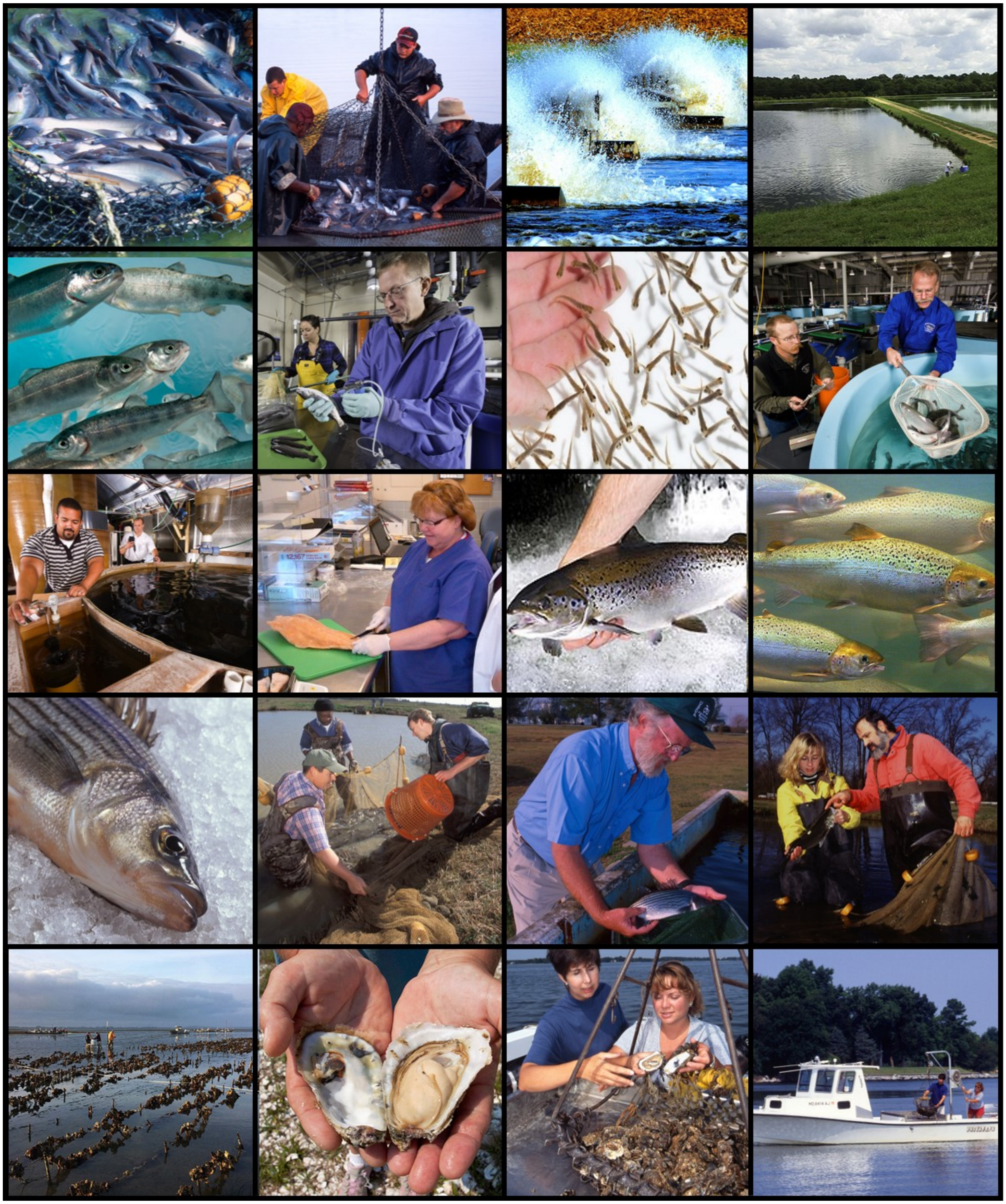

USDA ARS National Program 106
Aquaculture Action Plan 2020 – 2024

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National Program 106 – Aquaculture

Vision

Science-based use of our natural resources to meet the seafood demands of a growing global population.

Mission

The mission of National Program (NP) 106, Aquaculture, is to conduct research and deliver technologies that improve domestic aquaculture production efficiency and product quality while minimizing impacts on natural resources.

