Agricultural Research Service
U.S. DEPARTMENT OF AGRICULTURE

Aquaculture
National Program 106
Action Plan 2025 – 2029

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Vision

Science-based uses of natural resources meeting seafood demands of a growing global population

Mission

Conduct research and deliver information and technologies that improve domestic aquaculture production efficiency and product quality while minimizing impacts on natural resources.

Approach

Relationship of this National Program to the USDA Strategic Plan and the Agricultural Research Service (ARS) Strategic Plan 2023-2026.

This Action Plan outlines research that directly supports the USDA Strategic Plan Fiscal Years 2022-2026 and the ARS Strategic Plan 2023-2026: Finding Solutions to Agricultural Challenges with Agility, Innovation and Relevance. This plan specifically outlines research that supports Program Area 2: Animal Production and Protection and contributes to the following Strategic Goals and Objectives:

- Strategic Goal 2: Ensure America's Agricultural System is Equitable, Resilient, and Prosperous
    - Objective 2.2: Protect Agricultural Health by Minimizing Major Disease, Pests, and Wildlife Conflicts
- Strategic Goal 3: Foster an Equitable and Competitive Marketplace for All Agricultural Producers
- Strategic Goal 4: Provide all Americans with safe, nutritious food
    - Objective 4.1: Increase Food Security Through Assistance and Access to Nutritious and Affordable Food

Research in this Action Plan also aligns with other Federal strategic plans and initiatives including Grand Challenge Synergies, ARSX, The National Aquaculture Development Plan's National Strategic Plan for Aquaculture Research, and the Ocean Climate Action Plan (see Appendix A).

Relationship to the USDA Science and Research Strategy, 2023-2026

Research outlined in this Action Plan falls under Priority 4: Cultivating Resilient Ecosystems, in the USDA Science and Research Strategy, 2023-2026:Cultivating Scientific Innovation by contributing to the following Objectives:

- Objective 4.1 Genomics and Gene Editing
- Objective 4.2 Microbiome Research
- Objective 4.3 Sustainable Agro-and Aquatic Ecosystems
- Objective 4.4 Infectious Diseases and Pests
- Objective 4.5 Biodiversity

Notable updates to this Action Plan

This Action Plan reflects new and/or expanded program directions that are a result of new funding and guidance provided by the Congress and/or redirecting current capacities. For example, Component 3 has been expanded to include largemouth bass and baitfish, Component 4 now includes research on crawfish, and Components 5-7 were developed after the 2020-2024 NP106 Action Plan was first published. Specific examples of new directions are listed below.

Component 1: Catfish

- Developing data management and bioinformatic applications to aid in the genomic selection of

channel, blue, and hybrid catfish for improved growth and carcass yield traits
- Developing ante and postmortem strategies that improve the efficiency of processing and quality and consistency of catfish products

Component 2: Salmonids

- Implementing precision agriculture technologies to quantify new fish metrics associated with growth, disease status, and/or well-being in aquaculture production systems to increase efficiencies and profitability by defining phenotypes contributing to performance, developing methods for monitoring them, and strategies to improve performance through breeding and management practices
- Determining the susceptibility of North American Atlantic salmon selected for performance to new and emerging pathogens and developing strategies to improve their health
- Optimizing production efficiency in recirculating aquaculture systems (RAS) by developing breeding strategies and management practices that ensure the productivity and profitability of raising fish in RAS while maintaining high standards of animal well-being
- Reducing or eliminating off-flavor in salmonids

Component 3: Basses and Baitfish

- Developing genetic improvement strategies for largemouth bass
- Developing strategies to remove pests from baitfish harvests

Component 4: Mollusks and Crustaceans

- Improving prevention and control strategies for bacterial and parasitic diseases of crawfish and shrimp
- Applying genome-enabled selection to breed Pacific oysters for resistance to the oyster herpes virus microvariant-1
- Integrating quantitative genetics, molecular biology, and physiology to advance genetic improvement in eastern oysters produced on the Atlantic and Gulf of Mexico coasts

Component 5: Marine Warmwater Finfish

- Developing year-round spawning strategies for captive broodstock, larval culture methods for seed production, and genetic improvement technologies to optimize production efficiency

Component 6: Aquaponics

- Optimizing the integration of plant and fish production in aquaponic systems

Component 7: Tilapia

- Breeding tilapia for disease resistance and characterizing pathogens

Introduction

Aquaculture is the production of aquatic organisms under controlled conditions throughout part or all their lifespan. In 1980 Congress declared "***…*** *that aquaculture has the potential for reducing the United States trade deficit in fisheries products, for augmenting existing commercial and recreational fisheries, and for producing other renewable resources, thereby assisting the United States in meeting its future food needs and contributing to the solution of world resource problems. It is, therefore, in the national interest, and it is the national policy, to encourage the development of aquaculture in the United States.*" In response to this declaration, the ARS National Program for Aquaculture (NP 106) is focusing on research that supports the production of quality seafood products for human consumption.

Aquaculture production is growing because demands for healthy seafood products are increasing even as stocks of wild-caught seafood are dwindling from overfishing and other factors, including changing climates. Developing technologies that reduce production costs while maintaining or improving product quality will help U.S. aquaculture producers meet increasing demands. Producers, processors, and breeders need systems that maximize aquatic animal production, reduce environmental impacts, increase market competitiveness, sustain producers, and earn consumer confidence.

Aquaculture research is important for informing the development of science-based environmental policies that:

- Sustain aquaculture production while maintaining healthy and productive freshwater, coastal, and marine ecosystems, including offshore ecosystems
- Protect special aquatic areas
- Rebuild overfished wild stocks
- Restore populations of endangered species
- Restore and conserve freshwater, coastal, and marine habitats
- Balance competing uses of aquatic environments
- Create employment and business opportunities in rural inland, coastal, and urban communities
- Enable the production of safe and sustainably produced seafood and other products.

Research conducted in NP 106 supports commercial aquaculture production to ensure that a healthy, competitive, and sustainable aquaculture sector can produce an abundant, safe, healthy, and affordable supply of aquatic products. NP 106 work advances the efforts of more than 2,932 aquaculture farms annually producing goods worth more than $1.5 billion to meet the market demand generated by domestic and international customers.

Since the 1980s, capture fisheries production has been static and shows no signs of increasing. The *2020–2025 Dietary Guidelines for Americans* notes that Americans are consuming less than recommended amounts of seafood and recommends that they double their seafood intake. Domestic aquaculture production could displace seafood imports (about 50 percent of which are produced through aquaculture), meet increasing demands for seafood, and become the most readily available source of safe and sustainable seafood. In fact, aquaculture is now the source for about half of all fish produced for human consumption, and its contribution will increase as global demands for seafood increase. Currently, only 7 percent of domestic seafood production is from aquaculture.

In 2017, U.S. consumers spent an estimated $102 billion on seafood products, making it one of the top three seafood markets worldwide. Yet, U.S. marine and freshwater aquaculture production ranks 18th worldwide, producing 298,336 metric tons with a farm gate value approaching $1.5 billion annually. As a result, 90 percent of the seafood consumed in the United States (by value) is imported, resulting in a $17 billion trade deficit.

Seafood suppliers and producers recognize that wild-caught fisheries are producing at peak capacity. Aquaculture could play a critical role in using natural resources responsibly to meet the nutritional requirements of a growing global population. The United States is well-positioned to expand aquaculture production because of the following:

- *Dietary Guidelines* recommends that Americans double their seafood consumption, which would increase demand and more market opportunities for aquaculture products.
- The United States is a major producer of fish feeds and feed ingredients.
- There is an abundance of underused water resources, including the Exclusive Economic Zone and the Great Lakes.
- RAS support local production of native and non-native species.
- The U.S. regulatory framework ensures aquaculture production has minimal impacts on the environment and that harvested food is safe for consumption.
- The United States is a net seafood importer, so there is an existing domestic market demand and trade deficit for seafood products.

The U.S. capacity for innovation and technology development will enable the use of science-based approaches to expand responsible use of the Nation's natural resources and contribute towards meeting growing demands for aquatic products. Therefore, NP 106 focuses on research that supports the production of quality aquatic products. Research in the disciplines of genetics, nutrition, health, and physiology will support the production of aquatic animals, while studies in ecology, water quality, engineering, and food science will support the improvement of systems and products to ensure sustainability.

Stakeholder Input

In developing this Action Plan, USDA ARS scientists and the National Program Leader (NPL) for Aquaculture worked with the NPL covering aquaculture from USDA's National Institute of Food and Agriculture (NIFA) to solicit stakeholder input that would: 1) inform ARS about the status of ongoing industry challenges; 2) identify priorities to direct strategic research planning activities; and 3) inform ARS management about industry issues as they make programmatic decisions. ARS and NIFA representatives regularly communicate with industry stakeholders by taking part in meetings and maintaining connections with professional organizations and conferences. ARS, NIFA, and USDA's Animal and Plant Health Inspection Service (APHIS) hosted an internal USDA aquaculture listening session to identify the aquaculture science needs of other Agencies that our respective programs could address, and to identify collaborative opportunities. Appendix B lists specific outreach activities informing the development of this Action Plan. Finally, this Action Plan was informed by the results of a Retrospective Review conducted by an external panel of industry members and academic scientists, which provided a thorough evaluation of the effectiveness and impact of the ARS NP106 from 2018 to 2022.

ARS Aquaculture Research Capacity

ARS has 14 project teams (69 scientists total) at 15 different locations who conduct research that supports the ARS NP106 and participate in annually funded collaborations with 9 cooperating institutions (universities or non-profit institutions). Descriptions of ARS laboratories are provided in Appendix C.

