History, Status, and Future of Aquaculture in the United States

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I. INTRODUCTION

The recent rapid growth of the aquaculture industry in the U.S. and other countries has created a new demand and broader market for all kinds of technical information and aquacultural services. As novices enter aquaculture, they seek guidance from knowledgeable and experienced persons, commonly from state and Federal agencies, trade and marketing associations, producers' organizations, and professional societies. For both the aquacultural novice and the experienced practitioner, a review of where the industry began and where it has gone may provide guidance on where it will go. Although this author has no window through which to view the future, the objectives here are to briefly review the past, evaluate the present, and project the possible direction of development of tomorrow's aquaculture.

It is not an objective of this review to provide a detailed account of all of the important contributions made to fishery science or to aquaculture, nor to provide a detailed account of husbandry techniques for all species. The development of aquaculture as it relates to finfishes is the principal subject of this paper and the reader is reminded that similar developments have occurred, or are expected, in the culture of shellfishes, mollusks, and other aquatic organisms.

The term aquaculture as used here is considered a broad term that includes the culture of finfishes, shellfishes, and other aquatic animals-and even plants-in either saltwater or freshwater. Some authors equate the term aquaculture to underwater agriculture for the production of aquatic organisms as food for humans.45 Others distinguish between fish culture to support stocking programs and fish culture to produce commercial food products.5 Since aquaculture is a relatively modern term, its use is still evolving, but there seems to be a strong agreement among commercial fish producers and natural resource managers who culture fish that whether they are called fish culturists, aquaculturists, or fish farmers they use many of the same techniques and tools. Thus, in the interest of unity, the term aquaculturist is used to include them all.

In 1970, the American Fisheries Society published A Century of Fisheries in North America during the Society's centennial year. This 330-page volume edited by Benson' contains a wealth of information about fish culture in the early years. The individual sections by Benson,8 Bowen,9 Carlander,13 McHugh,30 Stroud,55 Swingle,57 and Thompson,59 were the primary sources for the early historical material in this paper. More recent works by Aanderaa,' Dupree and Huner,18 Larkin,26 McCoy,28 Parker,40 Reed and Drabelle,45 and others63-66 were used as the basis of current trends and projections.

II. AQUACULTURE BEFORE 1900

Fish culture was the earliest form of aquaculture in the U.S. Fishery resources of the New World were very important to England long before fish culture began in America. It has been estimated that England derived greater wealth from fisheries in the New World than Spain did from American gold. As early as 1762, overfishing had eliminated striped bass and sturgeons (Acipenser spp.) from the Exeter River, New Hampshire, and dams blocked the spawning runs of the alewife (Alosa pseudoharengus) and destroyed the fishery at Exeter before 1790. Throughout the New England area, other fisheries were similarly degraded or totally destroyed by habitat alterations or overexploitation. These changes did not go unnoticed by the professionals or the public. Fish were important.

Fishery science began in the U.S. in 1812 when the Philadelphia Academy of Science was formed and a curriculum in aquaculture was established for undergraduates at Cornell University.13 Ichthyologists began to travel throughout America to study and describe the nation's aquatic resources while others sought to transplant and propagate native species. As the public demanded corrective action to restore and maintain traditional fisheries, the culturing and stocking of fish appeared to be the most positive direct action. The very first fish managers in the U.S. were also fish culturists.

Both state officials and private citizens transplanted fish outside their natural ranges to augment the supply of native fish and to supply fish familiar to new immigrants, e.g., the common carp (Cyprinus carpio). As early as 1831, common carp were established by Henry Robinson in a pond at Newburgh, New York, from which some escaped into the Hudson River.9 In 1832, carp were being reared and sold in Sonoma, California.

By 1850, fish culture had been a common practice for centuries in China and was even well established in Europe.12 Ponds for fish culture were built in the Honan Province of China as early as 1100 B.C. when Wen Fang made the first written reference to fish culture. In 460 B.C., Fen Li described the culture of common carp for food and related the details of his experiments on fish farming in his Fish Culture Classics.

In Europe, the Romans had farmed fish and shellfish for at least 1000 years before fish culture began in America. Theodatus Garlick and H. A. Ackley were among the first American fish culturists and were the first, in 1853, to fertilize the eggs of brook trout (Salvelinus fontinalis).9 Ackley's farm near Cleveland, Ohio, which included three ponds but less than 1 ha of water, was probably the first fish farm in the U.S. to use artificial propagation.

Two years later in 1855, E. C. Kellog and D. W. Chapman at Simsbury, Connecticut, hatched 75 of 2000 eggs obtained from 1 brood female brook trout.9 They gradually improved their techniques and in 1857 produced 400 fry (young recently hatched fish). In that same year, Theodatus Garlick published a treatise on artificial propagation and culture of salmon and trout. In 1860, the year before the Civil War began, Kellog and Chapman produced 4000 fry. In 1864, the year before the end of the Civil War, Seth Green, with the advice and assistance of Stephen H. Answorth, established a trout hatchery near Caledonia, New York.9 After only 1 year of operation, he sold half interest in his hatchery for $6000 and began to give lessons in fish culture for $10 per day. His profits were $1000 in 1865 and had increased to $10,000 by 1868 when he sold 800,000 eggs.

The imbalance between supply and demand for eggs, fry, and food fish caused instability in market prices in 1868, just as it does today. The price of fish at the Fulton Fish Market in New York varied from $1.65 to $2.75/kg.9 Innovative fish culturists began to look for new markets. Livingston Stone created a new market when he began selling Atlantic salmon (Salmo salar) eggs and largemouth bass fry (Micropterus salmoides) for $50 per thousand. By 1870, the culture and sale of brook trout were well established, and six other species— Atlantic salmon, American shad (Alosa sapidissima), lake trout (Salvelinus namaycush), largemouth bass, lake whitefish (Coregonus clupeaformis), and yellow perch (Perca flavescens)¾ were being cultured.

