Overcoming Technical Barriers to the Sustainable Development of Competitive Marine Aquaculture in the United States

Summary of a Workshop on

Enhancing Competitiveness of Sustainable Marine Aquaculture in the United States: Addressing Measurement Barriers to Technological Innovation

Orlando, Florida
13-14 February 2008

Sponsored by

National Institute of Standards and Technology

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NOAA Technical Memorandum NMFS F/SPO-100

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FORWARD

Aquaculture is the fastest growing form of food production in the world. It is also a significant source of protein for people in many countries, including the United States. Globally, nearly half the fish consumed by humans is produced by fish farms. This worldwide trend toward aquaculture production is expected to continue. At the same time, demand for safe, healthy seafood is also expected to grow. It is clear that the United States needs a robust aquaculture industry to meet rising seafood demand and to enhance domestic commercial and recreational fish and shellfish stocks.

Technology innovation is a major source of the nation's economic well-being. Therefore it is critical to identify the technological roadblocks which impede innovation as well as identify the needs in measurements which are linked to technology innovation. The primary function of the Addressing Barriers to Technological Innovations in Aquaculture workshop was to generate information from private and public sectors to ensure that the nation's innovation and measurement needs in aquaculture were identified. If financial and other resources are made available and there is sufficient stakeholder interest, a research and innovation action plan could be developed based on this assessment.

The National Institute of Standards and Technology (NIST) and the National Oceanic and Atmospheric Administration (NOAA) jointly facilitated the Addressing Barriers to Technological Innovations in Aquaculture workshop. Other key agencies in aquaculture also participated as part of the workshop steering committee, including the U.S. Department of Agriculture (USDA) and the Food and Drug Administration (FDA). Founded in 1901, NIST is a non-regulatory federal agency within the U.S. Department of Commerce. The NIST mission is to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life. As a federal agency, under the U.S. Department of Commerce, NOAA is at the forefront of a national initiative to help the United States become more self-sufficient in the production of seafood. This initiative is based on sustainable commercial marine fisheries complemented by robust domestic aquaculture production.

In the fifteen previous industry workshops conducted as part of the U.S. Measurement System Assessment (usms.nist.gov) by NIST, 164 industry technology roadmaps were reviewed and 723 measurement needs in 11 industry sectors and technology areas identified. One would imagine technology and measurement needs across the sectors would vary tremendously. One would also imagine aquaculture's technological needs to be completely unique from other industries. However there are many notable similarities in the needs identified. Many needs identified from this workshop also touch upon previously identified needs that crosscut industry sectors:

- Requirements to improve process control transcend nearly all sectors and demand increased accuracy, precision, resolution, sensitivity, and repeatability.
- Opportunities to use sensors to detect, monitor, and control a wide variety of quantities, properties and processes—in real time—are abundant.

- Reliable metrics for quantifying overall system performance—such as interoperability and conformance to specifications—are critically needed, as products and services are integrated or networked into collections of hardware and software technologies, including complex systems.

Representing a variety of interests, including public and private research and development interests, industry, academia, and government and non-government entities, over 125 workshop participants helped identify and prioritize a more specific innovation and measurement needs agenda that addresses the technical infrastructure in the varied disciplines of aquaculture. By self-selecting into four working groups, participants identified how best to transfer knowledge and share priorities across industry, government, funding agencies, regulatory agencies, educational and not-for-profit institutions in order to build strong collaborations and partnerships. By the end of the workshop a roadmap of the innovation and measurement needs was outlined in four major areas: Biofloc-based Production of Marine Shrimp, Land-based Production of Marine Finfish, Coastal Shellfish Production, and Cage Production of Marine Finfish. The steps required to address these technical needs, as well as the consequences of inaction, were generally developed within these four breakout discussion groups.

If utilized effectively, this roadmap will make a difference for NOAA and NIST and the way we view aquaculture research needs and for the many other organizations public and private, who comprise the aquaculture infrastructure of the United States. It is our hope the varied technological barriers identified by this workshop will be a key component of the nation's innovative focus in aquaculture for the future. The industry comprises an incredibly diverse assortment of activities from commerce and trade to food safety, bio-security, animal health care and nutrition, environmental impacts, production technologies, as well as basic science oriented research and innovation. The results of this workshop provide a broad vision of the aquaculture industry in the U.S. and its innovation and measurement needs as we continue to move toward a more robust and sustainable domestic aquaculture industry that is both environmentally and economically sustainable.

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Workshop Executive Summary

Technological innovation drives economic growth and development and is a key source of ongoing competitive advantage in a global economy, but innovation can be impeded by unresolved measurement barriers. Measurement barriers include development of methods, standards, instruments, and capabilities to evaluate sector progress and technological advancement. This document summarizes the outcome of a NIST-NOAA workshop designed to identify the priority research needs, and where appropriate, the measurement barriers that impede U.S. marine aquaculture innovation. The workshop focused on the critical technology gaps that affect the sustainable development of a commercial marine aquaculture sector based on four types of production systems:

- shellfish aquaculture,
- cage culture of marine finfish,
- land-based culture of marine finfish, and
- biofloc-based culture of marine shrimp.

At the workshop, the main subject areas with identifiable technology gaps included:

- genetic improvement,
- nutrition,
- health management,
- reproductive control,
- production of larvae and juveniles,
- food safety and product quality,
- environmental performance and impact,
- system engineering and life-support systems, and
- economics and marketing.

It was clear from the workshop discussions that technical barriers to innovation can be addressed by strategic investment in high priority areas, particularly those with potential benefits that extend across technology platforms, and those that integrate research among disciplines. Also, cost-effective investments in research to address priority information and technology needs, combined with a stable regulatory environment, a streamlined permitting process, and public-private partnerships in demonstration systems can accelerate private-sector investment in the development of a sustainable and competitive marine aquaculture sector in the U.S. economy.

The following sections in this summary provide more detail the scope for an expanded marine aquaculture sector in the US, background on workshop structure and organization, as well as prioritized outcomes of the discussions of the workshop breakout groups. Research needs are summarized and prioritized. Specific measurement gaps are also described. During the workshop some very important non-technical barriers to sector development were identified and these have also been summarized in a section entitled Non-Technical Barriers. The final section in the workshop summary discusses roadmap implementation focusing on next steps to promote the advancement of US marine aquaculture.

The Scope for an Expanded Marine Aquaculture Sector

In 2007, the trade deficit for seafood in the U.S. was over $9 billion, with over 80% of the seafood consumed in the U.S. imported and about half of those imports from aquaculture. Production from U.S. marine aquaculture accounts for only 1.5% of the domestic seafood supply. Thus, there is enormous growth potential for production of safe, high-quality seafood that is farmed under federal and state environmental and food safety standards.

Marine aquaculture in the U.S. encompasses the production of a wide variety of finfish, shellfish, and algae, most of which are marketed as high-value seafood. