences marketability and probably predisposes the animal to other infections (42). The possible devastating impacts of various *Vibrio* bacteria are of particular concern.

Disease control is probably closely tied to good water quality. Characterization of lobster wastes and how they influence growth and health are important for refinement of experimental techniques and for design of wastewater treatment facilities for commercial culture.

Cooperation between Sea Grant and industry. Much of the technology of lobster aquaculture still must be tested commercially. Cooperation between Sea Grant researchers and industry is essential if maximum benefits are to be obtained. Formal communication between these groups should foster this cooperation and meet the sometimes contradictory needs of academic and proprietary research. For lobster aquaculture, this research must be coordinated beyond the regional level, and imaginative mechanisms of support must be developed to demonstrate the economic feasibility of large-scale production.

Marine Fishes

Aquaculture of marine fishes in the United States has not developed, primarily because information about their culture is inadequate, and natural supplies have met demands. In the early 1970s, prices of the marine fishes of potential aquacultural interest were so low that commercial culture was infeasible. Currently, however, prices of many marine fishes are at least as high as those of such commercially important species as the channel catfish and trout.

Because eggs of marine fishes are so small, mortality in aquaculture is high before the fish have adapted to prepared feeds. High fecundity somewhat offsets the problem, but rapid development of commercial culture requires good survival from hatching to the fingerling stage. High fecundity means that small numbers of broodstock can produce all the fish required for even a relatively large farm. Selective breeding has not begun with marine finfishes of aquacultural interest, but significant improvements in growth, survival and disease resistance could result from genetic and selective breeding studies.

Aquacultural status and problems are described for promising species below.

Atlantic Coast

The summer *(Paralichthys dentatus)* and southern *(P. lethostigma)* flounders are promising species for aquaculture. They are hardy, relatively fast-growing, sedentary and highly marketable (11). Many problems with spawning and rearing have been or are about to be solved. (For a more detailed discussion of the aquaculture of the southern flounder, see "Gulf of Mexico," below.)

The black sea bass *(Centropristis striata)* is fast-growing and exceptionally hardy. It is primarily benthic, so it may not require excessive space in an aquacultural system. It has spawned and been reared successfully in captivity.

The cobia *(Rachycentron canadum)* is a highly prized food fish with exceptional growth rates. However, information is scanty concerning spawning and the rearing requirements for eggs and larvae.

Aquaculture of the weakfish *(Cynoscion regalis)* and the spotted seatrout *(C. nebulosus)* has received little study. However, their high marketability and life histories suggest that they offer good potential. (See also "Gulf of Mexico," below.)

Reeffishes, particularly the snappers, are good aquacultural prospects, primarily because of their marketability. Spawning requirements and larval rearing for the red snapper *(Lutjanus campechanus)* are under investigation (12). (For a more detailed discussion of aquaculture of the red snapper, see "Gulf of Mexico," below.)

The vermilion snapper *(Rhomboplites aurorubens)* may be superior to the red snapper for aquaculture because it grows fast and matures early. Also, it is primarily benthic, which indicates limited space requirements. It is sometimes pelagic, which may allow more intensive use of culture space. A lower-order carnivore, it consumes macrozooplankton and may be less expensive to feed than related species, which are higher on the food chain.

Gulf of Mexico

The red drum *(Sciaenops ocellata)* is a popular sport and food fish and has been studied intensively by aquaculturists. The fish has responded well to spawning and culture techniques (11) and grows rapidly.

The best source of red drum broodstock is wild fish, but it has been reared to maturity in closed systems. It reaches maturity at about five years of age. Spawning has been induced hormonally, but natural spawning induced by manipulation of photoperiod and temperature results in more eggs and fry than hormonally induced spawning. Continuous year-round spawning has been achieved (9).

Larvae have been reared in glass and fiberglass tanks ranging in size from 40 to 2,400 liters (10.6-634 gal). Eggs have been hatched at salinities from 10 to 40 o/oo and at temperatures from 10 to 31°C (68-87°F). Optimum salinity and temperatures have been determined, but tolerances and optima of dissolved oxygen, pH and other water quality parameters are not yet known.

Red drum larvae have been successfully reared with rotifers *(Brachionus)* and wild plankton as food (11). Fingerling red drum have been reared successfully in ponds from two-day-old fry. Fry feed on plankton for the first two weeks and then on commercial feeds. Research is in progress on culture in closed systems and raceways. Fingerlings have been pond-reared in 220 days to a weight of 0.5 kg (1.1 lb) with food conversion ratios of two-to-one (g feed/g weight increase).

Two pathogens of the red drum have been identified. *Vibrio anguillarum* is successfully treated with terramycin at 2.5 g/45.3 kg for 10 days, and *Amylioodinium* sp. is successfully treated with 2 ppm copper sulfate.

The red snapper *(Lutjanus campechanus)* has been induced to spawn in captivity by temperature and photoperiod manipulations (12). The number of fertilized eggs has been extremely small, however, and attempts to rear the larvae for more than 10 days have failed.

Juveniles collected from the wild have been reared in captivity. They feed readily and grow at a rate of 0.4-0.5 percent of their body weight per day. The lower temperature limit for juveniles is 10°C (50°F). The upper limit is not known, but good growth occurs at 30°C (86°F).

No disease problems have been reported. Treatment of external parasites with 25 ppm copper sulfate for two hours has no adverse effects.

When research on spawning and larval rearing is complete, the red snapper should be an excellent aquacultural prospect. Natural populations could be increased by the release of aquacultured juveniles, an important consideration for the red snapper because its populations are easily overfished. (For additional information about aquaculture of the red snapper, see "Atlantic Coast," above.)

The spotted seatrout *(Cynoscion nebulosus)* is a highly valued foodfish, but its slow growth may deter commercial culture. Broodstock is easily captured in bays year-round. It can be maintained in large tanks and fed live or frozen shrimp, mullet or squid. Broodfish should not be handled.

Spotted seatrout may be induced to spawn by photoperiod and temperature manipulations or by hormone injection (10). Photoperiod- and temperature-induced maturation produces more fry over a longer period of time.

Larvae can be reared in glass aquaria or fiberglass tanks. Stocking density should not exceed five individuals per liter. Fry readily feed on rotifers. Fingerlings have been reared in tanks, but cannibalism is a major problem. Pond culture is most successful when 6- to 10-day-old fry are stocked, although survival barely exceeds three percent (31).

Spotted seatrout must be transported without anaesthetics because even small doses are lethal. Loading densities for transport have not been determined.

Florida pompano *(Trachinotus carolinus)* have been induced to spawn in captivity by temperature and photoperiod manipulations and by hormone injections, but larval rearing has not been successful. These studies used juveniles seined from the surf in the spring and summer. The temperature limits for rearing range from 10 to 37.8°C (50-100°F). Pompano can tolerate dissolved oxygen levels as low as 2.5 ppm. High turbidity and rapid pH changes do not adversely affect cultured pompano. Juveniles readily take prepared feeds, and growth rates of 454-960 g/year (1-2.1 lb/year) and 2.5-3 cm/mo have been reported.

Problems in pompano aquaculture include their constant swimming, which uses energy, their tendency to jump out of rearing tanks, and death at low temperatures. The pompano has been cultured with striped mullet, oysters, blue crabs, southern quahog and penaeid shrimp.

The southern flounder *(Paralichthys lethostigma)* has been raised in captivity, although techniques need much more attention. Fertilization rates have been low, only 30-50 percent. Hatching success is also low, between 6 and 35 percent. Metamorphosis begins in 40-47 days after the larvae have grown to 8-11 mm. Larvae eat brine shrimp nauplii, but juveniles do not readily take prepared feeds. Nothing is known about diseases, rearing densities or nutrient requirements of the southern flounder (see also "Atlantic Coast," above).