Fish culture was primarily in the hands of about 200 private citizens until 1870 when it was practiced in 19 of the then 37 states, plus the territories of Colorado and Kansas.9 On December 20, 1870, a group of practical fish culturists met in New York City and formed The American Fish Culturists' Association.59 The first members and officers—William Clift, President; Livingston Stone, Secretary; and B. F. Bowles, Treasurer—were men of action and pursued the Association's goals "to promote the cause of fish culture; to gather and diffuse information bearing upon its practical success; the interchange of friendly feelings and intercourse among members of the association, the uniting and encouraging of the individual interest of fish culturists."9

During the early years, fish culturists were making observations and developing techniques that eventually evolved from an art to the science of aquaculture. It was soon recognized that the addition of ice to water extended the time during which live fish could be successfully transported.9 Seth Green was the first American to use the dry spawning technique, with which he achieved a 75 to 98% fertilization compared with 25% when fish gametes were manually stripped into running water. Although Green offered fish culture lessons, he attempted to keep the dry fertilization technique a trade secret from 1864 to 1879. This technique was the first significant contribution of Americans to the practice of fish culture.

Other culturists soon began to add their refinements to the art of fish culture. Livingston Stone was apparently one of the first to combat fungal growth on eggs, doing so by charring the inside of wooden hatchery troughs.9 Seth Green painted his wooden egg troughs with asphalt to control fungus. Livingston Stone was also one of the first fish culturists to use salt as a therapeutic for fish. He found that salt was useful in the control of fungus, the parasitic trematode Gyrodactylus, and the protozoan parasite Trichodina. Livingston Stone described a total of 23 diseases on the basis of their signs in fish and determined that the best way to control disease was to improve the environment. He was the first person in the U.S. to apply the scientific method to investigations in fish culture and used controlled experimentation to evaluate the effectiveness of treatments. Even with Stone's contributions, fish culture was not a glamorous business in the early

20th century. The simple act of feeding fish was not simple; feeds had to be acquired, transported, prepared, and delivered to the fish. Early feeds consisted of a wide variety of materials: raw or cooked fish; boiled lean meat; egg yolk; liver; clabbered milk; a mixture of ground heart, liver, and lungs of beef and pork; and live minnows, worms, and insects (including maggots).

Members of the American Fish Culturists' Association were not sitting idly by during this time. One of their first projects was to reduce the confusion relating to names of fishes; they began to standardize the common names.59 They were also active on the political front and effectively lobbied Congress in 1871 to create the Commission on Fisheries, with Spencer F. Baird, Assistant Secretary of the Smithsonian Institute, as the first Commissioner. With the new Commissioner in place, the Association sought the assistance of Congress to provide funds for the propagation and introduction of shads, salmons, and other valuable fishes throughout the country. Congress appropriated $15,000 in 1872 to support these requests, and fish culture by the Federal Government began. Since the Federal Government had no fish culture facilities, the Association asked that the funds be provided to private fish culturists Seth Green and William Clift so they could release shad in the Mississippi River and enlarge Clift's salmon hatchery on the Penobscot River in Maine. The Association also requested that the funds be used to support unspecified work by Livingston Stone on the Sacramento River.

These early fish culturists were truly activists. In 1872, they not only lobbied Congress, but also mailed about 500 letters and 1000 circulars and papers to members and nonmembers, and to professional and amateur fish culturists. Fish culture was profitable; costs (per kilogram of fish) were $0.07 for feed, and $0.33 to $0.44 for production, and trout sold for $1.10 to $2.75 per kilogram.59 There was great interest in both commercial culture and in the restoration of native stocks in streams, rivers, and ponds.

Although fish culturists promoted the direct action of stocking fish in the nation's waters, they were also some of our first environmentalists. They voiced their concerns about pollution from manufacturing plants, sawmills, dams, siltation, and other industrial and municipal sources.59 Fish culturists sought to preserve the environment to support fish and fishing.

Fish culturists recognized the stocking of fish as a more attainable goal than that of eliminating pollution and restoring the habitat. After the completion of the first transcontinental railway, Seth Green transported 15,000 shad fry in 1871 from the Hudson River to California in only 8 days of travel.9 Between 1876 and 1880, 564,000 fry were stocked in the Sacramento River. By 1880, shad had become established from San Francisco Bay to Vancouver Island. During the period 1872 to 1880, the U.S. Fish Commission stocked over 8 million shad fry into the Connecticut River and over 84 million into the waters of 16 Atlantic Coast states. Stocking fish was popular, and the states responded to public pressure; in 1872 alone, the Massachusetts Fish Commission stocked more than 90 million shad fry. In 1881, the first train car designed specifically to carry fish was purchased for $8000 by the U.S. Fish Commission. It was designed to carry 4.8 million fry or 119 kg of fingerlings, all safely supported by the most modern conveniences of the day. Sport fishing proponents supported the introduction of brown trout from Germany and Scotland in 1883 to increase angling opportunities.

Although coastal areas and large rivers were being stocked with shad, salmon, and other species, these species were inappropriate for waters in the southern states. Spencer F. Baird envisioned that small ponds in the south could provide an important source of food fish and a ready supply of fresh protein.9 He considered the indigenous catfishes and buffalofishes as appropriate forms for culture in the south. Since little was known about the culture requirements of these fishes, he turned to the common carp, cultured for centuries in Asia and Europe. When Baird began to culture carp in 1875, the species was already well established in California and New York. In 1877, Baird was so impressed with the potential of carp that he stated:

I fully believe that within ten years to come this fish will become, through the agency of the United States Fish Commission widely known throughout the country and esteemed in proportion.

In that same year, 227 leather and mirror carp and 118 scaled carp were imported from Germany. Congress immediately provided $5000 to construct culture ponds for carp on the grounds of the Washington Monument.

The great carp culture era of the 1880s proved the effectiveness of fish culture and the benefits of stocking fingerlings rather than fry. In his 1882 report to Congress, Commissioner Baird indicated that carp fingerlings 5 to 8 cm long were distributed to applicants in every state and territory in the U.S. except Montana.9 Carp were provided to 298 of the 301 Congressional districts and to Congressional constituents in 1478 counties.

The American Fish Culturists' Association was undergoing change during this period, and in 1878 its official name was changed to The American Fish Cultural Association.59 However, by 1884 the membership had grown and interest had diversified to the point that fewer members were fish culturists and the group adopted the Society's current name–The American Fisheries Society–as they met aboard the U.S.S. Fish Hawk, which had been converted by the Commission into a floating fish hatchery. Arguments were made that this new name could bringthe organization into closer alignment with similar European organizations.