Research Components

Component 1: Improving the Efficiency and Sustainability of Catfish Aquaculture

The leading U.S. aquaculture industry is the pond production of catfish. The 2018 Census of Aquaculture reported 531 catfish farms, primarily in Alabama, Arkansas, and Mississippi, having sales valued at $366,843,000. ARS research priorities for catfish were developed using information generated by the virtual listening session on May 16, 2023; direct interactions between ARS scientists and stakeholders at Catfish Farmers of America and Aquaculture America; and other communications. Stakeholders identified many priorities that NP 106 does not currently have the capacity to address, including:

- Expanded extension activities to give information about tools and technologies to farmers
- Technologies to improve RAS production of catfish
- Non-lethal methods of reducing bird depredations to reduce losses and prevent spread of disease
- Identifying sources of tainting substances responsible for product recalls under the Food Safety Inspection Service (FSIS) catfish inspection program
- Marketing research to support increasing demand for catfish products, including studies on new products and advertising that targets millennials
- Commercially applicable technologies for sampling pond fish inventories to help scheduling harvests and postharvest processing
- Pond inventory control methods to reduce fish carryover during times of increased supply
- Harvesting technologies that reduce fish stress and increase harvest and grading effectiveness
- Developing value-added products (e.g., strips, fish sticks, loins, smoked fish)
- Increasing the shelf life of fresh and frozen products, including the possible use of flavor enhancers
- Automation of catfish processing, including adapting processing equipment used in other fisheries, poultry, and meat operations; this would include modifying fillet machines that automatically adjust to fish size and evaluating imaging systems to optimize catfish fillet cuts
- Identifying alternative species for catfish farmers

Problem Statement 1A: Improve Catfish Aquaculture Production Efficiency

Catfish producers, processors, and fingerling suppliers need systems that optimize and maximize production, reduce environmental impact, increase market competitiveness, support sustainable production, and earn consumer confidence. Research in the disciplines of genetics, nutrition, and physiology will support the biological improvement of aquatic animals, while studies in ecology, water quality, engineering, and food science will advance the improvement of systems that minimize environmental impacts and ensure production of consistently high-quality products that meet consumer demand.

Research Focus

Genetics: Genetic improvement of catfish is a key strategy for increasing efficient and sustainable production. Factors that hinder the rate of improvement include a lack of well-defined phenotypes, inadequate understanding of component traits and interrelationships among traits, incomplete understanding of the molecular basis of phenotypes and trait interactions, lack of methods to model and evaluate candidate traits for selection, and inefficient strategies to incorporate genomic data into breeding programs. Facilitating genetic improvements requires new information about the genome and its interactions with environmental factors that can be placed in a comprehensive framework pertaining to aquatic animal growth, adaptation, health and well-being, reproductive efficiency, nutrient utilization, conversion of feed to flesh, and product quality.

Reproduction: Research needs include management strategies, including the use of spawning aids, which increase the efficiency of egg, fry, and fingerling production of channel, blue, and channel x blue hybrid catfish; and new methods to extend the spawning season for production of high-quality gametes.

Nutrition, Feeds, and Feeding: Research needs include the evaluation of feed formulations and nutrient availability from non-conventional feedstuffs. Information is also needed on the evaluation of dietary additives or feed formulations that may improve reproductive performance of broodstock and the growth, quality, and health of fingerlings and food fish. Research is also needed to develop optimum feeding strategies for different phases of production and to develop feeding strategies that help reduce the impact of large fish carried over from one production cycle to the next.

Systems Engineering and Pond Production: Research needs include designing and engineering alternative systems for catfish production from fry to stocker production using innovative, non-conventional approaches that optimize production, increase economic competitiveness, and reduce environmental impacts. Studies are needed to characterize new and conventional pond systems to determine how production inputs (e.g., fish stocking densities, feeding rates, and aeration intensity) can be combined to optimize economic performance and product quality. Information is also needed on how improved aeration, water quality monitoring systems, dynamic process control systems, and automation technologies would increase aquaculture production system reliability, efficiency, and cost effectiveness. Studies are also needed to identify and characterize ecological factors supporting the development of harmful pond microbial communities that produce flavor-tainting substances and toxins, and to develop technologies for controlling these harmful microbial communities. Research is needed on assessing water usage throughout the production process, evaluating how aquifers are affected when groundwater supplies are used to fill ponds, and how climate change affects aquaculture water budgets. Alternative technologies (water reuse instead of flow through or single pass) must be developed and evaluated to reduce GHG emissions and limit how aquaculture affects the hydrological cycle in the Mississippi Delta aquifer.

Anticipated Products

- Genome enabled strategies that accelerate the pace of genetic improvement
- Germplasm selected for economically important traits
- Cryo-preservation of select germplasm
- Strategies that improve efficiency of producing fry and fingerlings of channel, blue and channel × blue hybrid catfish
- New sustainable sources of feed ingredients
- Diets optimized for growth and economic returns of fingerlings and food fish, and to improve reproductive efficiency of broodfish
- Economical feeding practices for all stages of catfish production, including feeding practices to reduce the impact of large carryover fish
- Ecologically optimized pond production systems that improve productivity and economic returns
- Strategies to control harmful microbial communities that support the production of toxins and flavor-tainting substances
- Quantification of GHG emissions from catfish aquaculture ponds by eddy covariance observations

Potential Benefits

- The development of genome-enabling tools and technologies will facilitate the continued genetic improvement of catfish and identify the functional roles and interactions of gene products in aquatic production animals.
- An improved understanding of the biology underlying economically important traits will facilitate the development of improved management practices, increase the proportion of variation attributable to genetic sources, and enhance the accuracy of selective breeding.
- Increased reproductive success will lead to more stable and economical production of channel, blue, and channel × blue hybrid fingerlings.
- Formulating diets will promote optimal growth at different life stages and reproductive performance, improve product quality, and improve production efficiency. Increasing the number of high-quality alternative ingredients will supply flexibility in formulating the most economical diets. Developing feeding strategies to reduce the impact of carryover large fish will improve economic returns during periods of fish oversupply.
- Technological developments to improve pond production systems will increase productivity, reduce yield variations, reduce emission of potential pollutants, improve water quality, and increase water use efficiency.
- Gathering information about how current catfish aquaculture practice affects the annual methane flux from pond production and its impact compared to other aquaculture methods and agricultural practices.
- Compiling water use information that can provide data for improving system and management inefficiencies.

Problem Statement 1B: Reduce the Impacts of Disease in Catfish Aquaculture

Health management strategies, technologies, and biosecurity plans that are safe for the environment are necessary to reduce disease-related losses. Industry growth in catfish aquaculture has been hindered by a lack of validated technologies for early and rapid disease detection, prevention, and treatment. Validated diagnostic tools are needed in production systems to quickly detect disease agents. Developing effective control strategies and therapeutants to manage disease is also a priority, since there are currently only a few drugs that have been approved for treating sick fish. New research will support the development of effective vaccines and methods for mass vaccination of aquatic animals.

Research Focus

Research needs include developing new methods of combatting the effects of disease in catfish aquaculture. Stakeholders identified the following pathogens as particularly problematic:

- *Flavobacterium columnare* outbreaks in fingerlings;
- *Edwardsiella tarda* outbreaks at the food fish stage;
- *Aeromonas hydrophila* outbreaks, primarily in west Alabama and east Mississippi; and
- *Edwardsiella ictaluri,* the causative agent of widespread enteric septicemia in catfish.

Host Immunity: Developing new disease control strategies will require identifying host molecular pathways involved with innate and acquired immune responses and understanding host immune system responses to pathogens and/or the development of disease. Identifying genetic variation in immune disease response will advance efforts to breed fish that are more tolerant of or resistant to disease. Finding new ways to deploy multiple lines of protection in catfish will first require understanding how the catfish immune system responds to vaccination and the variation of response exhibited by different catfish lines.

Pathogens: Methods and reagents to rapidly detect pathogens and diagnose diseases in aquatic species are still unavailable or lack farm scale application. Microbial genomic sequences (e.g., diagnostic regions of the genome) will be important tools for pathogen identification and for understanding pathogenesis. Strategies are needed to find effective treatments, understand their pharmacokinetics, and apply therapeutants for control. Disease challenge model development is needed for key pathogens to evaluate therapeutants and host resistance and/or response to disease.

Catfish producers have few vaccines available to prevent infectious disease agents and it is not always economically possible to use these vaccines in aquaculture production. Vaccine research must deliver products that are safe, easy to administer, and effective in aquaculture production systems. The development of new vaccines will require killed, modified-live, DNA, and recombinant technologies, as well as information obtained from microbial genomics and proteomics. Additionally, mass vaccination strategies, such as immersion or oral delivery, need to be developed to make vaccination possible in aquaculture production systems.

Anticipated Products

- Identification and characterization of catfish pathogens
- New vaccine development and optimization
- Integrated approaches for managing fish health

Potential Benefits

- Information on immune system components will identify targets that can be enhanced to improve fish health.
- Sequence information on microbial genomes will facilitate pathogen identification and improve understanding of disease pathogenesis and virulence factors. Identification of microbial genes and pathways critical for pathogenesis will inform vaccine development.
- Fish with enhanced resistance will form the basis of select disease-resistant lines.
- Vaccines would increase producer profits by reducing the need for therapeutants (e.g., antibiotics) and chemical treatments.
- Reduced antibiotic use will lessen the environmental impact of aquaculture production.
- Integrated approaches that reduce on-farm losses to disease will increase production efficiency and profitability and improve aquatic animal health and well-being.