Relationship of this National Program to the USDA Strategic Plan

This Action Plan outlines research that directly supports the USDA FY2018-2022 Strategic Plan by contributing to Strategic Goal 2: Maximize the Ability of American Agricultural Producers to Prosper by Feeding and Clothing the World. Specifically, it addresses the following Objectives:

> Objective 2.2: Increase Agricultural Opportunities and Support Economic Growth by Creating New Markets and Supporting a Competitive Agricultural System; and
>
> Objective 2.3: Protect Agricultural Health by Preventing and Mitigating the Spread of Agricultural Pests and Disease.

Relationship of this National Program to the USDA Research, Education and Economics (REE) Action Plan

This Action Plan outlines research that directly supports the 2014 REE Action Plan by contributing to Goal 1: Sustainable Intensification of Agricultural Production, specifically including the following Subgoals:

- Subgoal 1A. Crop and Animal Production
- Subgoal 1B. Crop and Animal Health
- Subgoal 1C. Crop and Animal Genetics, Genomics, Genetic Resources, and Biotechnology

Aquaculture research in this Action Plan also relates to the following REE Action Plan Goals:

- Goal 2: Responding to Climate and Energy Needs
- Goal 3: Sustainable Use of Natural Resources
- Goal 4: Nutrition and Childhood Obesity
- Goal 5: Food Safety
- Goal 7: Rural Prosperity/Rural-Urban Interdependence

Relationship of this National Program to the USDA Agricultural Research Service Strategic Plan

Research outlined in this Action Plan falls under Strategic Goal Area 4, Animal Production and Protection, in the 2012-2017 ARS Strategic Plan. This plan specifically outlines research that supports Goal 4.1: Provide Scientific Information and Biotechnologies to Enhance Management Practices that will Ensure an Abundant Supply of Competitively Priced Animal and Aquaculture Products, and Goal 4.2: Prevent and Control Pests and Animal Diseases that Pose a Threat to Agriculture, Public Health, and the Well-Being of American Citizens.

Performance Measure 1.4.1: Provide scientific information to maximize the production efficiency of our food animal production systems. Develop new technologies and tools contributing to improved systems to meet current and future food animal production needs of a broad range of consumers while ensuring economic and environmental sustainability and animal well-being.

Performance Measure 4.4.2: Provide scientific information to protect animals, humans, and property from the negative effects of pests and infectious diseases. Develop and transfer tools to the agricultural community, commercial partners, and government agencies to control or eradicate domestic and exotic diseases and pests that affect animal and human health.

Relationship to the ARS Grand Challenge

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 substantial environmental footprint. ARS research leadership recognized these issues require holistic and synergistic approaches and developed a Grand Challenge to encourage and facilitate collaboration across projects, locations, and programs within the Office of National Programs (ONP). The goal of this Grand Challenge is the development of systems approaches for addressing national and international agricultural research needs.

ARS aquaculture research can contribute to the ARS Grand Challenge 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 will require collaborating with scientists working on other ARS goals that affect aquaculture production systems, including:

1) Developing crops optimized for use as fish feed ingredients and reduce the demand on ingredients from wild-caught fisheries (Goal 3.1);

2) Modifying production systems and developing technologies that ensure product quality (Goal 1.3), healthfulness (Goal 1.1), and food safety (Goal 1.2);

3) Modifying production systems and developing technologies that optimize agricultural water use (Goal 2.1) and identify beneficial uses of fish waste (Goal 2.4); and

4) Developing technologies that improve fish health and welfare by developing alternatives to antibiotics and reducing on-farm antibiotic use (Goals 4.1 and 4.3).

Introduction
Aquaculture is the production of aquatic organisms under controlled conditions throughout part or all of 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 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. Developing technologies that reduce production costs and maintain or improve product quality will help U.S. aquaculture producers meet that increasing demand. 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;
- protect special aquatic areas;
- rebuild overfished wild stocks;
- restore populations of endangered species;
- restore and conserve freshwater, coastal, and marine habitat;
- balance competing uses of aquatic environments;
- create employment and business opportunities in rural inland and coastal communities; and
- enable the production of safe and sustainable seafood.

Research conducted in NP 106 supports efforts to ensure that a healthy, competitive, and sustainable aquaculture sector is able to produce an abundant, safe, and affordable supply of seafood products. NP 106 work advances the efforts of more than 4,300 aquaculture farmers producing more than $1 billion dollars' worth of goods annually to meet the potential market demand generated by 300 million U.S. consumers.