Pacific Coast and Hawaii

The fry of the mullet *(Mugil cephalus)* is a hardy baitfish used by Hawaii's skipjack tuna and surface albacore fisheries. The potential for the development of a successful aquacultural technology is now being evaluated. Much of the basic research on spawning and larval rearing is complete. Progressive refinements in hatchery technology and spawning techniques will permit the construction of a large mullet hatchery.

A hypothetical five-year research investment of $1 million and $1.5 million for facilities would directly and indirectly produce 200,000 kg (440,529 lb) of mullet fry. This amount of bait could harvest 4 million kg (8.8 million pounds) of tuna, based on an estimated 1 kg (2.2 lb) of bait to catch 20 kg (44.1 lb) of skipjack. The present price of skipjack in Honolulu is $1,213/metric ton ($1,100/ton). The 200,000 kg of bait would result in nearly $10 million in increased fish-handling revenues in Hawaii and West Coast ports. Using a multiplier of 4.2 on the expressed value of $10 million yields a first-order estimate of $42 million/year associated with the increased landings.

No negative economic, social or environmental impacts should result. Wastewater will be used to enrich other aquacultural systems, such as clam or shrimp facilities.

Research is needed in the physiology of gonadal maturation, larval nutrition, and genetics.

The milkfish *(Chanos chanos)* is one of the main seafoods of several densely populated Southeast Asian countries. Milkfish larvae are among the fastest growing and hardiest of marine fish larvae. Milkfish fry are also the most important live bait for the tuna fisheries of many countries. Raising the fish from fry to adult in three years presents almost no problem because they feed on plant matter and detritus.

The main impediment to the production of milkfish fry is in the control of gonadal maturation. Females spawn easily if they are gravid when collected, but spawning in captivity requires control of gonadal maturation, possibly with luteinizing hormone/releasing hormone or an analog.

The primary markets for milkfish fry are American and foreign fishing vessels. The Hawaiian fishery alone requires 227 metric tons (500,000 lb) of baitfish per year. Japanese tuna boats buy bait near Japan for about $4.40/kg ($2/lb) and catch about 11,350 metric tons (25 million pounds) of tuna near Hawaii each year. If milkfish were available at the same price, fishermen would buy as much as 227 metric tons (500,000 lb) a year, creating a sustainable million dollar industry.

No negative economic, social or environmental impacts are expected. Wastewater will be passed through other aquacultural systems.

The dolphin or mahi mahi *(Coryphaena* spp.) is an excellent foodfish that is easily filleted and yields delicious white meat when cooked. In Hawaii alone, between 2,270 and 2,724 metric tons (5-6 million pounds) are consumed annually. Of that amount, 90 percent is frozen and imported, reflecting substantial demand for more fresh dolphin in Hawaii. In the United States consumers would readily accept a white-fleshed fish such as the dolphin.

Commercial dolphin aquaculture could be established within the next five years. Controlled spawning, successful larval rearing, acceptable growth and food conversion rates, and control of the life cycle, the greatest technological problem of aquacultural development, have already been attained for the dolphin.

Research is needed to refine culture methods and determine economic feasibility. Returns from such research would be more direct than basic research on "new" species.

Land-based dolphin aquaculture will be very intensive, requiring small areas of land. Much high-quality water will be needed, but wastewater will be fairly clean and used to fertilize other aquacultural systems. The dolphin is distributed worldwide and therefore will present no importation problems. Because of its behavior and wide distribution, no established commercial fisheries for the dolphin exist in the United States. Aquacultural production would not compete with fisheries.

Anadromous and Catadromous Fishes

Anadromous fishes spawn in fresh water and mature in salt water. Catadromous fishes spawn in salt water and mature in fresh water. Therefore, aquaculture of anadromous and catadromous fishes requires both types of water.

The migration of anadromous fishes to fresh water to spawn facilitates their capture and harvest, making them among the most valuable species for commercial, recreational and subsistence fisheries in the United States. In 1980 the landed value of Pacific salmon was almost one-third that of the total value ($1.1 billion) of finfish landings of the U.S. fishery (102).

These fishes are among the most heavily exploited recreationally and commercially. Major private and public investments have been made for the development of the aquaculture of Pacific salmon, and initial research on sturgeon and striped bass indicates that their aquaculture could enhance fisheries and help meet the increasing demand for products derived from these fishes, such as sturgeon roe for caviar.

A catadromous species whose aquaculture is an important part of the Sea Grant research program is the American eel.

Production and aquacultural technology are discussed below for salmon, sturgeon, the striped bass and the eel.

Pacific Salmon

Of the species whose natural populations are augmented by aquaculture, Pacific salmon *(Oncorhynchus* spp.) offer the greatest potential due to their value and social acceptability and because vast increases in production are possible.

The Pacific salmon fishery is the second most important U.S. commercial fishery. For example, the 1980 ex-vessel value of the 279,000 metric ton (614 million pound) catch was $350 million, 31 percent of the volume and 34 percent of the value of all edible fishery products landed in U.S. waters that year (102). In addition, salmon export is vital to U.S. interests. In 1979, salmon export yielded $404 million and in 1980, $357 million, 40 and 39 percent, respectively, of all edible fishery product exports (102).

Pacific salmon support sport and subsistence fisheries from mid-California to the Arctic Ocean and a rapidly expanding fishery in the Great Lakes. In 1978 the value of the salmon catch in Washington was about $160 million for 4.7 million fish, of which the recreational fishery contributed $41.7 million, about 26 percent (136). These estimates are probably conservative. Economic activity generated in coastal towns and manufacturing centers for salmon sportfishing gear may increase the value of the sport fishery to that of the commercial fishery. The value of the combined salmon fisheries is much more than $1 billion a year. Increased development of salmon aquaculture would increase this value.

Between 1970 and 1975 the average yearly landing of salmon was 600,000 metric tons (about 1,321 million pounds), only two-thirds of the landings between 1935 and 1939, the most productive era of the fishery (43). Carrying capacities of habitats of the various species are not known, but only aquaculture can enhance the fisheries, because much of the fresh water that allowed such high production in the 1930s is either no longer accessible or of such low quality that it cannot support such levels of natural production.

Aquacultural production of Pacific salmon is described in four categories, depending on the source of financial support of the facility and the method of operation: (1) public hatcheries supported by state and federal agencies; (2) private, non-profit hatcheries supported by private funds (Alaska); (3) private, for-profit hatcheries supported by private funds (Oregon and California); and (4) marine net/pen facilities supported by private funds and completely captive-rearing.

Publicly supported salmon hatcheries practice "ocean ranching." Adults are spawned and young hatch and are reared in fresh water. The young are released when they are ready to migrate to sea, and the harvested product is the larger immature fish in the ocean or the maturing fish as it migrates to fresh water to spawn. The publicly supported salmon hatcheries in Alaska, California, Idaho, Oregon and Washington are among the most technologically advanced in the world, operating on favorable cost/benefit ratios (134,135).

In 1979-1980, more than 467 million salmon were released from these hatcheries (see Table 12) (3). In 1980 the commercial fishery harvested almost 279 metric tons (613.8 million pounds), worth more than $352 million to the fishermen (102). Also, sportfishermen catch more than 2.1 million salmon annually (103) with a value of more than $200 million. The contribution of the public hatcheries to both fisheries depends on species and location. For example, in Puget Sound, hatcheries contribute an estimated 50 percent of the fishery catch of coho salmon (89). The spring chinook fishery in Oregon's Willamette River relies almost totally on hatchery-produced fish (28).