Problem Statement 1C: Improve Catfish Product Quality

The success of the catfish aquaculture industry depends on supplying a consistently high-quality product that meets consumer expectations for flavor, color, texture, and firmness.

Research Focus

Product Quality: Studies are needed to determine how genetics, rearing, and harvesting practices affect product quality. Results must support the development of economically viable methods that measure quality attributes such as off-flavors, color, firmness, and texture; the evaluation of production system practices that affect these quality parameters; and the development of systems that optimize product quality and uniformity. Additional research includes work that supports enhancing and improving pond management, developing technologies to reduce off-flavor in fish by controlling the phytoplankton species that comprise the photosynthesizing biomass in production ponds, and continuing to develop strategies for remediating off-flavor compounds and identifying other compounds contributing to off-flavors.

Anticipated Products

- Production strategies that improve and ensure consistency of flavor, color, firmness, texture, and other catfish product quality attributes
- Development of new and improved methods to evaluate quality and consistency of color, firmness, flavor, and other sensory characteristics of catfish products

Potential Benefits

- Improved rearing and harvest strategies will enhance product quality.
- Reducing the negative impacts of undesirable microbial communities will reduce the number of off-flavor episodes and reduce product losses from algal toxins.
- Improving product quality could increase the demand for domestic products, while efforts to improve coproduct use will improve the efficiency of cost-effective and environmentally sustainable production.

Component 1 Resources

- Warmwater Aquaculture Research Unit, Stoneville, Mississippi
- Aquatic Animal Health Research Unit, Auburn, Alabama
- Food Processing and Sensory Quality Research Unit, New Orleans, Louisiana

Component 2: Improving the Efficiency and Sustainability of Salmonid Aquaculture

Rainbow trout (*Oncorhynchus mykiss*) are the most widely farmed cold freshwater species and the second most valuable finfish aquaculture product in the United States. Thirty-five states produce rainbow trout for food; production primarily occurs in the Snake River Valley of Idaho, California, Washington, North Carolina, Pennsylvania, and West Virginia. The 2018 *Census of Aquaculture* identified 334 farms whose sales were valued at $116,704,000. In addition to food fish, rainbow trout are key contributors to the economic success of recreational and sport fisheries. Therefore, many trout farmers produce fish for both food and recreation, which significantly broadens the impact of trout aquaculture on the U.S. economy.

The 2018 *Census of Aquaculture* also reported 13 Atlantic salmon farms producing food fish. In 2017, the United States imported 122,002 metric tons of Atlantic salmon. These numbers suggest that expanding and optimizing the U.S. use of natural resources to increase aquaculture production could greatly reduce the seafood trade deficit. More than 100 net pen sites are currently available for farming, and to date commercial investments of more than $1 billion have been made towards expanding land-based production. ARS research priorities for salmonids were informed by the virtual listening session on May 17, 2023, associated correspondence; direct interactions between ARS scientists and salmonid stakeholders at meetings of the United States Trout Farmers Association and Aquaculture America; and other communications. Stakeholders identified many priorities that ARS does not currently have the capacity to study, including:

- Traceability issues, including marketing narratives about fish production
- Targeted workforce development, including academic-industry partnerships, and programs for students in high school, vocational programs, and undergraduate programs
- Counteracting misinformation and negative media perceptions of farmed fish
- Revising or eliminating regulatory policies not originally intended for aquaculture, including those that may have significant administrative costs associated with documenting compliance
- Research in coho salmon

Problem Statement 2A: Improve Salmonid Aquaculture Production Efficiency and Ensure Product Quality

Salmonid producers need systems that optimize and maximize production, reduce environmental impacts, increase market competitiveness, sustain producers, and earn consumer confidence. Research in the disciplines of genetics, nutrition, and physiology will support the biological improvement of aquatic animals, while studies on water quality and engineering will support system improvements that minimize environmental impacts.

Research Focus

Genetics: Genetic improvement in salmonids is a key strategy for increasing production efficiency, but much more information is needed to advance these efforts. This includes the need for:

- More well-defined phenotypes
- Information about component traits and interrelationships among traits
- Information about the molecular basis of phenotypes and trait interactions, including epigenetic components
- Methods to model and evaluate candidate traits for selection
- Improved strategies to incorporate epigenetic and genomic data into breeding and production broodstock programs

To facilitate genetic improvement, new knowledge of the genome and epigenome and their interactions with environmental factors needs to be consolidated in a comprehensive framework pertaining to aquatic animal growth, adaptation to pathogen and environmental stresses, health and well-being, reproductive efficiency, nutrient utilization, feed conversion to aquatic animal products, and product quality. Research has demonstrated that fish epigenomes can be altered so that intake and metabolization of plant proteins and carbohydrates, thermotolerance, and upregulation of disease moderating immunological factors are improved during developmental stages. Research is needed in this area for more rapid or trait specific improvement in a subset or entire population of animals.

The creation of transgenic animal lines has demonstrated biotechnology can potentially be used in the genetic improvement of animals for superior performance. Gene editing technologies recently developed for salmonids may potentially offer dramatic advances in efforts to develop superior genetics and elucidate the functions of genes that underlie the biology of production traits. However, precision breeding strategies that use gene editing technology to improve yields and/or enhance production efficiency need to be validated before these advances can be achieved.

Hatchery: Research needs include developing and optimizing hatchery practices (i.e., handling, feeding) to improve egg quality. Research is also needed to advance the development of new strategies controlling gonadal development and spawning; this work will help optimize production efficiency and reduce the potential impact of escapes by inducing sterility.

Management Practices and Production Systems: Research is needed to develop nutritionally optimized and environmentally sustainable feeds, and to reduce and remove waste from flow-through, net pens, and RAS systems. Using sustainable feeds that are developed and formulated for optimal nutrient uptake will improve feed utilization while incorporating feed components from multiple sustainable production streams and reduce cost and the release of excess harmful waste products. Furthermore, improving mineral and solid waste removal from production systems can reduce stress, improve the taste and health of fish in these production systems, and allow producers to meet daily allowed limits for phosphorus, nitrogen, and other monitored waste products. Consequently, this research will reduce production costs and enhance fish health. It will also improve water quality around net pens, in RAS discharge, and in flow through systems, which will protect the environment and improve public perception of aquaculture. Although mostly observed in pond aquaculture, RAS can experience build up of off-flavor compounds such as geosmin and 2-methylisoborneol that are absorbed through the gills and retained in fish flesh, research is needed to eliminate or reduce off-flavor compounds in these systems.

Fish density, feed, water chemistry, endemic pathogens, microbiomes, and management practices are all factors affecting the environment in dynamic aquaculture production systems. Scientists need to confirm that research performed under laboratory conditions is applicable under production settings. Researchers need to test strains of trout and varied dietary formulations under replicative and controlled production system conditions that can be accurately monitored and that will provide useful evidence of how modifications in feed, fish, and production practices will function at commercial facilities.

Using lumpfish to control sea lice infestations in Atlantic salmon net pen aquaculture is an effective strategy for improving animal well-being and product quality, but more research is needed on using native genetic resources to establish lumpfish broodstock populations that are effective for sea lice control.

Anticipated Products

- Atlantic salmon and rainbow trout germplasm selected for traits associated with production efficiency and/or product quality
- Genome-enabled strategies for selective breeding
- Programming strategies for epigenetic improvement of fish for specific critical production traits
- Evaluations of the potential use of gene editing technology as a precision breeding tool for trait improvement
- Cryo-preservation of select germplasm
- Competitively priced, nutritionally optimized, and sustainably produced formulated feeds that will improve nutrient utilization and feed efficiency
- Feed formulations that reduce the release of harmful effluent materials from net pen environments, in RAS systems, and in pond and flow through production
- Defined criteria for water and fish monitoring that will improve production efficiency when proper management, trout strains, and feeds are employed
- Enhanced methods for ingredient processing to improve nutritional value
- Defined nutrient requirements and digestibility for fish consuming diets supplemented with non-conventional protein and fat sources
- Lumpfish control of sea lice
- Strategies that improve egg quality, hatch, and survival
- Sterile fish technologies that direct metabolism towards growth and prevent impacts from escapes
- Improved operational technologies to enhance the viability of land-based salmonid RAS
- Defined criteria for optimal environmental conditions for salmonids in RAS
- Precision aquaculture technologies for estimating fish biomass and indicating status of fish welfare
- Methods to detect off-flavor in salmonids and strategies to reduce or eliminate off-flavor compounds in RAS
- Improved technologies for waste capture and effluent reuse, and using waste for viable revenue streams

Potential Benefits

- The development of gene editing and other genome-enabling tools and technologies will facilitate continued genetic improvement for aquatic animal production systems. These tools will identify the functional role and interactions of gene products in aquatic production animals. Better understanding of the underlying biology will allow improved management and enhance accuracy of selective breeding.
- The improved definition of complex traits will support more targeted genetic improvement. These traits include key characteristics associated with profitability, such as feed efficiency and disease resistance. Moreover, more accurate identifications of elite genetic seed stock will reduce the time needed to introduce genetic changes. Enhancing genetic improvement programs by defining and adding traits will let producers and breeders use available genetic enhancements more effectively and determine the optimum environments and diets for more profitable and sustainable aquaculture.
- Increased reproductive success will lead to more stable, profitable, and cost-effective production of aquatic animals by improving overall farm productivity and increasing the uniformity of growth rates and body conformation.
- Increasing RAS automation levels will lower labor costs and improve the cost competitiveness of domestic aquaculture products. Improved efficiencies in production and waste removal will maximize production per unit of volume. These improved efficiencies include reducing energy demands, increasing the optimization of RAS and systems that tightly control the fish production environment, limiting pathogen migration in and out of the RAS; and enhancing RAS with waste capture/utilization loops.