Since the 1980s, capture fisheries production has been relatively static and has shown no signs of increasing. The *2015–2020 Dietary Guidelines for Americans* now suggests Americans should increase their seafood intake from an average of about 4.8 ounces per week to 8 ounces or more per week (8 to 12 ounces is recommended for pregnant or breastfeeding women). Aquaculture production could fill in the gap between current supplies of wild-caught seafood and 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 probably increase as the demand for seafood increases.

In 2014, U.S. consumers spent an estimated $91.7 billion on fishery products, making it one of the top three seafood markets worldwide. Yet, U.S. marine and freshwater aquaculture production ranks 14th worldwide, producing 275,695 metric tons of fishery products with a farm gate value approaching $1.3 billion annually. As a result, 90 percent of the seafood consumed in the United States (by value) is imported.

Seafood suppliers and producers recognize that wild-caught fisheries are producing at peak capacity and that aquaculture will be a critical component in meeting the nutritional requirements of a growing global population and in protecting natural resources. The United States is well-positioned to expand aquaculture production because of the following:

- *Dietary Guidelines* recommendations for increasing seafood consumption;
- the United States is a major producer of plant-based fish feeds and feed ingredients;
- there is an abundance of underused water resources, including the Exclusive Economic Zone and the Great Lakes;
- Recirculating Aquaculture Systems 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; and
- since the United States is a net seafood importer, there is an existing market demand 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 the nutritional demands of a growing global population. Therefore, the ARS National Program for Aquaculture focuses on research that supports the production of quality seafood products for human consumption. 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 National Program Leaders (NPLs) for Aquaculture worked with the NPLs for 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 participating in meetings and maintaining connections with professional organizations such as the U.S. Trout Farmers Association, Catfish Farmers of America, Striped Bass Growers Association, Pacific and East Coast Shellfish Growers Associations, and the National Aquaculture Association. Appendix A lists specific outreach activities informing the development of this Action Plan. Appendix B lists recent reports on relevant agricultural sciences and/or U.S. aquaculture that were consulted while developing this Action Plan. Finally, this Action Plan was informed by the results from a Retrospective Review conducted by an external panel of industry members and academic scientists; this review provided a thorough evaluation of the effectiveness and impact of the ARS National Program for Aquaculture from 2013 to 2017.

ARS Aquaculture Research Capacity

ARS conducts research under the ARS National Program for Aquaculture at 10 different locations through 14 projects performed by 50 ARS scientists and in funded collaborations with 12 cooperating institutions. Descriptions of ARS laboratories are provided in Appendix C.

Component 1: Improving the Efficiency and Sustainability of Catfish Aquaculture
The leading U.S. aquaculture industry is the pond production of catfish. The 2013 Census of Aquaculture reported 605 catfish farms, primarily in the states of Alabama, Arkansas, and Mississippi, sold market-size fish and that their sales valued at $354,337,000. In this Action Plan, ARS research priorities for catfish were largely developed using information generated by the virtual listening session on July 25, 2018, and associated direct email input; a stakeholder listening session in Greensboro, Alabama, on July 31, 2018; a stakeholder listening session in Stoneville, Mississippi, on August 2, 2018; a "Utilizing Advanced Processing Technologies in Catfish" workshop held in Stoneville, Mississippi, April 9-10, 2018; and direct interactions between ARS scientists and catfish stakeholders. Stakeholders identified many priorities that ARS does not currently have the capacity to address, including:

- 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 for harvest planning and plant scheduling;
- 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); and
- Developing 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 consistent 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, that 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-traditional 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.

Production Systems: Research needs include developing new pond systems for catfish production using innovative, non-traditional approaches that optimize production, increase economic competitiveness, and reduce environmental impacts. Studies are also needed to characterize new and traditional 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 harmful microbial communities.

Anticipated Products

- Genome enabled strategies that accelerate the pace of genetic improvement;
- Broodstock selected for economically important traits;
- 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; and
- Technologies that minimize the impacts of toxic algae.

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 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 provide flexibility in formulating least cost 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 fish pond systems will increase productivity, reduce variation in yields, reduce emission of potential pollutants, and increase water-use efficiency.

Problem Statement 1B: Reduce the Impacts of Disease in Catfish Aquaculture
Health management strategies, technologies, and biosecurity plans that are safe for the environment and for consumers of aquaculture products 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 detection, prevention, and treatment of diseases. 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 say the following pathogens are 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, or diagnostic regions of the genome, will be important tools for pathogen identification and for understanding pathogenesis. Strategies are needed to identify effective treatments, understand their pharmacokinetics, and apply therapeutants for control. Disease challenge model development for key pathogens is necessary 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 feasible to use these vaccines in aquaculture production. Ultimately, 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 feasible in aquaculture production systems.