In Alaska and Oregon, changes in the laws governing ownership facilitated private ocean ranching of Pacific salmon, allowing their private rearing, release and recapture (94). In Alaska, hatcheries must be non-profit, and six hatcheries currently operate as fishermen's cooperatives, augmenting the local commercial fishery. In 1980, 1.5 million adults returned to the hatcheries, and 35.7 million young were released (see Table 13) (3). The contribution of these hatcheries to the commercial fishery has not been assessed, but data from 1981 indicate that harvests were larger than average in some areas where hatcheries are located.

In Oregon, 12 private salmon hatcheries operate for profit, regulated by the Oregon Department of Fish and Wildlife. One small experimental facility under private ownership operates in California. These facilities recapture and sell bright adults that are returning to fresh water to spawn. However, releases from hatcheries also augment the commercial fishery. In 1980 the Oregon facilities released more than 16.5 million young (3). Although it is too early to determine the level or value of production by these firms, estimates of private investments in the hatcheries exceed $50 million, indicating industrial interest and anticipated returns.

Other North Pacific states have not yet passed legislation to permit private ocean ranching of salmon. However, in Washington marine net/pen culture is practiced. Fish are reared in fresh water until they are ready to enter salt water. Then they are placed in floating net/pen enclosures to grow in salt water. The salmon are harvested at 350 g (0.77 lb) and sold as plate-sized fish. The largest net/pen operation produces about 863 metric tons (1.9 million pounds) of salmon annually, with a wholesale value of approximately $2.25 million.

Pacific salmon introduced into the Great Lakes now support a sport fishery worth about $600 million per year. Hatchery-reared stocks must be used because natural reproduction contributes less than 25 percent of the recruitment to the fishery (14). This fishery will continue to rely on production by Pacific Coast and local hatcheries.

Return on this investment is quite good, primarily because survival in the Great Lakes is higher than in the marine environment. In addition, the salmon control the alewife *(Alosa pseudoharengus)*, whose periodic die-offs foul Great Lakes beaches, causing losses of millions of dollars in tourist revenues (121). The potential of the Pacific salmon industry in the Great Lakes is not known because the carrying capacity of the Lakes is unknown. However, stocking rates have increased consistently since 1967, apparently limited by funding levels of the hatcheries.

Table 12. Salmon releases from public West Coast hatcheries in 1979, in millions of fish.

State	Summer Chinook	Spring Chinook	Fall Chinook	Coho	Chum	Sockeye	Pink	Total
Washington	3.17	15.68	122.37	67.55	89.23	10.09		308.09
Oregon		11.20	30.40	14.60	0.90			57.10
Idaho	0.12	5.30	0.22	1.03				6.67
Alaska		5.88[1]		1.67	9.77	9.26	31.46	58.04
California			36.16	1.28				37.44

[1] All chinook returns combined.

Table 13. Salmon releases and returns, in numbers of fish, for private, non-profit hatcheries in Alaska, 1979-1980.

	1979		1980	
Hatchery	**Releases**	**Returns**	**Releases**	**Returns**
Alaska Aquaculture Foundation, Inc.				
Pink	2,000,000		250,000	800
Douglas Island Pink & Chum, Inc.				
Pink	2,200,000	10-20,000	2,178,500	5,000
Chum	50,000		224,104	
Total	2,250,000	10-20,000	2,402,604	5,000
Prince William Sound Aquaculture, Inc.				
Pink	23,000,000	500,000	21,576,000	1,493,090
Chum	250,000		395,000	1,390
Total	23,250,000	500,000	21,971,000	1,494,480
Nerka, Inc.				
Pink			200,000	450,000
Sheldon Jackson College Aquaculture Program				
Pink	2,500,000	45,000	7,650,000	5,540
Chum	600,000		50,000	200
Coho			12,196	
Total	3,100,000	45,000	7,712,196	5,740
Southern Southeast Regional Aquaculture Association				
Chum			2,672,000	
Coho			549,000	
Total			3,221,000	
Total, All programs				
Pink	29,700,000	558,000	31,854,500	1,504,880[1]
Chum	900,000		3,341,104	1,590
Coho			561,196	
Grand Total	30,600,000	558,000	35,756,800	1,506,470[1]

[1] Excludes returns to one firm, which are not yet derived from culture.

Until recently, most physical and monetary resources to support salmon aquaculture were provided by public agencies (132). The salmon aquaculture industry annually invests an estimated $1.5 million in research and development, much of which focuses on practical problems encountered in individual facilities. The work emphasizes operational problems, such as developing methods to supply adequate oxygen to rearing containers with high densities of fish, or devising more efficient techniques for treatment and care of fish.

Industrial research also emphasizes technical services. The types of programs are a function of available talent and need and include such problems as evaluation of diet quality, diagnosis of diseases, and engineering modifications.

The salmon aquaculture industry also supports federal and university programs with "seed money" and matching funds. Ocean ranching companies endeavor to understand factors affecting marine survival of salmon, to determine the carrying capacity of marine waters, and to evaluate the contribution of adult salmon to commercial fishing. The marine net/pen industry provides resources for genetic research to develop broodstocks and for nutrition work to determine dietary requirements for broodstock.

As the salmon aquaculture industry develops further, products and markets will diversify. For example, the 350-g, single-serving salmon was not available before this type of aquaculture came into practice. The economic consequence is a new source of financial development and additional industrial stability.

Adverse environmental impacts of salmon aquaculture are minimal. The industry uses and improves a natural resource. The impacts resulting from the concentration of effort needed for efficient operation are being addressed and solved by current technology.

Aquacultural production of salmon increased from 1,090 metric tons (2.4 million pounds), worth $900,000 in 1979, to 3,450 metric tons (7.6 million pounds), worth $3.4 million in 1980 (102). If the industry continues to grow at this rate it will soon be a major contributor to the U.S. economy.

Research Needs

Fry and smolt management. The quality and quantity of Pacific salmon reared in aquaculture depend on successful rearing of young in fresh water. Research has emphasized this stage of the salmon's life history, but before the industry can become economically viable, research must determine release strategies to maximize survival in the ocean, identify imprinting requirements, diagnose and treat diseases, and determine nutritional requirements.

Growth, behavior and physiology can be modified in the hatchery by environmental control, feeding and genetic selection. However, the effects of these alterations on salmon survival after its release and on its return migration are not known. Research is needed to isolate, study and apply the factors that affect the growth, behavior and physiology of salmon in aquacultural facilities.

Nutrition. Nutritional requirements for growth of young chinook and coho salmon have been tentatively established, but they are unknown for pink and chum salmon. In addition, the role of nutrition in animals under stress, which may result from situations such as high-density rearing, has not been adequately studied. Research is needed to determine dietary requirements at various life stages and under the environmental conditions of the hatchery.

Routine microchemical tests must be developed that can determine the nutritional status of the animals and detect nutritional deficiencies before they produce clinical symptoms, at which time the animal may be beyond treatment.

Fish meal, the main protein supplement in salmon diets, is no longer a primary product of many fisheries. For example, the major product of the Pacific herring fishery is now herring roe. As a result, herring meal is no longer made from the entire fish, and its nutritional characteristics have changed. Increased demand for high-quality fish meal for production of other types of animal feeds and for increased salmon aquaculture heighten this problem. Therefore, other fishes are made into meal for salmon feeds. These factors have changed the nutritional characteristics of open-formula salmon diets. Research is needed to formulate new diets and to investigate alternate dietary ingredients, such as fish-processing wastes or "by-catch" from the commercial fishery.