Problem Statement 2B: Reduce the Impacts of Disease in Salmonid Aquaculture

Environmental conditions exacerbate disease outbreaks and increase infectious disease losses from viral, bacterial, and parasitic pathogens, which often occur in mixed combinations. Developing new strategies to control disease requires identifying the host molecular pathways associated with innate and acquired immune responses to common pathogens and understanding how the host immune system evades pathogens and prevents or mitigates the onset of disease. Acquiring the information needed to develop genetic enhancements for disease resistance requires studying aquatic animals with divergent responses to disease challenge and identifying the genetic sources of variation correlated with innate and/or acquired immune status. In addition, more information is needed about how the immune system of aquatic animals responds to vaccination, the variation in vaccine response, and the mechanisms of protection, all of which will help identify options for deploying multiple lines of protection. Understanding how environmental conditions influence host immunity and pathogen prevalence may reveal new strategies for reducing disease outbreaks in production environments.

Research Focus

Host Immunity: Research needs include evaluating the immune responses of aquatic animals exposed to key pathogens. The availability of near-complete genome sequences of rainbow trout and Atlantic salmon will support the comprehensive identification of immune genes. Additionally, studies of aquatic animals with resistant/susceptible phenotypes will facilitate understanding the biochemical functions of genes that lead to reduced mortality. Researchers can identify genetic variations in response to vaccination and use that information to select traits associated with robust responses and determine the relationship between genes and vaccine efficacy.

Few vaccines are available for preventing viral and bacterial diseases and there are no vaccines to prevent parasite infestations and associated losses. It is not always economically feasible to use vaccines that are currently available because of their costly injection delivery; in addition, scientists still need to determine how long these vaccines convey immunity. Vaccine research must result in a product that is safe, easy to administer, and protects against disease throughout the production cycle. The development of new vaccines will require techniques such as killed, modified-live, DNA, and recombinant technologies, while microbial genomics, proteomics, and functional genetics will inform the development of novel vaccines. Additionally, feasible vaccination strategies for many fish species require mass vaccination, such as vaccination through immersing juveniles or eggs or by providing oral vaccinations through feed supplements. In addition, vaccines delivered to young fish need to prevent disease up until harvest and oral booster vaccinations may be needed to provide this level of protection. Determining how immunostimulants, probiotics, and post-biotics augment innate immunity or vaccination is a priority.

Pathogens: Methods to rapidly detect pathogens and diagnose diseases in aquatic species are still unavailable or lack farm-scale application. Microbial genomic sequences, or diagnostic regions of the genome, will be important tools for identifying pathogens, understanding pathogenesis, and predicting antibiotic resistance. Developing strategies to identify pathogen-specific treatments is a priority. The development of disease challenge protocols for key pathogens is needed for studies of host resistance and responsiveness. Analysis of the microbiome of aquaculture tanks and water systems is important for pathogen source tracking in flow-through and RAS.

Environmental parameters influencing disease outbreaks: Salmonid fish aquaculture occurs in diverse environments that influence host immunity and pathogen prevalence through complex interactions. For example, some producers rear trout under large temperature variations (3-19^{o} C) and disease outbreaks are associated with high temperature. Other producers maintain constant water temperatures of 14-15^{o} C, but water reuse can lead to limited oxygen levels correlated with disease outbreaks. The availability of defined genetic lines reared under laboratory and farm conditions will facilitate an understanding of how environmental conditions affect host immunity and pathogen susceptibility and will support efforts to breed more resilient genetic stocks.

Anticipated Products

- Development of germplasm with increased pest or pathogen resistance
- Development of vaccines for controlling outbreaks of harmful pathogens
- Understanding of how on-farm environmental parameters affect the immune system
- Genome sequences of emerging pathogens that support the development of diagnostic assays and new vaccines
- Rapid assays for major pathogens
- Microbiome analysis of on-farm environments and development of methods to disrupt pathogen establishment in production systems
- Improved understanding of the epidemiology of emerging pathogens

Potential Benefits

- Information on immune system components will help identify genetic locations that can be targeted to enhance immune system responsiveness. Aquatic animals with enhanced resistance will form the basis of select disease-resistant lines. Identifying genes and markers related to immunity will also help locate genetic markers that can be used to reduce mortality.
- Sequence information on microbial genomes will permit better pathogen identification, improve understanding of pathogenesis and virulence factors, and support the identification of vaccine antigens.
- Vaccines hold the potential to reduce the need for other therapeutants (*e.g.*, antibiotics), which

improves cost-effective aquaculture production by reducing the need for reactive drug use and improves environmental sustainability by reducing the use for antibiotics and other antimicrobial compounds. Improved biosecurity and pathogen refuge disruption should lessen the frequency and dispersion of disease problems, improve aquatic animal well-being, and increase system productivity and reliability.

Component 2 Resources

- National Center for Cool and Cold-Water Aquaculture, Leetown, West Virginia
- Small Grains and Potato Germplasm Research Unit, Hagerman, Idaho
- National Cold Water Marine Aquaculture Center, Franklin, Maine
- Food Processing and Sensory Quality Research Unit, New Orleans, Louisiana

Component 3: Improving the Efficiency and Sustainability of Bass and Baitfish Aquaculture

The 2018 *Census of Aquaculture* reported 62 farms producing fingerling and food-size hybrid striped bass with sales valued at $34,878,000; Similarly, the Census reports 195 largemouth bass farms with a farm gate of $27,458,000, and 168 baitfish farms valued at $32,778,000. Key farming states include Arizona, Arkansas, California, Colorado, Florida, Illinois, Indiana, Kansas, Kentucky, Maryland, Mississippi, Nebraska, New York, North Carolina, Ohio, Pennsylvania, Texas, Utah, and Virginia.

ARS research priorities for basses and baitfish were informed by the virtual listening session on May 18, 2023, the February 2023 meeting of the Arkansas Bait and Ornamental Fish Growers Association, and direct interactions between ARS scientists and bass and baitfish stakeholders. Stakeholders identified many priorities that ARS does not currently have the capacity to study, including:

- Technologies to develop sterile hybrid striped bass that do not sexually mature during the production cycle
- Development of an effective, cheap tranquilizer with short withdrawal periods that is approved for use in the United States
- Changing state regulatory policies around effluent requirements
- Reducing the impacts of bird predation on aquaculture ponds
- Research on marine baitfish

Problem Statement 3A: Enhance Bass Aquaculture Production

Bass producers need systems that optimize and maximize production, reduce environmental impacts, increase market competitiveness, sustain producers, and maintain and enhance consumer desirability. Research in the disciplines of genetics, nutrition, microbiology, and immunology will support the biological improvement of aquatic animals, while research in water quality management and production system engineering will improve water quality, fish well-being, and product quality.

Genetic improvement of parental strains that results in increased hybrid performance is a highly desirable step toward increasing production. White bass populations have been particularly difficult to establish. Available domesticated strains can be propagated at the experimental station, but do not always perform well when transferred to commercial aquaculture conditions. As a result, hybrid striped bass producers prefer to use wild-caught white bass in their breeding programs, a strategy that is costly, unsustainable, and often results in hybrid offspring characterized by uncontrolled variation.

Nutritional advances will support the continued expansion of bass production. A critical component of these advances will include using more sustainable sources of protein, fat, and energy to improve and expand feed efficiencies and ingredients. Replacing marine fish meal and marine oils with practical feed formulations developed from plant and animal industry byproducts and coproducts, enzymes, and nutritional supplements is a priority, and the safety and efficacy of these byproducts and coproducts must be determined. The market for larger hybrid striped bass is also expanding, and emerging consumer issues associated with fat accumulation and fillet quality require the development of diet formulations to optimize lean gain and muscle integrity.

Production practices and water quality affect interactions among nutrients, water, and aeration inputs, and together affect the environmental impact of effluents. Information is needed to improve intensified management strategies and systems that optimize water quality management, production, and water utilization efficiency, and reduce environment impacts. In addition, consumer preferences for larger fish results in reduced production efficiency and has negative impacts on water quality conditions.

Health management strategies, technologies, and biosecurity plans are needed that protect the environment, ensure the safety of food supplies from aquaculture production, and reduce disease-related losses. The growth of the hybrid striped bass industry has been hindered by the lack of validated technologies for early and rapid disease detection, prevention, and treatment in hybrid striped bass aquaculture. To overcome this obstacle, research is needed on the development of validated, rapid diagnostic tools that detect pathogenic organisms from fish grown in various production systems, as well as on the development of effective control strategies and therapeutants for managing disease outbreaks.

Research Focus

Genetics: Research needs include developing domesticated and genetically improved white bass optimized for hybrid striped bass performance and eliminating reliance on wild-caught broodstock. Developing broodstock and production techniques that provide a reliable year-round supply of hybrid striped bass is a priority.

Nutrition: Research needs include optimizing grow out diets for cost effectiveness, meeting nutrient requirements, maintaining water quality in various production systems, and enhancing product quality.

Production Systems: Research needs include optimizing management strategies for stocking rates, feeding regimes, dissolved oxygen levels, and dissolved inorganic nitrogen levels for use in intensified production systems. More information is also needed about factors that affect ammonia toxicity under various production systems to develop rapid assessment and management practices.