Anticipated Products

- Identification and characterization of catfish pathogens;
- Genetic improvement for disease resistance;
- New vaccine development and optimization; and
- 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.
- Improved genetics and vaccines have the potential to increase producer profits by greatly reducing the need for therapeutants (*e.g.*, antibiotics) and chemical treatments; reduced antibiotic use will also 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 the relationship between genetics, rearing, and harvesting practices on 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

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

Potential Benefits

- Enhanced product quality will result from improved rearing and harvest strategies.
- 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 by improving traits important to U.S. consumers could increase the demand for domestic products, while efforts to improve coproducts 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
Natural Products Utilization Research, Oxford, Mississippi

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 2013 *Census of Aquaculture* identified 313 farms whose food fish sales were valued at $93,911,000. 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 2013 *Census of Aquaculture* also reported 4 Atlantic salmon farms producing food fish with sales valued at $88 million and production estimated at 19,715 metric tons. In 2017 the United States imported 122,002 metric tons of Atlantic salmon. These numbers suggest that expanding and optimizing the United States use of natural resources to increase aquaculture production could greatly reduce the seafood trade deficit. Over 100 net pen sites are currently available for farming, and to date commercial investments of over $1 billion have been made towards the expansion of land-based production.

ARS research priorities for salmonids were largely informed by the virtual listening session on July 24, 2018, and associated direct email input; a “Genomic Technologies for Assessing Continent of Origin for Atlantic Salmon” workshop hosted by ARS and NIFA and the USFWS in Orono, Maine, on June 5, 2018; a listening session hosted by ARS and NIFA at the National Cold Water Marine Aquaculture Center in Orono, Maine, on June 6, 2018; the U.S. Trout Farmers Association “Change and Adapt: Get More out of Less” meeting at the USFWS National Conservation Training Center in Shepherdstown, West Virginia, on September 6-8, 2018; and direct interactions between ARS scientists and salmonid stakeholders. Stakeholders identified many priorities that ARS does not currently have the capacity to conduct research on, including:

- Traceability issues, including marketing narratives about fish production;
- 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; and
- Regulatory policies not originally intended for aquaculture; these policies may have significant administrative costs associated with documenting compliance, especially for small businesses; policies that regulate effluent requirements and other programs may also be run inefficiently.

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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 improvement 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; methods to model and evaluate candidate traits for selection; and improved strategies to incorporate genomic data into breeding programs. To facilitate genetic improvement, new knowledge of the genome and its interactions with environmental factors needs to be consolidated in a comprehensive framework pertaining to aquatic animal growth, adaptation, health and well-being, reproductive efficiency, nutrient utilization, conversion of feed to aquatic animal products, and product quality.

The creation of transgenic animal lines has demonstrated biotechnology's potential use 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. But 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.

Management Practices: 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.

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

Research is needed to determine if non-traditional sources of protein and oil meet the nutritional needs of salmonids throughout their lifecycles.

Production Systems: Research is needed to determine how biological aspects related to salmonids raised in recirculating aquaculture systems (RAS) can be targeted to improve health, performance (growth, feed conversion, and reduced maturation), and welfare. Work is also needed on optimizing RAS environmental conditions for improved salmonid health, performance, and welfare and improving waste capture and effluent reuse. Research is also needed on developing technologies for viable revenue streams using RAS waste and fish harvest byproducts and on improving RAS operation and viability to meet the growing needs of this aquaculture sector.

Anticipated Products

- Atlantic salmon and rainbow trout broodstock selected for traits associated with production efficiency and/or product quality;
- Genome-enabled strategies for selective breeding;
- Evaluations of the potential use of gene editing technology as a precision breeding tool for trait improvement;
- Characterizations of genetic x environment interactions of Atlantic salmon selected for performance in net pens through evaluations in RAS;
- Strategies that improve rainbow trout egg quality, hatch, and survival;
- Enhanced methods for ingredient processing to improve nutritional value;
- Defined nutrient requirements and digestibility for fish consuming diets supplemented with non-traditional protein and fat sources;

- Improved operational technologies to enhance the viability of land-based salmonid RAS;
- Defined criteria for optimal environmental conditions for salmonids in RAS; and
- Improved technologies for waste capture, effluent reuse, and utilizing waste for viable revenue streams in recirculating systems.