Ecological studies. Much of the salmon aquaculture industry uses the ocean as a pasture for aquaculturally produced fish. However, the impact of this large number of fish on the system is not known, and interactions between aquacultured salmon and other species have not been documented. The capacity of the ocean to support these fish is unknown, and the impact and importance of genetic interchange between hatchery-produced salmon and natural populations must be evaluated. Knowledge of the effects of ocean ranching on the ecosystem could eliminate some overregulation and allow more complete utilization of the environment.

These studies must be multidisciplinary and needs in various regions will differ. Therefore, specific studies should be funded, such as an investigation of factors that determine survival of salmon smolts in the transition from fresh to salt water.

Genetics. Basically, salmon aquaculture raises a wild fish. Reliance on the availability of eggs from public sources limits production because some areas have periodic shortages. Further, imported stocks generally exhibit suboptimal production in a new environment, and these stocks are not domesticated. Domestication would produce salmon strains that are more productive than the wild strains. In addition, interbreeding of released fish with the natural population, caused by migratory straying, could result in a loss of genetic variability that will be needed in the future. Thus, studies are needed to assess the genetic impact of interbreeding between cultured and natural stocks.

Disease and parasite control. Prevention is the most effective means of disease control. For salmon, the method varies among hatcheries, species and stocks. Research is needed to identify conditions that promote disease outbreaks and methods to eliminate them. At present, only a few drugs are certified for foodfish, but more are urgently needed. Also, while a limited number of vaccines have been successful, work is needed to broaden the spectrum of diseases treated to make vaccines more effective. Furthermore, detection and evaluation of specific diseases are often slow and costly. Better, more efficient diagnostic methods are needed.

Sociopolitical considerations. A clear definition of their roles in ocean ranching has not yet developed between the private sector and public agencies. In the past, the salmon resource has been supported by public agencies and has been considered common property. Serious questions have arisen concerning the role of private enterprise in salmon ranching, and opposition by commercial fishermen and environmentalists have kept private enterprise from entering the field (69).

Accurate data and predictive economic models regarding salmon aquaculture are lacking. Commercial fishermen are concerned that the market will be overwhelmed with salmon from aquaculture, resulting in decrease of ex-vessel price.

Striped Bass

The striped bass *(Morone saxatilis)* supports one of the most important sport and commercial fisheries in the United States. In 1980, the recreational catch on the East and Gulf Coasts was 1.2 million fish, with a total weight of more than 1,100 metric tons (2.5 million pounds) (102). The commercial harvest accounted for 2,000 metric tons (4.5 million pounds), at a total ex-vessel price of $4.09 million (102). However, the striped bass has not produced a dominant year class since 1970, and increased fishing pressure has decreased the standing crop, creating concern for future supplies (45).

The range of the striped bass originally extended along the Atlantic Coast from the St. Lawrence River south to the St. John's River in northern Florida, and along the Gulf Coast from western Florida to Louisiana (127). In 1879 and 1881, yearling striped bass from New Jersey's Navesink River were released in San Francisco Bay. On the West Coast the bass' range now extends 40 miles south into Mexican waters and north to British

Columbia, but the only important bass populations and fisheries in the West are in the Sacramento/San Joaquin estuary in California and in the Coos and Umpqua Rivers in Oregon (126). The striped bass has also been used successfully to enhance freshwater sport fisheries in 17 states (127).

At present, the major market for aquaculturally produced striped bass is for fingerlings to enhance recreational and commercial fisheries. The annual demand for this product may be as many as 250 million fish. The success of this effort to improve the catch in various areas of the country would increase economic returns in many sectors. The popularity of striped bass as a sport fish and its demand and price on the commercial market would ensure a viable market.

The best estimate of economic return is derived from the increase in the recreational fishery expected to result from nursery production of fingerlings. In 1975, 22 million man-days were spent fishing for striped bass in sea-run fisheries (38). The program outlined below would increase this participation by at least 25 percent. This would allow another 5.5 million man-days per year of sea-run angling, which, at an estimated value of $20 per day, would equal $110 million per year. A similar increase in value would be expected for inland waters. The overall projected return totals $220 million per year. The development of a successful foodfish production system and the augmentation of the commercial fishery would increase the economic return value even more, but lack of data precludes estimating how much.

Environmental impacts of stocking striped bass into natural waters must be considered. For example, transplants of the fish into non-native habitats may result in hybrids that, if fertile, could negatively affect natural production.

The development of net/pen culture of striped bass and striped bass hybrids is a potentially viable industry. Conflicts are possible, such as impairment of navigation or conflict between public and private users of estuaries, but with proper planning these can be minimized or eliminated.

The economic and social impacts of striped bass aquaculture should be positive. Increased returns of this highly desirable fish will improve and stabilize striped bass fisheries and positively affect related industries.

The adaptability of the striped bass and high consumer demand indicate a promising outlook for commercial aquacultural development. At present, full-scale hatcheries in at least 13 states produce more than 15 million fingerlings annually (15). The fingerlings are used to enhance recreational fisheries in estuaries and reservoirs and commercial fisheries in estuaries. The potential exists to at least double that production.

Commercial grow-out systems to produce market-sized, 2- to 3-pound fish show promise for development. Although a major foodfish aquacultural venture in the United States failed in the mid-1970s, recent advances in technology and markets have improved the outlook for striped bass aquaculture. At present, three commercial organizations are investigating the feasibility of producing marketable striped bass in captivity.

Research Needs

Genetics and broodstock development. The major constraint to private striped bass aquaculture is that seedstock is scarce and its production levels vary. This problem is multi-faceted, and development of a satisfactory broodstock will require more than five years. A few short-term investigations, however, should address the problem now.

At present, the only source of gametes is mature adults from wild populations (15). As a result, a constant supply of gametes is not available, which decreases quality control of the aquacultural product and retards industrial expansion of the industry. Research is needed to genetically characterize the stocks, determine those that are amenable to culture, and develop selected stocks for gamete production. For salmon, quality of the fry produced can be improved if the broodstock's genetic background is known.

Hybrids, especially the *Morone saxatilis* X *M. chrysops* (white bass) hybrid, exhibits consistently higher post-stocking survival and growth than the pure striped bass (127). A more detailed understanding of the population structure would provide guidance on the choice of stocks for culture.

Intensive larval culture. Intensive culture of striped bass larvae is almost competitive with pond culture (126), but its application is still limited. The critical period is the 40-day period during which larvae grow to 1.5- to 2-in fingerlings. Survival during this period averages only 30 percent (128). Research is needed to devise methods that will ensure predictable fingerling production. Physical and environmental requirements of the fry during this period must be defined, and physiological and nutritional requirements of larvae must be determined. Advances in feed formulation, disease control and culture technology would allow application of intensive techniques at any location and reduce the costs of hatchery operation.

Improved efficiency in pond-rearing fingerlings. Under present management, survival in culture ponds ranges to more than 50 percent, averaging 10-25 percent (15). The causes of this variation are not known but may involve variation in quality of the zooplankton used for food, variation in fry quality, and subtle differences in biological condition at stocking. Research being conducted in this area should solve these problems within five years.

Commercial grow-out systems with artificial feeds. Most effort on the culture of striped bass has been directed toward enhancing natural stocks (15). However, recent work with enclosures like the net/pen system used in salmon aquaculture indicates some promise for complete culture in captivity. Stocking rates, water requirements, feeding rates, dietary requirements, and other conditions must be determined to make this technique feasible within five years.

Reproductive physiology. The use of hormones for inducing maturation in the striped bass is routine (127), but information is still needed on the environmental requirements that will ensure maturation and spawning of adults reared in captivity. Also, research on gametogenesis is needed to guarantee the production of high-quality gametes.