Commissioner Baird recognized the need for fishery research and established the first Federal fishery research program at Woods Hole, Massachusetts, in 1873.30 The research program was rather minor compared with the hatchery program and operated primarily during summer when university professors were available for field research. In 1877, David Starr Jordan, a student of Louis Agassiz, with the assistance of Charles H. Gilbert, conducted an extensive survey of the fishes of the Pacific Coast.13 Similar work was conducted with Commissioner Baird's support, but after his death in 1887, research by his agency received much less emphasis. From 1873 to 1885 the annual budget averaged

$70,000 for propagation of fish at Woods Hole, but was less than $4000 for research.30 Advances in fish culture apparently stagnated even further after the reference book A Manual for Fish Culture10 was published by the Commission in 1897. The manual contained descriptions of culture techniques for more than 40 species or groups of finfish, plus lobsters, oysters, clams, and frogs; apparently, in the view of the Commission, it contained all the information needed by fish culturists. At the 1899 annual meeting of the American Fisheries Society, Herman C. Bumpers of Woods Hole complained, as follows, about the deterioration of the research program at the U.S. Commission of Fish and FisheriesLaboratory:59

In the meantime the work of fish-hatching had continued, but only along the old lines and in the perfunctory way that prevails for those who take no vital interest in their work.

I believe that the history of the Woods Hole Station during its dark ages of scientific inactivity will be the history of every station and sub-station that attempts to confine its energies to the merely mechanical work of hatching fish. Close up your drafting room, and your machinist becomes a blacksmith; do away with your schools of design. and the standard of even yourso-called practical builder is immediately lowered. More progress has been made in practical medicine during the past twenty-five years than during the previous twenty-five centuries. Who shall say that the progress is not the direct result of laboratory activity and the application of the scientific method? The scientific and practical work of a fisheries station cannot be divorced.

III. AQUA CULTURE IN 1900 - 1945

Although the pre–1900 years were dominated by commercial fish culturists and fledgling Federal and State programs, it was not until after 1900 that educational institutions became involved in fish .13 The importance of the U. S. Fish Commission's few and sparsely located laboratories was recognized; however, as noted by Raymond C. Osburn in the Transactions of the American Fisheries Society in 1920, "without exception they are far behind the average agricultural experiment station in personnel, this being due to insufficient financial support."37

The American Fisheries Society recognized the need to elevate fishery training from the apprenticeship stage to a formal series of courses. At the Society's annual meeting in 1918, a resolution was passed calling for "the establishment of courses in fish culture".13 As it does today, the Society worked primarily through committees and duly established a Committee on University Courses in Fish Culture. This Committee recommended that universities develop courses for general fishery investigators, fish pathologists, teachers of fish culture, and practical fish culturists. At the following annual meeting (in 1919), the Society commended the University of Washington for establishing a School of Fisheries and Cornell University for developing courses in fisheries as early as 1812.

Dr. Hugh Smith, U.S. Commissioner of Fisheries, proposed in 1913 that formal courses in fisheries be established at agricultural colleges throughout the U.S., but no formal action was taken.59 Fish culture was a broad, all-inclusive term in the early 1900s and covered all aspects of fishery management. When the School of Fisheries was established at the University of Washington in 1919, fish culture was one of the dominant themes and research in canning and development of gear technology were of major interest. One of the three temporary buildings formerly used by the Navy was converted into a classroom one into a hatchery, and the third was converted into a fish-processing laboratory and cannery.13 Beginning in 1920, emphasis at the University of Washington and at a new laboratory established at Stanford University was onthe propagation of anadromous salmonids.

Fishery programs were developed and expanded at several universities. During the 1930s, the University of Michigan and Cornell University probably led the nation in numbers of graduates from fishery programs.13 Similar programs were developed at the Universities of Wisconsin, Minnesota, Indiana, Illinois, and Maine.

Hatchery programs continued to expand under Federal and state direction. In 1932, the New York Conservation Department, the U.S. Bureau of Fisheries and Cornell University established a research and training program at Cortland, New York.13 Also in 1932, Professor H. S. Swingle, an entomologist at Auburn University, began experimenting with fish in small ponds in Alabama, and the Bureau of Fisheries began construction of the Government's largest warmwater fish hatchery in Marion, Alabama. In 1933, in Germany, Schaeperclaus48 published his classic book (translated into English in 1948) on the culture of carp, trout, and other fishes in earthen ponds, which stimulated additional interest of Americans in the culture of fish in ponds.

L. L. Dyche of the Kansas Department of Game and Fish published in 1914 one of the earliest books, Ponds, Pond Fish and Pond Fish Culture, with guidelines for construction of ponds and for the culture of warmwater fish.57 He recommended stocking crappies (Pomoxis spp.), black basses (Micropterus spp.), catfishes (Ictalurus spp.), sunfishes (Lepomis spp.), and common carp. In the 1930s, H. S. Swingle and E. V. Smith at Auburn University and David Thompson and George Bennett at the Illinois Natural History Survey began formal investigations of fish production and management in small lakes and ponds. The Illinois group used field-sampling techniques to study the standing crop of fish in small lakes and ponds. The Auburn group studied production in small experimental ponds by draining them to remove and gather data on the total fish population. In these first experiments, the scientists evaluated the influence of aquatic vegetation on the presence of mosquitoes in ponds, as well as the use of fertilizers to promote phytoplankton rather than rooted aquatic plants (which were more favorable to mosquito production).