Potential Benefits

- The development of gene editing and other genome-enabling tools and technologies will facilitate the continued genetic improvement of 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 recirculating systems 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 responsiveness, 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 of 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. Ultimately, 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 pathogen identification, 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 recirculating aquaculture systems.

Environmental parameters influencing disease outbreaks: Salmonid fish aquaculture occurs in diverse environments that likely 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 broodstock having increased disease resistance;
- Identification of correlates of protection and protective antigens for existing vaccines that are useful for monitoring long-term vaccine effectiveness in production environments;
- 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 *Flavobacterium psychrophilium* and *F. columnare* strain typing and prediction of virulence;
- Microbiome analysis of on-farm environment and development of methods to disrupt establishment of pathogens in production systems; and
- 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 greatly 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, Hagerman, Idaho
National Cold Water Marine Aquaculture Center, Franklin, Maine

Component 3: Improving the Efficiency and Sustainability of Hybrid Striped Bass Aquaculture

The 2013 *Census of Aquaculture* reported 52 farms producing fingerling and food-size hybrid striped bass with sales valued at $48,362,000; farms were located in Arkansas, Colorado, Delaware, Illinois, Florida, Mississippi, North Carolina, Texas, and Virginia. ARS research priorities for hybrid striped bass were informed by the virtual listening session on July 26, 2018, and associated direct email input; the 2018 North Carolina Aquaculture Development Conference, March 7-10, 2018, in New Bern, North Carolina; and direct interactions between ARS scientists and hybrid striped bass stakeholders. Stakeholders identified many priorities that ARS does not currently have the capacity to conduct research on, including:

- Technologies to develop sterile hybrid striped bass that do not sexually mature during the production cycle;
- Development of an effective, cheap tranquilizer approved for use in the United States; and
- Changing state regulatory policies around effluent requirements.

Problem Statement 3A: Enhance Hybrid Striped Bass Aquaculture Production

Hybrid striped 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 support production improvement and reduce potential adverse environmental impacts.

Genetic improvement of parental strains that results in increased hybrid performance is a highly desirable step toward increasing hybrid striped bass 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 hybrid striped 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. While replacing marine fish meal and marine oils with practical feed formulations developed from the byproducts and coproducts of plant and animal industries, enzymes, and nutritional supplements is a priority, 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 detection, prevention, and treatment of diseases 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 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.

Management Practices: Research needs include developing strategies to minimize the effects of seasonal egg release by large females in production ponds, such as production of sterile hybrid striped bass. Developing effective control measures for toxic algae in pond systems is a priority.

Nutrition: Research needs include optimizing 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;
- Effective vaccines for controlling disease;
- Validated improved diets for intensive production systems;
- Sustainable sources of ingredients to provide dietary protein and lipids;
- Nutrient requirements and digestibility for fish consuming diets supplemented with non-traditional protein and fat sources;
- Improved efficiency of intensive production systems; and
- Refined techniques to rear hybrid striped bass from egg to one gram to facilitate year-round fish availability.

Potential Benefits

- Genetic improvement for hybrid species production requires developing genome 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.

Component 3 Resources:
Harry K. Dupree Stuttgart National Aquaculture Research Center, Stuttgart, Arkansas

Component 4: Enhancing Shellfish Aquaculture
The 2013 *Census of Aquaculture* identified 306 farms producing the eastern oyster with sales valued at $65,383,000; 140 farms producing the Pacific oyster with sales valued at $81,721,000; and 48 shrimp farms with sales valued at $14,350,000. Recently, shellfish production is on the rise 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. A 2017 shrimp trade deficit of $6.4 billion signals ample opportunity for expanding domestic production to meet market demands.

ARS research priorities for shellfish were largely informed by the virtual listening session on August 15, 2018, and associated direct email input; a listening session on inland shrimp aquaculture hosted by ARS and NIFA and Auburn University in Demopolis, Alabama, on July 31, 2018; the Eastern Oyster Breeders Round Table held October 4, 2018, at the University of Rhode Island, Kingston Campus; sessions on shellfish breeding and disease at the National Shellfisheries Association Meeting in Seattle, Washington, on March 18-22, 2018; the Pacific Coast Shellfish Growers/ Pacific Coast Section NSA meeting held in Blaine, Washington, on September 18-20, 2018; the “West Coast Shellfish Research Goals 2015 Priories” report provided by the Pacific Coast Shellfish Grower’s Association; and direct interactions between ARS scientists and shellfish stakeholders. Stakeholders identified many priorities that ARS does not currently have the capacity to address, including:

- Protection and enhancement of water quality in shellfish growing 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; and
- Drafting regulatory policies.