Host Immunity and Pathogens: Research needs include understanding the variability of disease susceptibility among striped bass, white bass and hybrid striped bass and developing genetic improvement strategies that address these vulnerabilities. Additional research to understand the immune system function and capability of hybrid striped bass will assist in the development of effective therapeutants to reduce on-farm disease losses.

Anticipated Products

- Genetic improvement of production traits in hybrid striped bass such as growth, nutrient efficiency, fillet yield and/or resistance to disease
- Transfer of germplasm selected for economically important traits
- Cryo-preservation of select germplasm
- Effective strategies for controlling disease
- Nutrient requirements and digestibility for fish consuming diets supplemented with non-conventional protein and fat sources
- Improved efficiency of intensive production systems

Potential Benefits

- Genetic improvement for hybrid species production requires developing genomic tools and technologies for both parental species. Implementing these tools to improve the performance of the hybrid will also increase our understanding of hybrid vigor and non-additive genetics and provide insight into the biological processes underlying important production traits.
- The identification of microbial genes and pathways critical for microbial pathogenesis will aid in the development of vaccines and other approaches for preventing disease.
- Determining the value of alternative feed ingredients will provide cost effective diet formulations that meet the nutrient requirements of hybrid striped bass throughout the production cycle.

Problem Statement 3B: Aquatic Pest Management in Baitfish Aquaculture

Research Focus

Removing Aquatic Pests at Harvest: Research is needed to develop strategies to prevent the capture of aquatic pests during baitfish harvests. Pests such as crawfish can carry pathogens, require expensive labor to remove, and can be illegal to ship across state lines, even if inadvertently included in product packaging.

Anticipated Products

- Effective strategies for removing aquatic pests from baitfish harvests

Potential Benefits

- Reducing or eliminating aquatic pests from baitfish harvests will improve production efficiency.
- Reduce farmer liabilities for inadvertently shipping pests across state lines.
- Reduce potential legal consequences associated with pest shipments.

Component 3 Resources

- Harry K. Dupree Stuttgart National Aquaculture Research Center, Stuttgart, Arkansas

Component 4: Enhancing Molluscan and Crustacean Aquaculture

The 2018 *Census of Aquaculture* identified 528 farms producing the eastern oyster with sales valued at $134,385,000; 145 farms producing the Pacific oyster with sales valued at $89,467,000; 39 shrimp or prawn farms with sales valued at $45,626,000; and 482 crawfish farms valued at $50,848,000. Recent shellfish production has been increasing through the addition of land-based shrimp farms and facilitated access to new oyster leases. Oyster farms are currently enjoying increased demands due to changing food trends and recognition that oysters provide ecosystems services via habitat creation/restoration, shoreline stabilization, water filtration and clarification, and carbon sequestration, which increases opportunities to expand and optimize production. In addition, a 2019 trade deficit of $17 billion due to shrimp imports signals a chance for expanding domestic production to meet market demands.

ARS research priorities for mollusks and crustaceans were informed by the virtual listening session on May 19, 2023, and associated correspondence; stakeholders identified many priorities that ARS does not currently have the capacity to address, including:

- Protection and enhancement of water quality in shellfish production areas
- Work on molluscan species other than Pacific and Eastern oyster
- Aquaculture training, education, and outreach
- Harvesting and processing technologies

- Marketing and promoting shellfish culture
- Drafting regulatory policies such as amending the Fecal Coliform Standard
- Providing aquaculture extension support

Problem Statement 4A: Enhance Molluscan Aquaculture Production

Molluscan shellfish producers need systems that optimize and maximize production, reduce environmental impacts, increase market competitiveness, sustain producers, and earn consumer confidence. Research in the disciplines of genetics and physiology will support the breeding and management of improved stocks of aquatic animals that are resilient to threats posed by disease and other stressors in changing production environments, while research in ecology will support improving production systems by characterizing the spatial scale and ecological function of these systems and finding strategies to minimize their impacts on other important habitats.

Research Focus

Genetics: Research is needed for using genome information to accelerate genetic improvement and generate oysters that are resistant or tolerant to disease but retain optimal performance across production environments. More information is needed about the genome and its plasticity and diversity to fully use genome enabled management strategies. While several oyster genomes are now available, improved and higher-quality annotated genomes for diverse oyster stocks would facilitate their use in breeding programs and provide a better understanding of interactions with multiple stressors such as disease, ocean acidification, water temperature, salinity, algal blooms, and microbes. This includes:

- Identifying and understanding the function of oyster genes and genetic pathways associated with important traits such as disease resistance and/or tolerance as targets for selection
- Understanding the interactions between the oyster genome and environmental factors, such as ocean acidification, salinity, water temperature, algal blooms, and microbes, to create or select for resilient oyster stocks
- Characterizing existing genetic diversity within available stocks and in naturalized populations to investigate sources for new traits and to evaluate the full potential of a breeding program
- Expanding the use on precision phenotyping to study physiological mechanisms regulating growth, reproduction, disease resistance, and stress tolerance in oysters and developing criteria for assessing these mechanisms that can be applied within selective breeding programs

There is a need to enhance the efficiency of Pacific oyster production and reduce operational costs. More comprehensive information on oyster physiology and genes associated with traits for growth and reproduction is needed. Oysters invest energy in reproduction, which reduces tissue growth and condition, particularly when these oysters spawn. The industry currently, produces triploids to obtain non-fertile oysters, but triploid oysters and diploids that have just spawned are more susceptible to summer mortality, probably because of other stressors. Strategies to produce non-fertile oysters either by manipulating ploidy or using molecular tools including RNA interference or CRISPR need further investigation.

Production Systems and Estuarine Environment: Research needs include understanding the biology and ecology of shellfish parasites and pests to develop strategies to reduce mortality at local and regional scales. This involves monitoring pest and parasite abundance and multiple environmental stressors at representative sites where shellfish are farmed and breeding program families deployed.

Research is needed to identify and quantify interactions between aquaculture practices and natural resources. Estuarine landscape-scale ecosystem services provided by shellfish production systems also need to be defined and quantified.

Anticipated Products

- Genome-enabled strategies for genetic improvement of oysters
- Oyster stocks genetically improved for disease resistance
- Information on genetic diversity across oyster populations
- Cryo-preservation of select germplasm
- Predictive tools for evaluating and adjusting shellfish grow-out practices to avoid juvenile mortality, potentially mitigate for stressors due to climate change, and confer strategies for new and expanded shellfish operations
- Strategies for reducing the impacts of burrowing shrimp on shellfish tidelands

Potential Benefits

- Improved understanding of infectious oyster diseases and development of control measures
- Environmentally compatible practices to combat shellfish pests
- Published science that the shellfish industry can use to complete environmental management plans and policy makers can use to develop science-based policy that sustains production and maintains the marine environment
- Information on genetic diversity across oyster populations
- Tools for evaluating and adjusting shellfish grow-out practices to minimize juvenile oyster mortality due to pests and parasites, potentially mitigate for stressors due to climate change, and confer strategies for new and expanded shellfish operations

Problem Statement 4B: Enhance Crustacean Aquaculture Production

Shrimp and crawfish producers need systems that are free of disease, optimize and maximize production, reduce environmental impacts, increase market competitiveness, sustain producers, and earn consumer confidence. Research in aquatic animal health and diseases is needed to reduce on-farm losses from pests and pathogens.

Research Focus

Reducing Mortality: Research needs include identifying the cause of late term mortality experienced by inland shrimp farmers and developing strategies that improve shrimp survival. Research is also needed to reduce on-farm losses to white spot syndrome virus.

Production Systems and Water Quality: Research needs include developing strategies to reduce mortality caused by pests and identifying and quantifying interactions between aquaculture practices and natural resources to benefit crustacean production and satisfy regulatory constraints.

Anticipated Products

- Strategies to reduce on-farm disease losses for inland shrimp and crawfish production

Potential Benefits

- Improved understanding of infectious crustacean diseases and development of control measures

Component 4 Resources

- National Cold Water Marine Aquaculture Center, Franklin, Maine (worksite: Kingston, Rhode Island)
- Pacific Shellfish Research Unit, Newport, Oregon
- Aquatic Animal Health Research Unit, Auburn, Alabama

Component 5: Developing Marine Finfish Seedstocks

The United States has tremendous capacity for meeting the domestic demand for seafood by expanding aquaculture in marine waters and land-based RAS. The United States is the largest importer of seafood products, so expanding domestic production will reduce our reliance on imports and the trade deficit. Acknowledging this opportunity, Congress in the FY2019 Budget issued the following guidance: "*The Committee is concerned that vital seedstock to support the development of aquaculture in federal waters of the Gulf of Mexico will be sourced from foreign aquaculture producers. Domestic on-land recirculating aquaculture systems and offshore aquaculture are highly capable of producing a steady supply of marine fish seedstock to support new offshore and aquaculture industries. This includes broodstock acquisition and care, spawning, larval culture techniques, and juvenile rearing*."

In support of this guidance, Congress provided ARS with funding "*for the development effort of aquaculture technology that will ensure a steady supply of warm water marine fish seedstock for economic growth of the U.S. aquaculture industry*." This component outlines research that will facilitate the development of marine finfish seedstocks in support of expanding U.S. aquaculture production.

In the 2019 NOAA publication *Fisheries of the United States*, harvests from U.S. commercial capture fisheries were reported for more than 85 individual marine finfish species. These species are already sold commercially and are candidates for developing aquaculture industries that will meet increasing seafood demands through domestic aquaculture production. Adding other species with markets that are too small to quantify to this list results in a list of more than 100 U.S. native species that are potential candidates for aquaculture. Non-native finfish species that are imported for U.S. consumption are also candidates for domestic aquaculture production in land-based closed containment systems.