Increasing public interest in fishing increased the use of baitfish until demand exceeded the natural supply. Dr. Swingle recognized the potential market for baitfish and in 1934 began research on the culture of goldfish (Carassius auratus), fathead minnows Pimephales promelas), and golden shiners (Notemigonus crysoleucas).57 Common carp were considered the premier food fish for culture in ponds, but soon fell into disfavor because of the limited market demand and their ready availability from rivers and streams throughout the U.S. In 1944, research on the production of bigmouth buffalofish (Ictiobus cyprinellus) and catfishes was begun at Auburn University. Although little was then known about the culture of these species, state personnel in Kansas began propagation of channel catfish as early as 1910.50

Also during 1900 to 1945, the fish car era of the U. S. Bureau of Fisheries peaked and began to decline. The last fish car, commissioned in 1929, was capable of transporting 34,000 8cm fish or 500,000 2.5-cm fish.27 Trucks, because of their far greater mobility, became the major mode of fish transportation after about 1930. Even airplanes began to displace railroad fish cars. The first air shipment of fish was in 1928 when 27,000 trout were flown from Northville, Michigan, to Dayton, Ohio.9 Although there was growing interest in freshwater and warmwater species, 98% of the eggs and 75% of the fry produced in 1940 were of marine species–principally Atlantic cod (Gadus morhua), flounder (Bothidae and Pleuronectidae), and pollock (Pollachius virens). These marine species were stocked apparently because they could be easily produced by culturists and not because they produced successful fisheries.

IV. AQUACULTURE IN 1945-1960

After World War II, Americans began to travel, to eat in restaurants more frequently, and to have more free time available for sport fishing. The commercial fishery for shrimp quickly emerged as the Nation's most valuable fishery, but it was not until after the war that research was directed toward this fishery.30

Both undergraduate and graduate courses in fish culture were established at Auburn University in 1946.13 The U.S. Bureau of Sport Fisheries and Wildlife established the Warmwater Training School at the National Fish Hatchery in Marion, Alabama, in 1951 to provide training for managers of Federal hatcheries. Cooperative Fishery Research Units, jointly supported by the U.S. fish and Wildlife Service, the host university, and the department of conservation of the host state, were first established in 1960, 25 years after establishment of the first Cooperative Wildlife Research Unit.13

Research in fish nutrition was conducted at several universities, at a few government laboratories, and at several hatcheries throughout the country before the first dependable drypelleted diet for trout was brought to the market in 1958.9 The Oregon moist pellet diet, jointly developed by the Oregon Fish Commission and Oregon State University in the early 1950s, reduced feed costs from $0.97 to $0.46/kg of fish produced.24

Fish culturist, D. C. Haskell, of the New York State Conservation Department, demonstrated in 1959 that growth of trout proceeded at a constant rate under hatchery conditions, and this observation led to the development of mathematical formulae for hatchery operations.9 Biological processes such as feeding, respiration, and growth could be related to environmental conditions such as temperature, water flow, and the biomass of fish per unit of area. The development of these formulae enabled the scientific evaluation of fish culture to be on an objective basis rather than as a subjective art.

By 1950, there were an estimated 1.6 million ponds in the U.S.9 The U.S. Department of Agriculture encouraged farmers to build ponds to conserve soil and water. The potential for these ponds to support sport fishing was quickly realized and the demand for fish to be stocked in them was placed on the government. H. S. Swingle and associates at Auburn University established the concept of balance between prey andpredator species stocked in ponds.57 They reported the annual catch from unmanaged and unfertilized ponds to range from 11 to 56 kg of black bass and bluegills per hectare. With proper management and fertilization, annual catches of 101 to 336 kg/ha were possible, and an averagesustained yield of about 196 kg/ha. During the period 1950 to 1960, annual trout production was estimated at 907 to 1360 t/year, but there was essentially no production of channel catfish.9

Public Law 85-342. known as the Fish-Rice Rotation Act of 1958 authorized the establishment of the Fish Farming Experimental Station, to be operated by the U.S. Bureau of Sport Fisheries and Wildlife, in Stuttgart, Arkansas. In the following year, the Southeastern Fish Cultural Laboratory was established also by the Bureau of Sport Fisheries and Wildlife on the grounds of the Marion (Alabama) National Fish Hatchery. With establishment of these two laboratories, the Federal Government through the Bureau of Sport Fisheries and Wildlife, entered the modern era of fish culture research. The program was designed to benefit fish culturists specifically and other aquaculturists in state, Federal, or private hatcheries.

V. AQUACULTURE IN 1960-1987

Until the early 1960s, commercial fish culture in the U.S. was principally restricted to rainbow trout (Salmo gairdneri), baitfish, and a few warmwater species. Most warmwater fish produced in the U.S. were reared to be stocked in public waters by state and Federal agencies or to be
used as bait to catch warmwater fish.

The expansion and potential of aquaculture were recognized by the U.S. Fish and Wildlife Service in 1978 when several laboratories were reorganized under the National Fisheries Center at Leetown, West Virginia.64a The former U.S. Fisheries Experimental Station in Leetown was christened the National Fish Research Laboratory and along with the Tunison Laboratory of Fish Nutrition (Cortland, New York), theSoutheastern Fish Cultural Laboratory (Manor, Alabama), the Fish Farming Experimental Station (Stuttgart, Arkansas), and the National Fishery Research and Development Laboratory, (Wellsboro, Pennsylvania) became the nucleus of aquaculture research administered by the Center in Leetown. From 1983 until 1987, the National Fisheries Research Laboratory in Gainesville, Florida, was directed from Leetown. In 1987, the Gainesville Laboratory was renamed the National Fisheries Center and began to administer the warmwater aquaculture research programs of the laboratories in Marion, Alabama, and Stuttgart, Arkansas.

Today, important warmwater aquaculture facilities are located throughout most of southeastern U.S. and in southern California. The tropical fish industry is primarily restricted to Florida and southern California. In 1985, warmwater species constituted about 70% of the fish reared in the U.S., and the most important commercially cultured species was the channel catfish (Figure 1).

Total fish and shellfish production in the U.S. was estimated to exceed 190.000 t in 1982.40 Private aquaculturists produced 94% of the total and state hatcheries produced about 4% and hatcheries of the U.S. Fish and Wildlife Service hatcheries produced less than 2%, but reared 52 species of finfish in 1981. The total value of privately produced fish was estimated at $393 million in 1983. Sport fishing was an even larger industry: an estimated 42.1 million fishermen spent over $17.3 billion on fishing and fishing-related equipment, transportation, food, lodging, licenses, and permit fees in 1980.65 A later survey in 1985 revealed that 46.6 million sport fishermen spent $28.2 billion on recreational fishing and allied activities.66 In addition to the fish produced by aquaculturists and those caught from the wild, the U.S. imported edible and nonedible fishery products worth $360 million in 1960, $3.6 billion in 1980, $6.7 billion in 1985, and 57.6 billion in 1986 (Figure 2). Although catfish constituted 51% of all aquaculture products reared in the U.S. in 1986 and processed catfish were valued at $275 million, production would have to increase more than 27-fold to equal the value of fish imports. This trade deficit indicates a tremendous potential for additional aquacultural production in the U.S. to satisfy both the food market and to meet the demands of sport fishermen.

FIGURE 1. The quantity (open bars) and value to producers (shaded bars) of aquacultural products reared commercially in the U.S. in 1985. (Data for tropical fish provided by T. K. Hennessy, Gibston, Florida. and all other data provided by Ben Drucker, National Marine Fisheries Service. Washington, D.C. Figures for oysters and Pacific salmon include some 1984 data when data were unavailable for 1985.)

Major crops in the 1980s include channel catfish, crawfish, and baitfish. Production systems for freshwater prawn (Mac robrachium rosenbergii), largemouth bass, penaeid shrimp (Penaeus spp.), and striped bass (Morone saxatilis) are being developed. A total of 12 aquaculture development plans were completed by the Joint Subcommittee on Aquaculture, established by the National Aquaculture Act of 1980 and chaired on an annual rotating basis by the Secretaries of Agriculture, Commerce, and Interior,25 for species now cultured in the U.S.; these included 6 groups of finfishes, 4 groups of mollusks, and 2 groups of crustaceans. The development plans reviewed the current status of production, the economic investment, development potential, constraints to development. current research, and research needed to support the expansion of aquaculture. A total of 24 other groups of aquatic organisms, consisting of over 57 species, were identified as potentially important to aquaculture in the U.S. They included reptiles, amphibians, fish, crustaceans, mollusks, worms, and plants.

Even though Congress expressed interest in aquaculture when it passed the National Aquaculture Act of 1980, no funds were appropriated for it. In 1986, the Act was modified to place aquaculture under the Department of Agriculture and $3 million was appropriated to establish four regional aquaculture centers, located at the University of Washington, Southeastern Massachusetts University, Mississippi State University, and a Center for Tropical and Subtropical Aquaculture to be jointly administered by the University of Hawaii and the Oceanic Institute. The four centers are expected to be the focal point for aquaculture research supported by the U.S. Department of Agriculture.

A. Culture of Channel Catfish

By 1960 only about 162 ha of catfish ponds were in commercial production.33 The growth of the industry thereafter was astounding (Figure 3). The surface area for catfish production ponds expanded to 948 ha in 1963 and 16,000 ha in 1969, and by late December 1985 to over 49,000 ha incatfish production-an increase of over 300-fold in only 25 years.18 In the state of Mississippi alone, more than 34,000 ha were devoted to catfish production. Some individual fish farms were as large as 2400 ha. The amount of fish food required by some large farms has been reported to be 18 t per day and airplanes are sometimes used to distribute food across the water surface.19

There are two basic markets for channel catfish–live and processed. Live fish are normally sold for restocking in farm ponds or private lakes to support sport fishing. Owners of private ponds or lakes usually charge fishermen an entrance fee to fish and an additional fee per unit weight of fish caught. Fish sold in this market usually command the highest price and may be worth $4.40/kg of live weight. These "fish-out" operations are normally more profitable in and near large metropolitan areas than in rural settings. However, some farmers in rural areas have attracted anglers who drive 500 km or more to catch high-quality fish.

FIGURE 2. Value of farm-raised processed channel catfish. 1970-1986, compared with value of fresh and processed fish imported into the U S from 1960 to 1986. (Data from U S. Department of Commerce.62.63)

FIGURE 3. Live weight of channel catfish raised on farms in the u.s. and processed for national markets, figure does not include farm-raised fish sold in local markets. (Data from U.S. Department of Commerce.63)

The second-highest return comes to the farmer who sells processed fish in a local market. Few fish are sold in this way, however, which seems to be best adapted to small family-size operations that involve little outside labor. Many southern restaurants specializing in catfish were established to provide this market outlet.

Most of the 109,000 t of catfish reared by U.S. farmers in 1985 were sold to processing plants. The price paid to farmers peaked at 51.76/kg, whole weight, in March 1985. However, as the supply of catfish increased, the price decreased to $1.50/ kg in June 1986 and to $1.39/kg by

September. Catfish are still considered to be a southern item, even though recent promotional campaigns have moved them into national markets.

Off-flavor and fatty fish pose the major problems in product quality control. Several organic compounds, including the geosmin produced by blue-green algae, concentrate in the flesh of catfish to produce off-flavor. To check for off-flavor, processors organoleptically evaluate, or taste test, a small sample of fish from each pond the week before harvest, the day before harvest, and again immediately before processing. Fish with off-flavor can be moved to tanks with fresh well water or can be held in a pond until flavor improves after the decline of the responsible algal bloom.

American consumers typically do not accept fat, strong-tasting fish, and much prefer lean. mild-tasting fish. Shelf life is shorter for fat fish than for lean fish. Many of the organic compounds producing off-flavors in catfish concentrate in lipids. Recent research has shown that lipid content of channel catfish is inversely correlated with stocking density, and that fish fed in the morning have less body fat than those fed in the afternoon.36 Additional research is under way to improve quality and shelf life of processed catfish. Although there is a considerable market for whole fish and fish steaks, an increasing proportion of the market is for fillets and other boneless products.68 Large firms that traditionally processed only beef, pork, and poultry have expanded their product lines to include catfish. Several of these national food marketing firms are developing new value-added products, i.e., rather than selling frozen fillets they are selling seasoned, breaded, and precooked fish products that require only heating before they are served. Although fresh frozen catfish sell for about $6/kg, value-added, precooked products may sell for $35 or more per kilogram.

B. Culture of Trout and Salmon

Trout have been cultured in the U.S. for well over 100 years. Production facilities were established near many springs and other types of water sources such as creeks and mill ponds before 1900, but most were rather small. Commercial producers were located in 48 of the 50 states (Florida and Hawaii are the exceptions) in 1987; the largest farms were in California, Idaho, Montana, Oregon, and Washington. Commercial farms in the Snake River Valley of Idaho produced about 95% of all trout reared as food fish in the U.S. in 1986. Trout production was 450 t in 1954, 13,400 tons in 1972, and 23,000 tons worth $55 million to fish farmers in 1985.

Salmon culture, which began in California in 1872, today has spread to Oregon, Washington, and Alaska on the Pacific Coast, to the Great Lake states of Minnesota, Wisconsin, Illinois, Indiana, Ohio, Pennsylvania, and New York; and to states on the northeastern Atlantic Coast. Most salmon, reared in hatcheries operated by states or the Federal government, are released as smolts and go to sea. These fish are important to both recreational and commercial fishermen.

Both Oregon and Alaska have licensed commercial ocean ranching operations in which fish are released to the ocean as juveniles and harvested when they return as mature adults. Ocean ranching is illegal in Washington and (except for one permitted operation) in California. Other operators, such a those in Washington, rear salmon in net pens, first introduced into the U.S. in 1967 by the U.S. Bureau of Commercial Fisheries, and market them as pan-sized fish.12 Net pens in California are legal only for use by nonprofit organization rearing fish in support of public programs.

On the Pacific Coast, the major species being reared for ocean ranching are chum salmon (Oncorhynchus keta), coho salmon (O. kisutch), and chinook salmon (O. tshawytscha) however, some pink salmon (O. gorbuscha) and sockeye salmon (O. nerka) are also reared. Coho, chinook, and Atlantic salmon (S. salar) in net pens in Washington, and coho and chinook salmon, and steelhead are reared in California.

C. Culture of Striped Bass and Their Hybrids

Anadromous striped bass (M. saxatilis) originally ranged from the St. Lawrence River in Canada south along the Atlantic Coast to the St. Johns River in northern Florida and occurred in 31 rivers from the Florida Gulf Coast westward to the Mississippi River.69 Both the Atlantic and Gulf Coast stocks have been severely reduced as a result of environmental degradation, the blocking of access to spawning grounds by dams and navigational locks, and strong commercial and recreational fishing pressure. However, inland populations of landlocked striped bass have increased dramatically since 1954, when the fish were first reported to have spawned in Santee-Cooper Reservoir, South Carolina.

Hatchery-reared progeny of Atlantic Coast striped bass and hybrids of striped bass x white bass (M. chrysops) have been stocked in at least 28 states and 456 reservoirs.51 Although striped bass mature in some inland reservoirs, few inland waters provide suitable spawning grounds to maintain stable populations. Most striped bass and hybrids are produced in hatcheries using techniques involving hormone injections that were established 20 years ago.52

Striped bass weighing 57 kg have been reported, but fish over 15 kg are often considered trophies. Hybrid striped bass may weigh up to 10 or

11 kg, but are commonly only half that size. Brood fish are collected with gill nets or electro-fishing equipment, or by hook and line, from inland reservoirs or as they migrate from coastal waters to their inland freshwater spawning grounds. Smaller brood fish weighing 5 to 10 kg are preferred in the hatchery because they are more easily handled than are larger fish. However, brood fish from Chesapeake Bay, Maryland, typically weigh 20 to 25 kg and one 38-kg fish were spawned in 1985.38

D. Culture of Baitfish

Although the 10,000 t of baitfish reared in 1982 was the fifth most abundant group by weight of fish produced in the U.S., they ranked third in value behind catfish and trout. The 1982 value of baitfish was $44 million compared with $120 million for catfish and $48 million for trout. The average per capita demand for baitfish is about 0.2 to 0.4 kg/year. Although baitfish are produced throughout the U.S., Arkansas is the leader by a wide margin and is the source of shipments to nearly all the 48 contiguous states.

Of the 20 species of baitfish raised commercially, the golden shiner (N. crysoleucas), fathead minnow (Pimephales promelas), and goldfish (C. auratus) are the most important.21 Most are cultured in shallow earthen ponds. The ideal-size pond for culture is about 4 ha for golden shiners and fathead minnow s and somewhat smaller for goldfish. Production ranges from 880 to 1100 kg ha in fertilized ponds, but may exceed 3300 kg/ha when ponds are fertilized and fish are fed commercially prepared diets.

E. Culture of Exotic Species

Common carp (Cyprinus carpio), Chinese carps (grass carp, Ctenopharyngodon idella: hybrids of grass carp and bighead carp, Aristichthys nobilis; and silver carp Hypophthalmichthys molitrix), and the tilapias are the major exotic species cultured in the U.S. as either food fish or for biological control of vegetation. Researchers at Auburn University, Alabama, who conducted a survey in 1981 located 30 producers rearing Chinese carps in 8 states.49 Only six of the producers reared carp as food fish, however; the largest market for the fish is for vegetation control. Chinese carps have been produced primarily in the southeast.

Possession of grass carp is illegal in many states, but sterile hybrids and triploid fish have been more acceptable to authorities for use in vegetation control.2 Hybrids do not control vegetation as well as do grass carp. Now that techniques for producing triploid fish (presumably sterile) have been developed, the market for hybrids has declined considerably.67

Since the Chinese carps do not spawn in static water ponds, they must be seined from ponds and induced to spawn by injection with hormones. In the southern states, they can be induced to spawn from mid-April to mid-June when the water temperature warms to 25°C.18

Outside the Asian community, the market for food-sized Chinese carps is very limited in the U.S. Most producers market fish for control of vegetation, maintenance of water quality, or to remove nutrients in municipal sewage and animal waste lagoons. Large fish may be reared in polyculture with catfish or other species native to North America.

Tilapia are reared both as food fish and for vegetation control in the southeastern states, California, Arizona, and (in geothermal raceways) in Idaho. They have been well received as food fish and in some markets sold for more than $6/kg in the round (i.e., with heads intact but with viscera removed). The market for tilapia as vegetation control agents is stable because in most locations the fish die during the winter and must be restocked each year. In some locations, the food fish market has received strong competition from the sale of wild fish taken from lakes and estuaries in Florida. Wild fish have sold for $0.40/kg in Florida before processing and for $1.32 to $1.43/ kg after processing and shipment to California. About 900 t of wild tilapia were marketed in 1986.12a

Tilapia are among the easiest fish to culture because of their unusual tolerance for low dissolved oxygen, high ammonia, and poor water quality.4 One of the major problems of culture is their rapid rate of reproduction and the resulting crowding and stunting. Although they are not predaceous, tilapia are aggressive and compete with native species for spawning sites and space. Several states have prohibited the introduction of tilapia.

Tilapia culture is primarily restricted to southern states or to areas where geothermal water or heated effluents from power plants are available.
Tilapia spawn at temperatures above 20°C, and prefer water between 26 and 32°C. They stop feeding at temperatures below 15°C and prolonged temperatures below 10 to 12°C are lethal.14 Tilapia aurea, the blue tilapia, appears to be the most cold tolerant of the tilapias cultured in the U.S.

F. Culture of Tropical Fish

About 1200 to 1500 exotic species have been imported into the U.S. for the hobby fish or aquarium trade.44a At least 41 of the species have established breeding populations and 63 others exist in public or private waters with native fish.17 Some tropical fish are cultured in nearly every state, but major commercial operations are restricted primarily to Florida and southern California. Although the annual retail value of tropical fish produced in the U.S. is estimated to exceed $200 million, that of tropicals imported from Africa, Ceylon, China, Japan, Malaysia, and Central and South America exceeds $500 million. More than 300 tropical fish farms (the greatest concentration in the U.S.) are in Florida and about 200 are within 1-h driving time from the airport in Tampa, Florida.16 Depending on species, fish may be spawned in aquaria or ponds. Brood fish are maintained indoors in heated tanks and aquaria throughout the winter and may be stocked in small ponds (6 x 24 m) or larger ones (24 x 30 m). Some ponds are covered with plastic greenhouse-type structures to protect them from low winter temperatures. Individual farms may have fewer than a dozen ponds or more than 200.

Vl. FUTURE OF AQUACULTURE

Although aquaculture has been practiced for well over a century in the U.S., the major increase in production developed in the last 10 to 20 years. Economic conditions on the American farm scene, resulting from overproduction of cereal grains and other agricultural commodities, have stimulated interest in aquaculture products. From 1975 to 1985, the per capita consumption of fish (including shellfish) increased 20% and that of poultry increased 44% (Figure 4). The per capita consumption of fish (6.6kg in 1985) is expected to continue to increase. The U.S. Department of Agriculture forecasts a 44% increase by year 2000, and a further increase to 13.6 kg is expected by year 2020.6'

Fish produced in the public waters of the U.S. are typically more valuable as recreational or sport fish than as commercial products. The use of gill nets for yellow perch was recently prohibited in Indiana because of the economic loss caused by the incidental catch of salmon smolts.43 In 1985, anglers along the Canadian Atlantic Coast took only 29% of the salmon catch, but accounted for 93% of the economic activity related to the total regional salmon fishery.60 Also, angler activities generated an estimated 2094 full-time jobs compared with only 163 created by the commercial fishery. As pressures from sport fishermen continue to grow and salmon farming operations are developed, some projections for the future forecast the cessation of the commercial fishery for salmon.60 Similarly, the demand for striped bass, red drum (Sciaenops ocellata), and other species has already outstripped natural production under contemporary environmental conditions, and commercial fish cries in several states have been closed. Formerly established markets, now unfilled, are increasingly attracting the attention of aquaculturists.

Although catfishes and bouts are the two principal group of food fishes produced by aquaculturists, the commercial culture of other species is sure to develop. Trout culture developed slowly over a 100-year period while markets were being established, husbandry techniques were being refined, and support industries were being developed to supply drugs, hardware. etc. The catfish industry and its infrastructure developed much more quickly, over a 20- to 30-year period. The basic culture techniques were developed from 1960 to 1970. Technical information was disseminated and the infrastructure of the industry developed from 1970 to 1980. It appears that the catfish industry was in an exponential growth phase in 1980 to 1986 (Figure 3). If the present trend continues, catfish production will double by 1992.

Now that feed mills, processing plants, water quality management techniques, chemicals and drugs, transportation equipment, and marketing techniques have been developed, the infrastructure exists to rapidly expand production of both traditional species and species new to aquaculture. The advances in aquaculture research and commercial production are reflected in the growth of computer data bases that list information on fish culture. In February 1987, a computer search of 275 data bases indicated that 53% contained from 1 to 3793 entries with titles that included the terms fish culture or aquaculture. Textbooks and manuals such as those of Bardach et al. ,5 McNeil and Bailey,31 Piper et al ,42 and Stickney53.54 translated research data and technical reports into understandable "how-to" directions and guidance. The aquaculture information available has increased sharply since the early 1960s when computer data bases were first established (Figure 5). This growth of technical information will greatly accelerate future expansion compared with that before the 1960s.

FIGURE 5. Cumulative number of publications with the words fish culture or aquaculture in the title in 7 of 275 computer data bases searched in February 1987. Since individual articles may be listed in more than one data base, the number of publications per year is less than the cummulative number shown. Few articles published in 1985 or later had been entered into the data bases at the time of the search.

Not only is the volume of available technical information increasing, but the number and effectiveness of producer, trade, and research organizations are growing. Membership is increasing in national organizations such as the U.S. Trout Farmers Association, the Catfish Farmers of America, the Fish Culture Section of the American Fisheries Society, and the World Aquaculture Society, and in state organizations such as the Catfish Farmers of Arkansas, the California Aquaculture Association, and the Florida Tropical Fish Farmers Association; all are having positive influences on the expansion of aquaculture.

Any real increase in per capita consumption of fish must be met by competition for natural resources or by the expansion of aquaculture. It is rather doubtful whether the commercial harvest of fish can continue to meet the demand. The estimated world harvest of marine and freshwater fish in millions of metric tons was 27 million in 1954, 56.8 in 1966, 73.5 in 1976, and 82.8 in 1984.