Problem Statement 4A: Enhance Shellfish Aquaculture Production
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 will support the breeding of aquatic animals, while research in ecology will support the improvement of production systems by characterizing factors that affect environmental conditions and finding strategies to minimize their impacts.

Research Focus
Genetics: Research needs include generating oyster seedstocks that are optimized for performance across production environments and that provide resistance to diseases. Work is also needed on accelerating the pace of genetic improvement through genome-enabled technologies that will result in increased tolerance or resistance to pathogenic parasites.

Reducing Mortality: Research needs include identifying the cause of late term mortality experienced by inland shrimp farmers and developing strategies that improve shrimp survival.

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 shellfish production and satisfy regulatory constraints.

Anticipated Products
- Genome-enabled strategies for genetic improvement of oysters;
- Genetic improvement for disease resistance in the oyster;
- 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;
- A functional evaluation of intertidal habitats found in West Coast landscape-scale estuaries, particularly habitat for oyster aquaculture and eelgrass for fish and invertebrates;
- Strategies for reducing the impacts of burrowing shrimp on shellfish tidelands; and
- Reduced on-farm disease losses for inland shrimp production.

Potential Benefits
- Improved understanding of infectious diseases of oysters 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.

Component 4 Resources:
National Cold Water Marine Aquaculture Center, Franklin, Maine (Kingston, Rhode Island)
Shellfish Genetics worksite, Corvallis, Oregon (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 recirculating systems. As the largest importer of seafood products, 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 over 85 individual marine finfish species. These species, for which markets already exist, are excellent candidates for developing aquaculture industries that will meet increasing demands for seafood through domestic production. In addition, there is aquaculture potential for many other species that have markets that are too small to quantify, resulting in a combined list of over 100 native candidate species. Furthermore, non-native finfish species that are imported for U.S. consumption are candidates for domestic aquaculture production in land-based closed containment systems.

To develop this Action Plan, ARS narrowed down the list of candidate species for research to 18 through a series of stakeholder input activities that considered their status towards domestication, potential market value, stakeholder interest and current culture limitations that could be addressed through research. Firstly, 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. Secondly, 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 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 http://www.fau.edu/hboi/aquaculture/finfish.php) included:

1) Summarizing the state of aquaculture readiness for each of the 18 species listed in the survey as commercially ready, technologically feasible, or experimental;
2) Categorizing the top species with respect to their readiness for growing and/or establishing industries; and
3) 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 which are Experimental/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 which 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 in state and federal marine waters where permissible and land-based production systems.

These 18 species identified by stakeholders represent significant biological diversity and various stages of domestication, therefore their research needs are species-specific. Given the resources allocated for this Component, we will initially focus on Red Drum and Florida Pompano and conduct research on the other species where resources permit.

Problem Statement 5A: Develop Warmwater Marine Finfish 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-traditional 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 needs on management strategies, 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 for production of 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 in general 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;
- Breeding programs for marine finfish;
- Diets optimized for growth and economic returns of fingerlings and food fish, and to improve reproductive efficiency of broodfish; and
- Strategies for reducing on farm losses to disease.

Potential Benefits

- Seedstocks optimized for production efficiency to 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 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 the different life stages and reproductive performance, improve product quality, and improve production efficiency. Increasing the number of high-quality alternative ingredients will provide flexibility in formulating least cost diets.

Component 5 Resources:
A project entitled “Establishing Seedstocks for the U.S. 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 for maximum resource use efficiencies that decrease water usage and maximize nutrient retention while ensuring food safety for the protection of consumers. 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, in the FY2021 Budget Congress provided the following guidance: "*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*."

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

- Production models for Nile tilapia in multiple aquaponics system types;
- Assessment of Nile tilapia health and disease susceptibility in aquaponics systems;
- Production models for alternative species, including freshwater and saltwater species; and
- 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; and
- Economic models for aquaponic vegetable production.

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 rational design of engineered components in aquaponics systems. Additionally, considerations of both 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 the impact of system changes on 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;
- Systems models that generate predictions of yields, energy usage, water and nutrient use, and economic potentials;
- System configurations (fish tank, solids separation, microbial reactors, and plant production approach) that maximize profitability and minimize environmental impacts; and
- Mass and energy flow requirements and emissions modeling for different systems connections options.