Pathology. Diseases, especially those caused by bacteria, are a primary limiting factor in aquaculture, particularly in the early rearing of striped bass in ponds (128). Few drugs and chemicals are available for disease control because of stringent regulation by the Food and Drug Administration. Research is needed to define management methods that reduce disease, to provide rapid diagnosis, and to develop new drugs, chemicals, and other disease control measures for ponds and recirculation systems.

Sturgeon

Eight species of the sturgeon family are found in the United States, and the four most abundant ones are being considered for aquaculture. They are the white *(Acipenser transmontanus)*, lake *(A. fulvescens)*, and Atlantic *(A. oxyrhynchus)* sturgeons and the paddlefish *(Polydon spathula)*.

The demand for sturgeon is increasing. In 1979, the sport catch was about 210 metric tons (460,000 lb), and the commercial catch was more than 240 metric tons (534,000 lb) (52). In 1980 sportfishermen made 100,000 trips for sturgeon, accounting for 57 percent of the sportfishing trips made on the Columbia River that year (66). Similar increases in the sturgeon fishery in other regions have resulted in the establishment of experimental sturgeon-breeding programs in California, South Carolina, Wisconsin and Tennessee.

Sturgeon aquaculture was first investigated in the late 1800s (14), but the first intensive effort to culture sturgeon in the United States was not made until 1979 (3). At that time increased interest initiated programs at the Center for Great Lakes Studies of the University of Wisconsin, Milwaukee, the University of California, Davis, and the South Carolina Marine Resources Institute. These programs have artificially propagated lake, white and Atlantic sturgeons from eggs to juveniles. Also, the paddlefish has been successfully propagated in Tennessee and at Auburn University (120).

The sturgeon is relatively hardy and easily cultured to a marketable size, which further enhances its commercial potential. Initial research on the white sturgeon indicates that culture is relatively easy and that growth rates are amenable to commercial propagation.

The large market and unfilled demand for high-quality sturgeon products further increases its aquacultural potential. Both foreign (primarily European and Japanese) and domestic markets are well established, and sturgeon could provide a valuable export commodity to those markets. Also, a Norwegian firm has provided a $20,000 grant to the Center for Great Lakes Studies for investigations of the biological and economic feasibilities of cage culture of the lake sturgeon (18). The domestic markets for caviar and smoked fish are expanding, especially in large cities. At present, one processor annually sells between 50,000 and 80,000 lb of Columbia River sturgeon annually. A Wisconsin processor has a smoked sturgeon market of at least 45.4 kg (100 lb) per week and has good prospects of expanding his market to other states (18).

An annual demand of 10 to 15 million 3- to 6-in fingerlings is anticipated for stocking lakes and rivers to enhance commercial and recreational fisheries (39). In addition, 1,362-2,270 metric tons (3-5 million pounds) of 1.4- to 2.3-kg (3- to 5-lb) sturgeon could be produced for the fresh and smoked fish markets (39).

Sturgeon are also used in aquaria. This is one of the most financially attractive markets, although there are legal problems with its development, especially for some of the less abundant species, such as the lake and shortnose sturgeons. Fingerlings for aquaria may sell for as much as $20 each. If this market becomes viable, an estimated five million sturgeon could be produced annually (39).

Because the products are unique and valuable, research investment to develop the technology for sturgeon aquaculture is justified by economic returns at almost any level of development. The best information on which to estimate returns is from return statistics from the Soviet Union, where large-scale hatchery production began 25 years ago. Adults are recovered 10-15 years after their release from the hatchery as juveniles, and returns average from one to three percent (14). Hatcheries on the Caspian and Azov Seas operate at 70 percent net profit. Commercial cage culture provides a net profit of 15-30 percent, although the technology is relatively unsophisticated, and the climate is so unfavorable that three growing seasons are required to raise a market-sized, 3-lb fish.

Although these figures cannot be directly extrapolated to sturgeon aquaculture in the United States, they show its potential profitability and can be used to estimate returns for specific regions. For example, if hatchery production provided enough fish to reach the carrying capacity of San Francisco Bay (about 2 million kg), based on a three percent return, seven million 1- to 3-in fingerlings would be required. The cost would be about three cents per fingerling or $210,000/year. Average returns on this investment would be 2 million kg of 8- to 10-year-old, 10-kg (22-lb) fish, at a wholesale price of $4/kg ($1.82/lb). Thus, a return of $8 million would be realized on a $210,000 investment. This level of return would justify a large research investment.

Public and private support for the development of sturgeon aquaculture is widespread in this country. If ocean ranching and stock replenishment were practiced, this support would probably be enhanced throughout the former range of each species. In addition, the development of aquacultural technology is vitally important to safeguard and increase populations of the endangered sturgeon species.

Other types of commercial sturgeon culture, such as cage or net/pen culture, would probably be conducted on private land with good water supplies. Thus, economic impacts should be positive, with minimal negative social or environmental impacts.

Research Needs

Identification and inventory of stocks. Information is needed on the natural biological and genetic subdivision of sturgeon populations, the sizes and structure of the populations, and characteristics of the various stocks. Also, the population dynamics of sturgeon must be studied and incorporated into aquacultural management schemes. This information will be the basis of choice of stocks for aquaculture.

Reproductive physiology. Sturgeon gametes are now obtained by natural or hormonally induced maturation (14). Successful aquaculture hinges on a readily available, predictable supply of gametes, which will be possible only through understanding the sturgeon's reproductive processes. Significant improvements have been made in the induction of ovulation and spermatogenesis in the white sturgeon, in spawning procedures and in the incubation of fertilized eggs. Rates of fertilization and hatching must be improved.

Pathology. Because sturgeon aquaculture is new, research in disease control has been limited. Bacterial and viral diseases prevalent under culture conditions must be defined and diagnoses and treatments documented.

Husbandry methods. Sturgeon life histories are poorly known, so basic rearing requirements have not been determined. General information is available on the influence of factors such as water flow, temperature and stocking density. Research should continue to develop efficient grow-out systems to rear fingerlings, larger juveniles and adults. Feeding behavior of young, rearing procedures, broodstock development, and husbandry techniques require special attention.

Nutrition. Current technology of sturgeon larval feeding requires labor-intensive, costly live foods, such as *Artemia* (14). Artificial feeds have been used with some success (39), and feeding techniques and diet formulation can be defined within five years. Feed will be the major expense in raising sturgeon. At present, no information is available from which to formulate a cost-effective diet. Nutritional requirements must be determined for each stage of the life history and metabolism must be assessed with respect to growth and nutrient utilization.

Education and advisory programs. The public does not understand the aquacultural potential of sturgeon nor the fragile nature of the sturgeon fishery. Programs to educate the public investors could enhance sturgeon aquaculture and determine major directions of research and industrial development.

American Eel

Cultured eels are a high-priced commodity with great demand, especially in Japanese markets. Taiwan is the leader in eel culture, and the annual value of eels exported to Japan is almost $200 million. Some sources predict that demand will annually exceed supply by 75,000 metric tons (16.5 million pounds). Therefore, both price and demand are favorable for the economic success of eel farming in the United States.

Culture of the American eel *(Anguilla rostrata)* is still at the developmental stage. Nine eel farms are located in South Carolina, Florida, Georgia, Guam, Maryland, New York and Massachusetts, only two of which are presently engaged in full-scale production. Annual production is less than 45.4 metric tons (100,000 lb) from less than 20.2 ha (50 acres) of ponds. The limited U.S. eel-farming industry is not directly involved in research and development. In the United States, eel culture is based on successful technology developed in Japan. Because hatchery techniques have not been perfected, all eel culture depends on the capture of juveniles, mostly in the 0-year age class, as they ascend coastal rivers and streams in late winter and early spring.