Projecting the future growth of the world's population and resulting demand for fishery products has interested fish culturists since at least 1899.59 During that year at the annual meeting of the American Fish Culturists' Association, one member projected that the world population would reach 1.2 billion by the year 2031 and suggested that "we draw more of our meat from the water." However, census data were gathered slowly in those days and the world population had already reached 1.2 billion in about 1850. Although that early futurist missed the mark as a demographer, he may have been on target with his projections for the importance of marine resources. The estimated world population was 5 billion in 1987 and is expected to be 7.5 billion by the year 2000. Although aquaculture production is not expected to feed the world's masses, it is expected to augment the limited catch of marine and freshwater fish. Pillay41 projected a doubling of aquaculture production from 1975 to 1985 and a fivefold increase from 1975 to 2000. Brown12 predicted that world aquaculture production would increase by 12 to 18 million t by the year 2000. There seems to be little disagreement that aquaculture production will increase; the question seems to be the amount of increase in a given period of time.8

As reflected in a 1984 exhibit and publication of the Smithsonian Institute titled "Yesterday's Tomorrows," few of yesterday's futurists were able to forecast the magnitude of the change in technology and society from the late 1800s to 1984.15 In fact, most projections fell far short of reality. Obviously, projecting the future is a risky business at best. However, participants at a 1968 conference at the University of Washington agreed that, "Most of our well-known natural stocks of fish are near the sustainable limit of production... and few will yield more sustainable catch no matter how hard they are fished. Aquaculture... offers many opportunities for the production and sale of high-priced fishery products. It does not seem to offer a significant promise anywhere in the near future. "20

Perhaps they were correct in their projections of sustained yield of world fisheries, but underestimated the future of aquaculture. Two years later another biologist projected that by 1980 over 500,000 t of catfish would be marketed annually.9 The truth, of course, lies somewhere between these extremes of 500,000 t and "does not seem to offer a significant promise"; 24,900 t of catfish were marketed in 1980. In 1968 and 1970, shrimp production was first beginning to attract the interest of researchers and aquaculturists. The World Mariculture Society (now the World Aquaculture Society to indicate the broad interest of members) was formed in 1969 by a small group of researchers working primarily along the northern coast of the Gulf of Mexico.3 Some members were interested in shrimp culture and pursued that interest in the U.S. and in other countries. Commercial production of penaeid shrimp has developed slowly in the U.S., but American technology has been important in expanding the shrimp farming industry in Central and South America. World production of tanned shrimp was 4000 t in 1980 and increased eightfold to 32,000 tons by 1984.28 The shorter growing season in the southern U.S. compared with that in Central America may be offset by savings in transportation and allow the expansion of shrimp farming in the U.S.

Limited expansion is expected in the production of coldwater species in inland waters. Most sites with adequate quantities of good-quality water have either been developed for raceways or are in parks or wilderness areas where development is prohibited. However, major gains in yield are expected as fish are improved through selective breeding and gene manipulation, with the help of advanced bioengineering technology. Improved environmental monitoring devices, computers, and software will allow culturists to monitor, regulate, and adjust aquatic systems to increase production in existing facilities.1.39

Aeration has been used in ponds in Israel to increase production from an average of 5000 kg/ha to as much as 20,000 kg/ha.46 In recent years, the total area of fish ponds in Israel decreased 30%, but total production remained unchanged. Accumulation of waste products is now the greatest obstacle to further increases in fish production. Culture of fish in intensively managed water reuse systems is expected to expand as groundwater supplies become more limited The immediate application for reuse systems will probably be in maintaining brood fish and supporting hatchery operations for the production of fry and fingerlings.34 If aquaculture develops in the next few years as agriculture has in the past 50 years, it will become necessary to maintain brood fish and produce fingerlings throughout the year.23 Already, environmental manipulation has been used to induce fish to spawn four times per year when they normally spawned only once.56 Through selective breeding and environmental manipulation, trout have been developed that spawn twice a year, in spring and fall."

Aquaculture expansion will probably be most pronounced in the south and southeast where the farmers, like those in other areas of the country, are searching for new cash crops and are expected to convert agricultural land to aquatic production.32 The long growing season and the availability of land and water make further expansion in the south most likely. Computer simulation models are expected to allow producers and researchers to identify limiting factors in existing aquaculture facilities and provide data for development of alternative management plans.54 Fish culture in effluents from power plants is expected to increase as Americans place greater importance on energy conservation and investors realize the potential of thermally enriched waters.22 In 1978, there were 24 freshwater and 32 marine sites in the U. S. where either research or commercial aquaculture projects used thermal effluents.58

There is tremendous potential for expansion of aquaculture of brackish water and marine species along the coasts. Sportsmen, conservationists, and state agencies have combined forces in Texas and other states to produce red drum in hatcheries for stocking and release in coastal areas.47 The U.S. Fish and Wildlife Service, in cooperation with states along the Atlantic Coast and Gulf Coast, is producing striped bass in hatcheries for release into coastal areas.29 Resource managers are once again beginning to view fish culture as a valuable tool to be used in conjunction with other techniques to restore, maintain, or enhance natural stocks.44

In the short term, legal constraints and competition for space for recreational, navigational, industrial, and municipal uses will continue to be strong impediments to aquaculture expansion. In 1978, the National Research Council examined constraints and opportunities for aquaculture in the U.S.35 Legal constraints were identified then as one of the major obstacles to future development. They remain so today and are not expected to improve greatly in the future. Nevertheless, aquaculture has grown dramatically in the past few years and has apparently entered an exponential growth phase. The future of aquaculture in the U.S. appears bright and rapid expansion is expected to continue.

The demand for sport fish will continue to increase and commercial aquaculturists may I day be viewed as allies of natural resource managers. Farm-raised fish can supply markets for food fish and thus reduce pressure on natural stocks, making them available for harvest by recreationists. In 1982, P. A. Larkin, assessing the future of aquaculture in North America, found it conceivable that through aquaculture "many of the species now seen as gourmet items (shrimp, abalone, trout, salmon, and oysters) would become staples, and the esoteric foods would be those that defy culture and are only available by hunting in the ocean (cod, tuna. herring, king crab)."26 However, he predicted these changes only in areas where the cost of production was equal to or less than the cost of capturing fish from the ocean or inland waters. For many species (Atlantic salmon, trout, catfish, striped bass, red drum, and crawfish), the consumer demand now exceeds the supply of organisms from the wild. In 1980, F. W. Bell predicted aquaculture production to increase fivefold by the year 2000.6 If the current trend continues, his projected goal will be exceeded and the quantity of farm-raised fish will still be inadequate to meet the market demand.

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