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:
A project entitled “Developing Sustainable Aquaponic Production Systems” located within the Aquatic Animal Health Research Unit in Auburn, AL.

Appendix A – Stakeholder Inputs

1) A series of virtual listening sessions hosted by USDA ARS and NIFA National Program Leaders during the summer of 2018 soliciting input on research, education and extension activities. Individual listening sessions included the following topics:
    a. July 24, 2018, 1 pm –4 pm (EDT): Salmonids (~51 participants)
    b. July 25, 2018, 1 pm – 4 pm (EDT): Catfish ~30 participants)
    c. July 26, 2018, 1 pm – 4 pm (EDT): Freshwater Finfish (~26 participants)
    d. August 14, 2018, 1 pm – 4 pm (EDT): General Aquaculture (~26 participants)
    e. August 15, 2018, 1 pm – 4 pm (EDT): Molluscan Shellfish (~23 participants)
    f. August 16, 2018, 1 pm – 4 pm (EDT): Production Systems (~23 participants)

2) ARS and NIFA also collected written input at Aquaculture2018@ars.usda.gov throughout the month of August 2018, receiving 19 submissions.

3) The "Food-Fish Aquaculture in Minnesota" workshop hosted by the University of Minnesota Sea Grant College Program on April 26-27, 2017 (~40 participants).

4) The "Marine Fish Aquaculture Scoping Workshop" hosted by the Harbor Branch Oceanographic Institute on March 23-24, 2017 (~27 participants).

5) The 2017 National Aquaculture Extension Conference held June 6-8, 2017, in Boise, Idaho (~63 participants).

6) The "Utilizing Advanced Processing Technologies in Catfish" workshop hosted by USDA ARS in Stoneville, Mississippi, on April 9-10, 2018 (~39 participants).

7) The "Genomic Technologies for Assessing Continent of Origin for Atlantic Salmon" workshop hosted by USDA ARS and NIFA and the U.S. Fish and Wildlife Service (USFWS) in Orono, Maine, on June 5, 2018 (~20 participants).

8) A Listening Session hosted by USDA ARS and NIFA at the National Cold Water Marine Aquaculture Center in Orono, Maine, on June 6, 2018 (~25 participants).

9) The 2018 North Carolina Aquaculture Development Conference, March 7-10, 2018, in New Bern, North Carolina.

10) Listening Sessions for catfish and shrimp hosted by USDA ARS and NIFA and Auburn University in Greensboro, Alabama, on July 31, 2018 (~34 and ~17 participants, respectively).

11) A Listening Session hosted by USDA ARS and NIFA and Mississippi State University in Stoneville, Mississippi, on August 2, 2018 (~21 participants).

12) The "Change and Adapt: Get More out of Less" meeting held by the U.S. Trout Farmers Association at the USFWS National Conservation Training Center in Shepherdstown, West Virginia, September 6-8, 2018, ~79 participants).

13) The Eastern Oyster Breeders Round Table held October 4, 2018, at the University of Rhode Island, Kingston Campus (~31 participants).

14) The “West Coast Shellfish Research Goals 2015 Priorities” report authored by the Pacific Shellfish Institute and provided by the Pacific Coast Shellfish Grower’s Association.

15) Sessions on shellfish breeding and disease at the National Shellfisheries Association Meeting held in Seattle, Washington, on March 18-22, 2018.

16) Sessions on shellfish breeding and disease at the Pacific Coast Shellfish Growers/ Pacific Coast Section NSA meeting held in Blaine, Washington, on September 18-20, 2018.

17) The “Status of Marine Finfish Species for US Aquaculture” special session on March 10 at Aquaculture 2019 in New Orleans, LA (~200 participants). The session has been archived at http://www.fau.edu/hboi/aquaculture/finfish.php.

Appendix B - Visions for Agricultural Sciences and Status of U.S. Aquaculture

Visions for Agricultural Sciences

Visionary documents authored by leaders in the agricultural sciences informed the development of this Action Plan, including:

1) A report from The National Academies of Sciences, Engineering and Medicine entitled, "Science Breakthroughs to Advance Food and Agricultural Research by 2030." DOI 10.17226/25059

2) A new USDA Blueprint for Animal Genome Research 2018 – 2027 entitled, "Genome to Phenome: Improving Animal Health, Production and Well-Being."