The captured juveniles are used as seedstock in ponds or raceways. They are fed diets of varying composition until they reach marketable size, between 0.25 and 0.5 lb, in 12-16 months. Systems vary from nearly static ponds to relatively sophisticated recirculating tanks or raceways.

Present obstacles to full-scale development of eel farming in the United States are: (1) lack of a source of seedstock (elvers) from natural waters; (2) a relatively expensive diet, which has not been adequately researched for alternate ingredients and least-cost formulations; (3) lack of knowledge of appropriate stocking densities, expected production rates, diseases and treatments, optimum feeding rates, and system management.

Before eel farming can become a viable industry, the extent, seasonality and cyclic nature of elver migrations must be known, at least until reliable husbandry techniques are developed.

Because feed costs represent approximately one-third of total production costs, the nutritional requirements and feeding dynamics of the eel should be determined so that feeding schedules and formulations can be optimized to improve the prospects of an acceptable profit margin for the farmer.

Finally, management strategies (i.e., stocking rates, water quality maintenance, harvesting, disease recognition and treatment, etc.) should be developed, providing the farmer with a decision-making that will promote economic success.

The establishment of a viable eel-farming industry rests upon the successful and continuing transfer of information and technology via advisory programs. Demonstration facilities are essential. Research and advisory programs related to eel culture must be expanded if the industry is to become self-sufficient within the next 5-10 years.

Great Lakes Fishes and Bait Organisms

Aquaculture contributes to the rural economy of the Great Lakes States. For example, in both Wisconsin and Michigan, annual sales of farm-raised trout exceed $1 million (12, 49). Minnesota baitfish farmers produce fish worth more than $1 million annually; Minnesota produces 80 percent of the world's wild rice crop, some of which is now cultured, and numerous Great Lakes fish farmers raise gamefish and operate fee-fishing ponds (2, 96, 108). The economic impact to the state economies due to transport, processing, sales and support industries is significantly greater than the crop value alone.

In the Great Lakes States, 72 producers raise trout (2, 49, 57, 108). Nationally, Wisconsin ranks fifth in trout production. Trout are sold fresh, frozen, smoked and to operators of fee-fishing ponds. Public hatcheries produce a significant number of trout and salmon for public stocking: Michigan produces 10 million yearlings and 5 million fingerlings; Wisconsin produces 6.7 million fingerlings; Minnesota produces 600,000 yearlings (2, 49, 54). The Wisconsin Department of Natural Resources has suggested that efficient commercial production could lead to revised state policies that would encourage the use of private rather than public production for stocking of game fish.

Recreational fishing on the Great Lakes, their tributaries and nearby areas has a tremendous impact on state and local economies. Baitfish culture, once thought to be profitable only in the South, is an important component of that industry. Total economic impact of local bait production and sales exceeds $50 million. In Minnesota, 35 percent of the fathead minnows and 95 percent of the white suckers are produced in ponds (108). Minnesota has 40 baitfish farmers and Wisconsin has eight active producers. Demand for baitfish far exceeds supply. For example, Ohio baitfish producers meet only 2.55 percent of the demand (57).

Various coolwater and warmwater sportfishes, including muskies, walleyes, northerns, yellow perch, smallmouth bass, largemouth bass, and various species of sunfish and sunfish hybrids, are being raised by 68 private fish farms and public hatcheries in Wisconsin, Michigan and Minnesota (2, 54). State hatcheries annually produce more than 12.4 million coolwater and warmwater fingerlings for stocking public waters. Total production in the private sector is not known because production data reports are not required. Fish produced by the private sector are stocked primarily into private waters and fee-fishing ponds.

Other species are being raised on a limited basis. Yellow perch are raised for food by two farmers in Wisconsin, and carp are raised on two farms in Michigan. Sturgeon, whitefish and bait leeches are raised experimentally and may become economically important in the future.

In recent years the leech *Nephelopsis obscura* (Erpobdellidae) has become the preferred live bait of most walleye fishermen in Minnesota. The leech is harvested from lakes. Although the harvests are not managed, the Minnesota Department of Natural Resources estimates that in 1978, nearly 90.8 metric tons (200,000 lb) of leeches were harvested in Minnesota and sold at a retail value of almost $4.25 million.

The market for bait leeches is confined to the upper Midwest, primarily Minnesota. However, export of leeches to adjacent states began recently and is expected to expand to all areas where the walleye is fished. Also, this bait is expected to become popular for bass fishing and warmwater angling.

Aquaculture of bait leeches is still in the early experimental stage, and industry has not begun research on its development for commercial production. A culture has been established at the University of Minnesota, Duluth, to permit analysis of survival, nutritional needs, growth and reproduction of the leech.

A number of young have hatched from cocoons deposited in captivity and have grown as large as leeches harvested from ponds in late summer. Cocoons have been deposited six months out of phase with the natural reproductive cycle, which means that continuous production in captivity may be possible.

Because the program has been so successful, extensive and pilot intensive culture technologies should be available within five years if certain basic needs are met. Commercial aquaculture of this leech should be possible within 10 years (30).

Aquaculture of the bait leech will relieve harvest pressures on natural populations, which are being depleted. Leech culture would provide a more stable supply of the popular bait to meet demands during the summer. Many private ponds may be converted to leech production by individuals or leased to leech farmers. Management of new or existing ponds would not interfere with aesthetic or recreational uses of ponds because the species is non-parasitic, secretive and nocturnal. In fact, new ponds will only attract wildlife typical of shallow ponds.

Research approaches to the removal of constraints of aquaculture of Great Lakes species are summarized in Table 14 and are described below.

Research Needs

Aquacultural systems. Cold water, insufficient suitable private waters, and hatchery effluent control are major restraints to aquacultural development in the Great Lakes area. Geology and climate cause wide variation in water temperature. The temperature of well and spring water is usually between 7 and 10°C (44.6-50°F). Open water may reach high temperatures during the summer, which can cause stress or death, while low winter temperatures suppress growth and reduce survival.

Standards for effluent quality may constrain aquacultural development. For example, state laws may enforce stricter effluent standards on trout hatcheries than federal statutes because larger volumes of water are involved.

Present production of baitfish in the Great Lakes area is extensive, but water management to increase production is minimal. Optimal stocking densities, fertilization rates, water flow rates, etc., have not been determined.

Bioengineering solutions to water quality constraints include (1) determination of optimum rearing conditions at local water temperatures and volumes; (2) development of alternate rearing techniques, such as energy-efficient water-recycling systems and improved water treatment systems (economically sound methods to heat water, increase oxygen levels, and decrease ammonia concentrations); and (3) development of cost-effective water treatment methods.

Improved baitfish management practices for the Great Lakes area require identification of proper fertiliz-

Table 14. Summary of aquacultural research recommended for Great Lakes species.