ARS research priorities for marine warmwater finfish were developed using information generated by a virtual listening session on June 6, 2023, and focus group meetings held at least once a year. ARS narrowed down the list of candidate species for research to 18 through a series of stakeholder input activities that considered species' status towards domestication, potential market value, stakeholder interest, and current culture limitations that could be addressed through research. To begin this process, a workshop entitled "Marine Fish Aquaculture Scoping Workshop" was hosted by the Harbor Branch Oceanographic Institute in March 2017. In this event, participants from federal and state agencies, academia, and the private sector discussed the merits of various marine species for advancing domestic aquaculture. Then a nationwide survey was distributed that sought technical information on various aspects of culture for 18 species highlighted in the workshop. Finally, a special session hosted by ARS, NIFA, NOAA, and the Harbor Branch Oceanographic Institute was held March 10 at Aquaculture 2019 entitled "Status of Marine Finfish Species for U.S. Aquaculture." This event, which is now held annually as a session at Aquaculture America, was attended by approximately 200 stakeholders from federal and state agencies, academia, and the private sector and provided expert analyses of the status of each species. The outcomes of this special session *(archived at* Status of Marine Fish | Florida Atlantic University (fau.edu)*)* included:

- Summarizing the state of aquaculture readiness for each of the 18 species listed in the survey as commercially ready, technologically feasible, or experimental
- Categorizing the top species by assessing their readiness for production in growing and/or establishing industries
- Identifying research directions for removing barriers to commercialization

Although many marine finfish species were proposed, the following 18 species were identified as primary targets for research that will facilitate the development of domestic aquaculture industries:

Species that are Experimentally/Technologically Feasible

- Spotted Seatrout, Cynoscion nebulosus
- Spotted Wolffish, Anarhichas minor
- California Halibut, Paralichthys californicus
- Southern Flounder, Paralichthys lethostigma
- Summer Flounder, Paralichthys dentatus
- Tripletail, Lobotes surinamensis
- Greater Amberjack, Seriola dumerili

Species that are Commercially Ready

- Almaco Jack, Seriola rivoliana
- California Yellowtail, *Seriola lalandi*
- Black Sea Bass, Centropristis striata
- Cobia, Rachycentron canadum
- Atlantic Cod, *Gadus morhua*
- Striped Bass, Morone saxatilis
- White Seabass, Atractoscion nobilis
- Red Drum, Sciaenops ocellatus
- Florida Pompano, Trachinotus carolinus
- Sablefish, Anoplopoma fimbria
- Olive Flounder, Paralichthys olivaceus

ARS research under this component will aim to develop seedstock and culture technologies for species selected from these lists and/or other high priority marine finfish species. Research will optimize production efficiency and facilitate expansion of domestic aquaculture permitted in state and federal marine waters and in land-based production systems. These 18 species identified by stakeholders represent significant biological diversity and various stages of domestication, so their research needs are species-specific. Given the resources allocated for this Component, research will initially focus on Red Drum and Florida Pompano and studies will be conducted on other species where resources permit. The 2018 Census of Aquaculture reported 12 farms valued at $19,448,000 for red drum, while data for Florida pompano was not listed, per NASS reporting criteria. Stakeholders identified many priorities that ARS does not currently have the capacity to address, including:

- Research on all marine warmwater finfish candidate species identified as having potential for domestic aquaculture production
- Research to address matters of regulation or policy at the federal or state level
- Social licensing for aquaculture
- Economic analyses to inform investment decisions

Problem Statement 5A: Develop Red Drum and Florida Pompano Seedstocks Optimized for Aquaculture Production Efficiency

Aquaculture producers need access to seedstocks that are available year-round and optimized for the production environment. Research is needed to develop seedstocks that are bred for maximum production efficiency and have minimal impacts on the environment and native populations. Research in the disciplines of genetics, fish health, nutrition, reproductive biology, and physiology will contribute to the development of seedstocks that meet these criteria.

Research Focus

Genetics: Developing marine finfish broodstock from domestic populations and establishing breeding programs is a key strategy for increasing efficient and sustainable production. Directed selective breeding efforts have been conducted on very few marine finfish species. Factors that hinder the rate of improvement include a lack of well-defined phenotypes, inadequate or lack of understanding of component traits and interrelationships among traits, incomplete or lack of understanding of the molecular basis of phenotypes and trait interactions, lack of methods to model and evaluate candidate traits for selection, and underdeveloped strategies to incorporate genomic data into breeding programs. Facilitating genetic improvements requires new information about the genome and its interactions with environmental factors that can be placed in a comprehensive framework pertaining to aquatic animal growth, adaptation, health and well-being, reproductive efficiency, nutrient utilization, conversion of feed to flesh, and product quality.

Nutrition, Feeds, and Feeding: Research needs include the evaluation of feed formulations and nutrient availability, including ingredients from non-conventional feedstuffs. Information is also needed on the evaluation of dietary additives or feed formulations that may improve reproductive performance of broodstock and the growth, quality, and health of fry (i.e., larvae), fingerlings (i.e., juvenile), and food fish. Research is also needed to develop optimum feeding strategies for the different phases of production.

Reproduction: Research on management strategies is needed, including the use of spawning aids that increase the efficiency of egg, fry, and fingerling production of marine finfish; and new methods to extend and control the spawning season to produce high-quality gametes.

Fish Health: Research is needed to develop health management strategies that are safe for the environment and reduce disease-related losses. This includes the development of technologies for early and rapid pathogen and pest detection, prevention, and treatment. Validated diagnostic tools are needed in production systems to quickly detect disease agents. Developing effective control strategies and therapeutants to manage and prevent disease is also a priority, since there are currently only a few drugs that have been approved for treating diseased fish and fewer have specific approvals for marine fish. New research will support the development of effective prevention programs, including vaccines and methods for mass vaccination of aquatic animals.

Anticipated Products

- Protocols optimizing marine finfish reproduction
- Germplasm selected for economically important traits
- Cryo-preservation of select germplasm
- Diets optimized for growth and economic returns of fingerlings and food fish, and to improve reproductive efficiency of broodfish
- Replacing live feeds for larval rearing
- Strategies for reducing on-farm losses to disease

Potential Benefits

- Seedstocks optimized for production efficiency will support expansion and economic growth of the U.S. marine finfish aquaculture industry.
- Increased reproductive success will lead to more stable and economical production of fingerlings.
- Broodstock will be selected for economically important traits.
- The development of genome-enabled selection tools and technologies will facilitate the genetic improvement of marine finfish.
- An improved understanding of the biology underlying economically important traits will facilitate the development of improved management practices and enhance the accuracy of selective breeding.
- Formulating optimized diets will improve growth and survival at different life stages, reproductive performance, product quality, and production efficiency.
- Increasing the number of high-quality alternative ingredients will provide flexibility in formulating cost-effective diets.

Component 5 Resources

- A project initiated to establish seedstocks for the U.S. warmwater marine finfish industry located with the U.S. Horticulture Laboratory in Fort Pierce, Florida

Component 6: Developing Sustainable Aquaponic Production Systems

Aquaponics is a resource-efficient, controlled environment agriculture (CEA) that integrates intensive aquaculture and greenhouse vegetable production systems. Aquaponics can help address food security and safety by contributing to food production in urban, suburban, and rural communities. To be sustainable, aquaponic system managers must optimize inputs and outputs (energy and materials) and internal biological production processes to maximize resource use efficiencies, reduce water usage, maximize nutrient retention, and control pathogens associated with foodborne illness. Aquaponics integrates aquaculture and hydroponic vegetable production, facilitates food production system diversification, creates new sources of employment and economic development, and provides a process for highly intensive and sustainable food production that addresses future food scarcity needs. Developing a model CEA aquaponic system that is scalable and commercially viable is critically important to address current and future sustainable food production and economic opportunity needs.

To this end, Congress included the following in the FY 2021 Budget: "*The Committee recognizes the need for improving the development of fresh food production technology to address domestic food security and safety demands*." In support of this guidance, Congress provided the ARS funding "*to coordinate with academic partners and industry to develop a model-controlled agriculture aquaponics system that is scalable and commercially viable with the purpose of advancing increased fresh food production, improved food safety, decreased water usage, improved nutrient utilization, and decreased negative environmental impacts*."

ARS research priorities for aquaponics were largely informed by a stakeholder listening session on June 7, 2023, and associated correspondence. Stakeholders identified many priorities that ARS does not currently have the capacity to address, including:

- Economic research on scalability of aquaponic operations
- Desalination systems
- Food safety in aquaponic systems
- Water quality testing services
- Funding aquaponic operations and opportunities for underrepresented communities in food deserts, especially urban areas

Problem Statement 6A: Optimize Aquatic Animal Species Production Systems for Aquaponics

Research Focus

Further research is needed to optimize aquatic animal production systems for aquaponics. Domestic aquaculture is expected to help meet increasing demands for sustainable protein, increase food production efficiency, and diminish negative impacts to natural fisheries. As aquaponics technology is developed and improved, aquaculture systems must be adapted to improve their integration with horticulture systems and optimize fish nutrition, species diversification, disease prevention, and waste management. ARS researchers need to develop a comprehensive understanding of these factors to optimize performance in aquaculture production systems and improve the economic potential of domestic aquaculture, particularly when combined with horticulture systems.

Anticipated Products

- Assessment of Nile tilapia health and disease susceptibility in aquaponics systems
- Production models for alternative species, including freshwater and saltwater species
- Economic models for aquaponic systems

Potential Benefits

- Improved understanding of aquatic animal production scalability in aquaponics systems will lead to better management practices.
- Enhanced diets for aquaculture systems will lead to higher yields and better economics.
- Clearer understanding of aquaculture production for species other than tilapia and catfish will increase the adoption of domestic aquaculture.

Problem Statement 6B: Optimize Plant Production Systems for Aquaponics

Research Focus

Multiple horticultural production systems that use hydroponics technology are calibrated for use in controlled environments to facilitate maximum yields and optimize space utilization. Research is needed to adapt and optimize state-of-the-art horticultural systems that can be integrated with aquaponics systems. Commercial greenhouse vegetable growers are unlikely to adopt aquaponics technology over hydroponics unless yields, quality, food safety, and the economic value of plant products from aquaponic systems meets or exceeds those from hydroponics systems. This research will address major pitfalls in aquaponic vegetable production, including reduced yields, nutrient sources and limitations, water use, waste capture, energy efficiency, greenhouse environments, climate, growing media, lack of predictable production models, and food safety and produce quality issues.

Anticipated Products

- Dynamic production models for major fruit and vegetable crops (tomato, cucumber, bell pepper, lettuce, and strawberry)
- Food safety protocols and educational materials for aquaponics

Potential Benefits

- Developing best management practices for greenhouse fruit and vegetable production in the southeast United States will increase technology adoption. Optimizing horticultural production in aquaponics will improve the economic outlook of aquaponics and increase adoption of aquaculture production.
- Integrating plant production in aquaponics will improve understanding of plant nutrition in a system with organic and inorganic nutrient sources and improve understanding of the role(s) of rhizospheric microbiomes in nutrient uptake and plant health.

Problem Statement 6C: Optimize the Integration of Fish and Plant Production Systems

Research Focus

Adopters of aquaponics technology need a clear understanding of the best ways to integrate aquaculture and horticulture systems and how production considerations may favor different approaches to integration. For example, coupled systems in which aquaculture effluent flows to and from horticultural systems may be beneficial from a water conservation perspective, but may not perform as well as de-coupled systems for certain combinations of fish and plant species. In addition, overall system performance may differ based on primary aquaculture or secondary horticulture system types and their associated microbiomes. Better understanding of the autotrophic and heterotrophic microorganisms and their roles in nutrient transformation can advance the design of engineered components in aquaponics systems. Additionally, considerations of environmental sustainability and economic productivity rely upon optimizing systems integration for mass and energy balance to maximize efficiency. Research will directly target the challenge of optimizing systems-level efficiencies by assessing system performance differences associated with discrete combinations of aquaculture and horticulture systems. Researchers will measure system performance with assessments of yield potentials, energy usage, water and nutrient use efficiencies, and economic potential. To that end, researchers will develop and refine mass and energy balance models based on field data to predict how system changes will affect profitability and environmental impacts. These process models will be coupled with economic and life cycle assessments to identify the most efficient combination of systems parameters.

Anticipated Products

- Fish diet formulations that improve fish and plant performance in aquaponics
- System configurations (fish tank, solids separation, microbial reactors, and plant production management) that maximize profitability and minimize environmental effects

Potential Benefits

- Developing economically viable aquaponics systems will increase adoption of aquaponics technology, which will increase fish and vegetable production in local communities and improve food security and safety.
- Conserving water and reducing nutrient loss will reduce the negative environmental effects of aquaculture systems.
- Identifying useful systems-level models will advance the planning and design of sustainable aquaponics installations and lead to widespread adoption within the aquaculture industry.

Component 6 Resources

- Aquatic Animal Health Research Unit, Auburn, Alabama

Component 7: Enhancing Tilapia Aquaculture Production

The 2018 Census of Aquaculture reported 137 tilapia farms valued at $39,395,000. ARS research priorities for tilapia were informed by letters from industry representatives requesting ARS research on their behalf.

Problem Statement 7A: Reduce the Impacts of Disease in Tilapia Aquaculture

Environmental conditions exacerbate disease outbreaks and increase infectious disease losses from viral, bacterial, and parasitic pathogens, which often occur in mixed combinations. Developing new strategies to prevent or control disease requires identifying the host molecular pathways associated with innate and acquired immune responses to common pathogens and understanding how the host immune system evades pathogens and prevents or mitigates the onset of disease. Acquiring the information needed to develop genetic enhancements for disease resistance requires studying aquatic animals with divergent responses to disease challenge and identifying the genetic sources of variation correlated with innate and/or acquired immune status. In addition, more information is needed about how the immune system of tilapia respond to vaccination, the variation in vaccine response, and the underlying mechanisms of protection to infectious disease, all of which will support developing preventative strategies.

Research Focus

Host Immunity: Research needs include evaluating the immune responses of tilapia exposed to key pathogens. The availability of near-complete genome sequences of tilapia and their pathogens will support the comprehensive identification of immune genes and virulence factors. Additionally, studies of aquatic animals with resistant/susceptible phenotypes will facilitate understanding the molecular pathways associated with disease resistance. Researchers can identify genetic variations in response to vaccination and use that information to select traits associated with robust responses and determine the relationship between immune responses and vaccine efficacy.

No commercial vaccines are available in the United States to prevent bacterial, viral, and parasitic diseases in tilapia. Vaccine research must result in a product that is safe, easy to administer, and protects against disease throughout the production cycle. The development of new vaccines will require techniques such as killed, modified-live, DNA, and recombinant technologies, while microbial genomics, proteomics, and functional genetics will inform the development of novel vaccines. Additionally, feasible vaccination strategies for many fish species require mass vaccination, such as vaccination of juveniles via immersion or by providing vaccines through feed. In addition, vaccines delivered to young fish need to prevent disease up until harvest and oral booster vaccinations may be needed to provide this level of protection.

Pathogens: Methods to rapidly detect pathogens and diagnose diseases in aquatic species are still unavailable or lack farm-scale application. Microbial genomic sequences, or diagnostic regions of pathogen genomes, will be important tools for identifying pathogens, understanding pathogenesis, and predicting antibiotic resistance. Developing strategies to identify pathogen-specific treatments is a priority. The development of disease challenge protocols for key pathogens is needed for studies of host resistance and responsiveness. Key pathogens include *Streptococcus agalactiae*, *Francisella orientalis*, *Streptococcus iniae*, and Tilapia Lake Virus.

Anticipated Products

- Development of technologies to increase pathogen resistance in broodstock
- Development of vaccines and vaccine delivery systems for economically important pathogens
- Genome sequences of emerging pathogens that support the development of diagnostic assays and vaccines
- Rapid assays for major pathogens
- Improved understanding of disease mechanisms of emerging pathogens.

Potential Benefits

- Information on immune system components will help identify genetic locations that can be targeted to enhance immune system responsiveness. Aquatic animals with enhanced resistance will form the basis of select disease-resistant lines. Identifying genes and markers related to immunity will also help locate genetic markers that can be used to reduce mortality.
- Sequence information on microbial genomes will permit better pathogen identification, improve understanding of pathogenesis and virulence factors, and support the identification of vaccine antigens.
- Vaccines hold the potential to reduce the need for other therapeutants such as antibiotics, which improves cost-effective aquaculture production by reducing the need for reactive drug use and improves environmental sustainability by reducing the use for antibiotics and other antimicrobial compounds. Improved biosecurity and pathogen refuge disruption should lessen the frequency and dispersion of disease problems, improve aquatic animal well-being, and

increase system productivity and reliability.

Component 7 Resources

- Aquatic Animal Health Research Unit, Auburn, Alabama

Appendix A. Alignment to Federal Strategic Plans, Initiatives, and an Executive Order

Relationship to ARS Grand Challenge Synergies

Farmers, consumers, and citizens share the intertwined goals of ensuring sufficient food supplies for a growing population, ensuring the production of wholesome food, and improving agriculture's environmental footprint. ARS leadership recognized that addressing these issues requires holistic and synergistic research approaches; therefore, ARS Grand Challenge Synergies was developed to unlock greater impact from conventional ARS projects by encouraging and facilitating synergistic interactions between scientists across locations, National Programs, and research systems. Synergies encourages scientists to broaden their thinking and collaborate on projects that use their expertise and support the direction of the 5-year plan but that might exceed the scope of project plan objectives. These synergistic projects channel the energy of diverse scientific teams to address complex problems of high national importance that may not be solved within the boundaries of a single discipline or project.

ARS aquaculture research will contribute to Synergies and other cross-disciplinary opportunities by developing technologies that increase the availability of healthy dietary protein from seafood through environmentally sustainable production that protects and enhances natural resources. This requires collaborating with scientists working in other ARS Program Areas that affect aquaculture production systems, including:

1. Developing crops optimized for use as fish feed ingredients and reducing the demand for ingredients from wild-caught fisheries (Program Area 3)
2. Modifying production systems and developing technologies that ensure product quality, healthfulness, and food safety (Program Area 1)
3. Modifying production systems and developing technologies that optimize agricultural water use (Goal 2.1) and identify beneficial uses of fish waste (Program Area 4)
4. Developing technologies that improve fish health and welfare by developing alternatives to antibiotics and reducing on-farm antibiotic use (Program Area 2)

NP 106 scientists currently participate in the following Grand Challenge Synergies Projects:

Holistic Management System to Enhance Vegetable Production under Protected-Cultivation

- Goal: Enhance protected horticulture while reducing environmental impact through (GxExMxP) approach

Developing Insect Meal as a Sustainable Feed Ingredient

- Goal: Debugging a new mini livestock commodity and developing a model of insect production to demonstrate their value as a safe solution for food waste and sustainable fish and livestock production

Relationship to ARSX

The ARSX2023 competition, *Secure Future Food Systems Through Safe and Sustainable Agriculture,* challenged scientists and researchers to propose high-risk, high-reward ideas for a transformative solution to a serious agricultural problem. Team Sterile Broodstock led by NP 106 scientists was a top winner for their proposal to develop a biological system to induce sterility in Atlantic salmon to enhance growth as they reach sexual maturity and prevent reproduction by escape.