3) The USDA Antimicrobial Resistance Action Plan

Status of U.S. Aquaculture

Government reports that describe the status of the United States Aquaculture industries informed the development of this Action Plan, including:

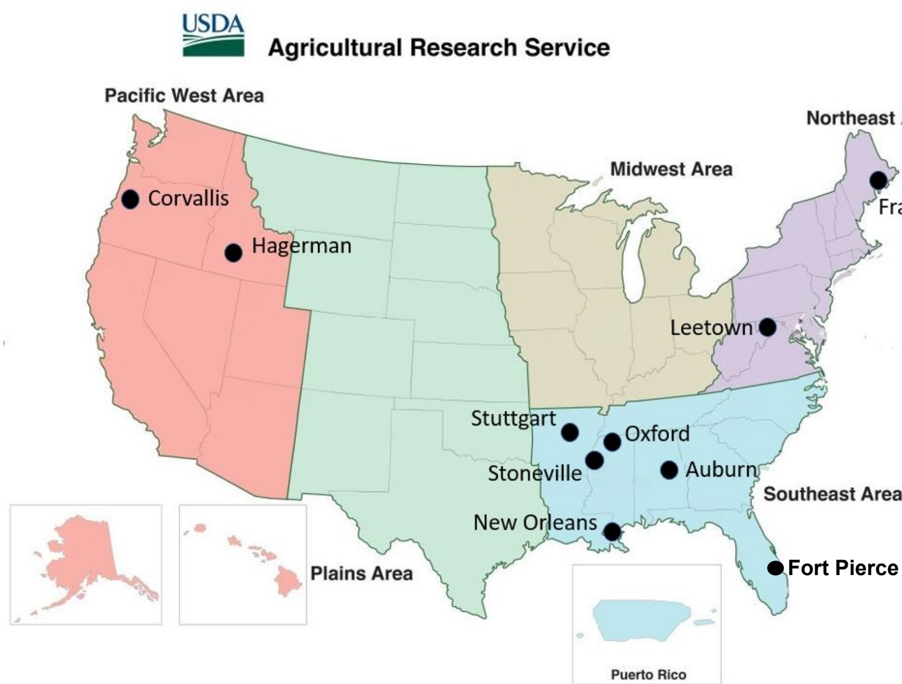
1) The USDA National Agriculture Statistics Service's *2013 Census of Aquaculture*.

2) The USDA Economic Research Service *Aquaculture Data*.

3) The National Oceanic and Atmospheric Administration 2015 report "Fisheries of the United States."

Appendix C. ARS Research Capacity

ARS conducts research under the ARS National Program for Aquaculture at 10 different locations through 14 projects performed by 50 ARS scientists and in funded collaborations with 12 cooperating institutions. The research facilities include:



The Small Grains and Potato Germplasm Research Center includes four scientists located in Hagerman, Idaho, and Bozeman, Montana, 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.

The National Center for Cool and Cold-Water Aquaculture includes 13 scientists at Leetown, West Virginia, and Milwaukee, Wisconsin, 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.

The National Cold Water Marine Aquaculture Center includes one scientist in Franklin, Maine, and one in Kingston, Rhode Island, 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.

A project aiming to improve Pacific oyster aquaculture includes two scientists at Corvallis, Oregon, who improves the sustainability of shellfish production systems in Pacific Northwest estuaries.

The Warmwater Aquaculture Research Unit includes six 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.

The Aquatic Animal Health Research Unit includes six scientists in Auburn, Alabama, who conduct research to develop control strategies to prevent large economic losses in the aquaculture industry caused by diseases and parasites.

The Harry K. Dupree Stuttgart National Aquaculture Research Center includes seven scientists in Stuttgart, Arkansas, who conduct research on hybrid striped bass with two aims: 1) development of feeds and improved culture strategies; and 2) disease therapeutics evaluation and control.

The Food Processing and Sensory Quality Research Unit includes one and a half scientist's time working in New Orleans, Louisiana to develop technologies that optimize the nutritional, functional, and sensory qualities of catfish.

The Natural Products Utilization Research Center includes one scientist in Oxford, Mississippi, who conducts research to reduce the impacts of off-flavor in recirculating aquaculture systems and pond production.

A project aiming to develop marine finfish seedstocks includes three scientists and collaborators at Florida Atlantic University's Harbor Branch Oceanographic Institute in Fort Pierce, Florida.

A project aiming to develop sustainable aquaponic production systems includes four scientists and collaborators at Auburn, University in Auburn, Alabama.