Area of Effort	Problem	Target Species	Benefits
Aquacultural Systems	Defining optimum rearing conditions	All species	Cost-effective means of production
	Alternate production techniques	All species	Economic ways to heat water, increase oxygen levels and decrease ammonia levels
	Energy-efficient water re-use systems	Larvae and fingerlings	Minimize water use; control pollution
	Cost-effective effluent treatment	Salmonids	Maintain water quality
	Water fertility	Baitfish	Increase production
	Management techniques	Baitfish	Determine optimum stocking densities; water management to increase production
Genetics	Cryopreservation of gametes	All species	Selective breeding
	Evaluation of strains and hybrids	Baitfish and salmonids	Increased survival, growth, disease resistance
	Management of wild broodstock	Coolwater fishes	Increased survival and quality
	Production of mono-sex populations	Yellow perch	Increased growth
Nutrition	Larval feed requirements and technologies	Coolwater and coldwater fishes	Increased survival and growth
	Nutrient requirements	Baitfish, coolwater and coldwater fishes	Improve feed formulation and lower feed costs
	Hormone supplementation	Yellow perch	Sex reversal
		Salmonids	Increase growth and smoltification
Diseases	Stress analysis	Coolwater and coldwater fishes	Predict disease outbreaks
	Establish certified disease-free hatchery program	Trout	Reduce disease transfer
	Production of disease-resistant strains	Salmonids, baitfish	Increase survival
Public Policy	Policies and regulation inhibit aquacultural development	All species	Identify role of aquaculture and its potential impacts
Economics and Marketing	Economic feasibility studies	All species	Optimize investments and prevent undercapitalization
	Fish farm business management	All species	Maximize producer efficiency
	Consumer education	All species	Increase consumer acceptance and generate demand

ation rates, optimum stocking densities, water management practices, etc., to increase production efficiency and quality.

In experimental leech culture systems, diseases or fungal infections cause high mortality rates, and control measures need urgent attention. Data suggest that mortality is density-dependent, and studies are needed to determine carrying capacities of culture systems. Cannibalism is also a factor. Feeding schedules have been modified in an attempt to alleviate this problem. It occurs most frequently at higher temperatures, so temperature must be monitored and that which deters cannibalism determined. Current studies of leech culture systems include a factorial analysis of the effects of temperature, light and diet on growth, survival and reproduction in the laboratory. Information is needed on minimal water flow, water quality and feeding schedules.

Reproduction and genetics. Most trout cultured in the Great Lakes come from stocks developed in the Northwest. These strains may not be optimal for growth and commercial production in the Great Lakes area.

Baitfish in the Great Lakes States are primarily cultured with wild broodstock, which prevents quality control and can result in lower survival and poorer growth in pond culture. Gravid white suckers are available during only a few months of the year.

Reproductive techniques and broodstock management are not well quantified or controlled for many coolwater and coldwater gamefishes. If wild-spawning individuals at optimum ripeness are not available, production levels are restricted, and progeny survival and growth rates decrease.

Analysis of available strains and development of stocks suitable to the Great Lakes area will improve survival and optimize growth rates for all species being cultured. Current cryopreservation research will let hatchery operators produce fish continually and facilitate selective breeding programs.

Management of wild gamefish broodstock requires special techniques to identify the period of optimum ripeness for production of high-quality seedstock, improving survival and growth rates, and enhancing the quality of recreational fishing.

An alternate method of increasing growth rates is mono-sex culture, which is being investigated for the yellow perch (2).

It must be determined whether or not the bait leech can spawn more than once, and if so, under what conditions. A breeding program to produce a multiple-spawning stock would be a significant contribution to the industry.

Nutrition and diets. Diet costs can account for as much as 60 percent of production costs in aquaculture. In salmonid culture, diets have been formulated based on studies of fingerlings raised at temperatures different from those of culture conditions in the Great Lakes area, perhaps resulting in inefficient feed conversion and slower growth rates. Nutritional requirements for other Great Lakes fishes being raised by commercial or public aquaculture are unknown. Consequently, diets developed for other species are used. Species-specific diets will result in improved feed conversion, growth and fish quality while reducing operating costs. Artificial diets and feeding techniques are unavailable for many coolwater fish larvae, which constrains commercialization and inhibits public hatchery production.

Nutritional studies of bait, coolwater and coldwater fishes throughout their life cycles and at temperatures characteristic of the Great Lakes area will improve feed formulation and decrease costs. Improved feed formulation will increase survival and growth rates.

Steroids can be used to induce sex reversal of larvae to produce mono-sex populations. Anabolic hormones can be used as dietary supplements to maximize protein utilization, resulting in increased growth of all fish. Additionally, dietary hormone supplements can be used to control salmonid smoltification, increasing growth, survival and returns.

Diseases. Fish reared at high densities under intensive culture are more susceptible to disease outbreaks induced by stress. Furthermore, rearing conditions in the Great Lakes area, especially water temperatures, may promote stress-related diseases. Diseases of fishes cultured in the Great Lakes area are poorly understood, and advice concerning treatment is not available.

Diagnostic services for fish diseases are not available to the private sector because the number of pathologists is limited. Most Great Lakes states require that trout be certified disease-free, but certification is not available throughout the region.

Methods should be developed for the prediction of stress-induced disease outbreaks. A readily available disease-free hatchery certification program should be established to reduce the potential for disease transfer.

Genetic programs should be initiated to produce disease-resistant strains of fishes, which may be done by mass selection or cross-breeding.

Economics and marketing. The economic feasibility of expanding current industries or establishing new aquacultural enterprises in the Great Lakes area is not known. Therefore, it is difficult for farmers to obtain financing to expand or initiate businesses. The economics of alternate rearing systems must be evaluated to encourage commercial involvement.

The fish farmer is often hindered by a lack of knowledge in business management and in product and market development. Assistance in these areas is generally unavailable.

Economic feasibility data should be developed to determine financing, production, costs, product demand and marketing potential for expansion of existing facilities and creation of new ones. These data will optimize investment potential and prevent undercapitalization.

Educational programs and materials are needed to train aquaculturists in fish farm business management and to maximize efficiency. Training is also necessary in product and market development because the aquaculturist often processes and distributes his own product.

Consumer education programs should be developed to identify the value of fish as food, to increase acceptance and to generate demand for aquacultural products. An integral component of this program should include handling and preparation techniques to increase acceptance of fish products.

Public policy. Federal, state and local laws constrain the orderly development of an efficient aquacultural industry, and these laws are not uniform throughout the Great Lakes States. Laws and permits that affect potential and existing aquaculturists are poorly defined and not consolidated under one agency.

Inadequate training materials have resulted in inappropriate regulations, poorly trained producers, and unrealistic expectations from the public and private sectors. Most materials developed for other areas of the United States are not transferable to the Great Lakes area without significant modification.

Public values can be changed only by education and public relations. Educational programs and advisory services must be developed to identify the role and potential impacts of aquaculture. An informed public is necessary for the development of progressive aquacultural policies in the Great Lakes area.

Seaweeds

Attached macroscopic and brown algae — seaweeds — are a valuable source of phycocolloids, algal storage products that are chemically extracted and used in diverse food (particularly dairy) and chemical industries (90). The annual harvest of seaweeds in the United States is about 115 metric tons (about 254,000 lb), with a landed value of more than $2 million (133). More than 80 percent of this seaweed is the giant kelp *(Macrocystis pyrifera)*, a major source of alginic acid worth more than $22 million per year (63, 95). The value of carrageenan, a phycocolloid extracted from the red alga Irish moss *(Chondrus crispus)*, is more than $11 million/year (95, 133).

The U.S. seaweed industry is rapidly expanding because of a variety of new applications for phycocolloids, which form colloids in water (63, 133). Growth of the industry depends on a stable, high-quality source of raw materials, which has caused increased interest in unialgal cultivation of seaweeds and in enhanced conservation and managed harvests of natural seaweeds.

U.S. scientists are the world leaders in the field of applied technology of seaweed aquaculture. Placing cost-effectiveness first in evaluating the potential of seaweed culture emphasizes production of biomass per unit area per time period, giving direct, nearly immediate results. Studies have concentrated on seasonal biomass production, life histories, colloid yields and chemical structure, quality and quantity, etc. (91, 92). The most important input from U.S. studies, then, has involved quantitative methods and basic science.

In the United States, studies of the aquaculture of economically important seaweeds began less than 10 years ago and have concentrated on those species that produce phycocolloids with industrial applications (91). Seaweeds are obtained by harvesting wild crops, by culture in raceways in captivity, and on nets or other structures in bays, estuaries and protected open ocean. Experimental ponds, communities of organisms and other arrangements are under study for seaweed culture but are not yet commercially productive.

The only large-scale seaweed culture practiced in the continental United States involves seeding and transplanting *Macrocystis* to revitalize overharvested kelp beds in southern California (21, 95, 107, 133). These efforts are approaching a very sophisticated level. The kelp crop is now successfully managed, but supplies still do not meet industrial demand.

Most other U.S. projects emphasize intensive raceway or tank cultivation of seaweeds of the genera *Chondrus, Gigartina, Gelidium, Eucheuma, Hypnea, Iridaea* and *Gracilaria* (91, 92). Tentative plans have been made to expand the aquaculture of nori *(Porphyra* spp.) in Washington State (92). In Japan, *Porphyra* is a major source of food with a value of $1 billion/year (67, 114). Net or rope cultivation programs for *Iridaea* are also being developed in Washington (91, 92). These programs show potential for producing a domestic source of carrageenan.

Several of these cultivation programs have been cooperative efforts of Sea Grant and industry. For example, industry has subsidized programs for tank cultivation of *Iridaea* and *Gigartina* in Washington State and for *Eucheuma isiforme* in Florida to enhance the development of a domestic source of carrageenan. Foreign sources include politically unstable countries, which makes imports uncertain. Industry typically has begun support of pilot facilities after preliminary ecological, physiological and biochemical studies, supported primarily by Sea Grant, have laid the technological base for successful aquaculture.

One of the most successful cooperative programs between industry, Sea Grant and academia has been developed in the Indo-Pacific, where *Eucheuma* farms produce large quantities of carrageenan (91, 92). Both natural and manipulated habitats are used in these farms. At present, 0.5-ha (1.24-acre) family farms in the Philippines can produce about 22,500 kg (almost 50,000 lb) dry weight of seaweeds in 90 days, from which a dry, salable weight of 2,250 kg (almost 5,000 lb) is recovered (37). The dried crops are sold to U.S. processors. Successful *Macrocystis* programs in California were also developed by a joint effort of industry, state agencies and academic concerns.

The demand for seaweed products depends on the market, the political situation in the foreign countries that are the major suppliers, and the market price. The need for enhanced energy production has stimulated several studies of seaweed cultivation for biomass production and its conversion into methane (91, 92). For example, Jackson and North (60) outlined a variety of information regarding the selection of *Macrocystis* for possible cultivation in offshore "marine farms." In addition, several recent studies have incorporated seaweeds into waste recycling marine polyculture systems (91, 92) to remove inorganic nutrients from sewage effluent and recycle them through commercially viable systems for the aquaculture of oysters, seaweeds, flounder and lobsters. The increased needs for waste recycling and food production have also stimulated seaweed polyculture using artificial upwelling (91, 92). The economic benefits of these projects may balance the cost of their development and reduce their costs.

Enhanced, continued research support by the U.S. government and industry is fundamental to the successful completion of cultivation programs and to the training of future seaweed aquacultural experts. The exchange of scientific information with Asian seaweed aquaculturists is important for further development of seaweed aquacultural programs. Removal of the primary technological barriers will depend on coordinated knowledge of plant growth, reproduction, physiology, biochemistry, ecology and population genetics. Also, a detailed consideration of engineering and economics is critical for enhanced and sustained seaweed aquaculture.

Neushul et al. (106) outlined the critical research needs for the development of a successful U.S. program of seaweed biomass production. Many of these needs are equally relevant to a broadly based seaweed aquacultural program. They emphasized that funding for seaweed research has been minimal, and that this has been a serious shortcoming. A significant remedy would be the initiation of a long-term national research effort, with cooperation with foreign programs, especially with China and Japan. The establishment of a U.S. culture collection for marine macroalgae is imperative. One or more centers for the development, testing and storage of seedstock should be initiated. Similarly, more basic knowledge is needed to quantify seaweed production potential by determining nutrient requirements and fertilization strategies. Experiments with seedstock production should be continued to determine the most desirable genetic strains for seaweed aquaculture, both for productivity and for tissue chemistry and composition.

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Appendices

APPENDIX 1: FUNDING PROJECTIONS

The following tables give projected funding by discipline and taxonomic group for FY 1983-1987. Values are in thousands of dollars and include both a 10 percent annual inflation factor and changing research emphases.

1983

Group	Systems	Genetics	Nutrition	Diseases	Policy	Economics
Molluscs	430.3	77.0	154.9	49.6	104.4	220.3
Crustaceans	193.3	194.2	166.0	72.3	21.4	56.9
Marine Fishes	74.8	44.9	74.8	59.8	15.0	29.9
Anad. and Catad. Fishes	143.2	278.4	135.2	103.4	79.5	55.7
Great Lakes Species	45.6	42.0	42.9	42.9	20.6	20.6
Seaweeds	50.4	50.4	75.6	25.2	25.2	25.2
Total	937.6	686.9	649.4	353.2	266.1	408.6

1984

Group	Systems	Genetics	Nutrition	Diseases	Policy	Economics
Molluscs	457.7	51.8	251.5	22.4	114.2	242.3
Crustaceans	212.7	202.0	194.4	84.1	18.8	62.6
Marine Fishes	82.3	49.4	82.3	65.8	16.5	32.9
Anad. and Catad. Fishes	166.2	288.7	157.5	113.7	87.5	61.2
Great Lakes Species	49.1	47.2	47.2	47.2	22.7	22.7
Seaweeds	55.4	55.4	83.1	27.7	27.7	27.7
Total	1,023.4	694.5	816.0	360.9	287.4	449.4

1985

Group	Systems	Genetics	Nutrition	Diseases	Policy	Economics
Molluscs	471.4	95.5	215.8	77.9	190.4	203.1
Crustaceans	221.8	221.9	220.4	103.5	20.7	63.6
Marine Fishes	90.5	72.4	72.4	72.4	18.1	36.2
Anad. and Catad. Fishes	163.6	259.8	211.7	154.0	96.2	77.0
Great Lakes Species	53.0	53.0	50.9	53.0	24.9	24.9
Seaweeds	61.0	61.0	91.4	30.5	30.5	30.5
Total	1,061.3	763.6	862.6	491.3	380.8	435.3

1986

Group	Systems	Genetics	Nutrition	Diseases	Policy	Economics
Molluscs	516.7	104.9	237.3	80.1	286.2	153.8
Crustaceans	242.0	238.4	246.9	117.5	23.5	69.0
Marine Fishes	99.6	79.7	79.7	79.7	19.9	39.8
Anad. and Catad. Fishes	190.5	211.7	232.9	190.5	127.0	105.9
Great Lakes Species	57.1	58.3	55.9	58.3	27.4	28.5
Seaweeds	33.5	83.8	83.8	33.5	50.3	50.3
Total	1,139.4	776.8	936.5	559.6	534.3	447.3

1987

Group	Systems	Genetics	Nutrition	Diseases	Policy	Economics
Molluscs	565.1	115.5	261.1	88.2	318.4	169.1
Crustaceans	242.6	266.1	278.0	129.2	39.2	75.7
Marine Fishes	109.5	87.6	87.6	87.6	21.9	43.8
Anad. and Catad. Fishes	209.6	232.9	256.2	209.6	139.7	116.4
Great Lakes Species	62.9	62.9	60.3	64.1	31.4	32.7
Seaweeds	36.9	92.2	73.8	36.9	55.3	73.8
Total	1,226.6	857.2	1,017.0	615.6	605.9	511.5

APPENDIX 2: CONTRIBUTORS

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Asterisks denote group leaders.

Nutrition

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