Relevance to ARS Artificial Intelligence, Machine Learning, and Big Data Initiatives

Many ARS approaches to addressing stakeholder challenges could be enhanced through Big Data integration with artificial intelligence (AI) and/or machine learning (ML) applications that predict yields, inform management decisions, automate processes, monitor production system parameters, and predict onset of disease. AI methods involve automated decision-making or inference from data and use:

- Machine learning (including deep learning)
- Mathematical optimization (integer programming and operations research)
- Machine reasoning and logic programming
- Knowledge representation
- Recommender systems

ML involves training a model with data and then making decisions or answering questions using that model. Methods include:

- Tasks such as classification, regression, dimensionality reduction, and clustering
- Domain areas such as natural language processing, computer vision, and time-series analyses
- Statistical methods such as Gaussian processes, neural networks, Bayesian networks, and support vector machines

Research in NP 106 is also relevant to broader aquaculture initiatives across the Federal government.

Relationship to the National Aquaculture Development Plan and the National Strategic Plan for Aquaculture Research

The National Aquaculture Development Plan (NADP) is a product of the Subcommittee on Aquaculture (SCA), a statutory subcommittee that operates under the Committee on Environment of the National Science and Technology Council (NSTC) under the Office of Science and Technology Policy in the Executive Office of the President. The SCA serves as the federal interagency coordinating group to increase the overall effectiveness and productivity of federal aquaculture research, regulation, technology transfer, and assistance programs.

As outlined in the Executive Order 13921 "Promoting American Seafood Competitiveness and Economic Growth", the NADP is currently being updated for 2024. It will document ongoing efforts by U.S. Federal agencies to work with the aquaculture community to address major constraints limiting the expansion and uses of aquaculture and identify opportunities to support users of aquaculture technologies. The 2022 National Strategic Plan for Aquaculture Research (NSPAR) is a chapter of the NADP that discusses Federal priorities for research and technology development for facilitating responsible expansion of domestic aquaculture. Research outlined in this Action Plan falls under Goals 2 and 3 of the National Strategic Plan for Aquaculture Research:

Goal 2. Improve Aquaculture Production Technologies and Inform Decision-making

- **Objective 2.1:** Provide farmers with access to improved genetics
- **Objective 2.2:** Develop and refine production technologies to increase environmentally responsible food production and contribute ecosystem services
- **Objective 2.3**: Advance fish nutrition and feed production technologies to produce healthy fish, reduce environmental impacts, and provide nutritious seafood
- **Objective 2.4**: Improve engineering systems for aquaculture

Goal 3. Uphold Animal Well-Being, Product Safety, and Nutritional Value

- **Objective 3.1:** Develop strategies to protect the health and well-being of aquaculture species
- **Objective 3.2**: Promote the safety and nutritional value of U.S. aquaculture products

Relationship to the Ocean Climate Action Plan

The Ocean Climate Action Plan (OCAP) is a whole-of-government plan to advance climate solutions, promote environmental justice, create good-paying jobs, and ensure sustainable coastal communities and a healthy ocean economy. Recognizing that effective action will require broad national participation, the OCAP was developed with input from across the Federal Government, Tribal Nations, other Indigenous Peoples, stakeholders, and the public. Research in the NP 106 Action Plan supports the following section:

- Enhance Community Resilience to Ocean Change: Climate Ready Fisheries, Protected Resources, Aquaculture, and Fishing Communities

Appendix B. Stakeholder Inputs for the Action Plan and Program Planning

USDA ARS and NIFA hosted a Series of Stakeholder Listening Sessions organized by Component to obtain input for the development of this Action Plan.

- May 16, 2023, 1 pm – 3 pm (EDT): Catfish
- May 17, 2023, 1 pm – 3 pm (EDT): Salmonids
- May 18, 2023, 1 pm – 3 pm (EDT): Basses and Baitfish
- May 19, 2023, 1 pm – 3 pm (EDT): Mollusks and Crustaceans
- June 6, 2023, 1 pm – 3 pm (EDT): Warmwater Marine Finfish
- June 7, 2023, 1 pm – 3 pm (EDT): Aquaponics

USDA ARS, NIFA, and APHIS hosted an internal USDA Listening Session on June 8, 2023, entitled Visioning Aquaculture Health, Food Safety and Security

USDA ARS and NIFA hosted a virtual Listening Session entitled Research and Extension in Support of Tribal Aquaculture on June 12, 2023.

Listening Session Participation

Session	Registered	Attended
Catfish	100	65
Salmonids	130	80
Basses and Baitfish	105	37
Mollusks and Crustaceans	178	69
Warmwater Marine Finfish	140	54
Aquaponics	175	52
Tribal Aquaculture	168	38
Total Unique	**245**	**304**
USDA Internal Session		46

Listening Session Representation

Sector	Registered	Attended
State or Federal Government	95	67
Academia	65	25
Commercial	106	37
Organization	22	9
Other or Unknown	16	112

ARS representatives regularly interact with stakeholders at state, national, or species focused meetings, and through informal and written communications. ARS scientists and/or the NPL often attend the following meetings/interact with allied stakeholder organizations.

- American Fisheries Society
- Arkansas Bait and Ornamental Fish Growers Association
- Catfish Farmers of America
- East Coast Shellfish Growers Association
- National Aquaculture Association
- National Aquaculture Extension Conference

- National Shellfisheries Association
- Northeast Aquaculture Conference and Exposition
- Pacific Coast Shellfish Growers Association
- State Aquaculture Associations
- The Aquaponics Association
- U.S. Aquaculture Association
- U.S. Trout Farmers Association

Correspondence to inform the development of this Action Plan was received from the organizations listed below.

- Aquasafra
- Atlantic Sapphire
- Benchmark Genetics USA
- Blue Ridge Aquaculture
- Bodega Bay Oyster Company
- Kennebec River Biosciences
- Live Advantage Bait, LLC
- Louisiana Farm Bureau
- Louisiana Crawfish Promotion Board
- North Carolina Aquaculture Association
- Pacific Coast Shellfish Growers Association
- Superior Fresh LLC
- The Aquaponics Association
- University of Florida
- Veterans Produce
- World Wildlife Fund

Appendix C. ARS Research Capacity

ARS conducts research under the ARS NP106 at 11 primary locations and their worksites through 14 project teams totaling 69 scientists and in funded collaborations with 9 cooperating institutions. The primary research facilities are listed below.

1. ***The Small Grains and Potato Germplasm Research Center*** includes four scientists located in **Hagerman, Idaho**, and **Bozeman, Montana**, and their university collaborators who conduct breeding and genetics research to enhance rainbow trout production nationwide and increase rainbow trout production efficiency using plant-based feeds and increased knowledge of trout physiology and nutrition.
2. ***The National Center for Cool and Cold-Water Aquaculture*** includes 11 scientists in **Leetown, West Virginia**, and their non-profit and university collaborators who enhance U.S. aquaculture production by developing improved germplasm and technologies that increase farm efficiency, product quality, and environmental sustainability. Research focuses primarily on rainbow trout and encompasses genetics, genomics, physiology, aquatic animal health, and aquaculture engineering.
3. ***The National Cold Water Marine Aquaculture Center*** includes six scientists in **Franklin, Maine**, and five in **Kingston, Rhode Island**, and their university collaborators who conduct research that will solve problems limiting production efficiency of cold-water marine aquaculture. The current primary research focus is genetic improvement using an applied selective breeding program to increase efficiency and sustainability of Atlantic salmon and eastern oyster culture.
4. ***The Pacific Shellfish Research Unit*** includes four scientists in **Newport, Oregon**, and their university collaborators who improve the sustainability of shellfish production systems in Pacific Northwest estuaries.
5. ***The Warmwater Aquaculture Research Unit*** includes 11 scientists in **Stoneville Mississippi**, and their university collaborators who develop technologies that improve the efficiency, profitability, and sustainability of fish farming in the United States through development of improved fish strains and hybrids and by developing better production technologies.
6. ***The Aquatic Animal Health Research Unit*** includes 12 scientists and their university collaborators in **Auburn, Alabama**, who conduct research to develop control strategies to prevent large economic losses in the aquaculture industry caused by diseases and parasites, and to optimize sustainable aquaponic production systems.
7. ***The Harry K. Dupree Stuttgart National Aquaculture Research Center*** includes seven scientists in **Stuttgart, Arkansas**, who conduct research on basses and baitfish to develop feeds, improve culture strategies, and improve disease control strategies.
8. ***The Food Processing and Sensory Quality Research Unit*** includes two and a half scientist's time working in **New Orleans, Louisiana** to develop technologies that optimize the nutritional, functional, and sensory qualities of catfish.
9. ***A project aiming to develop marine finfish seedstocks*** includes four scientists and collaborators at Florida Atlantic University's Harbor Branch Oceanographic Institute in **Fort Pierce, Florida**.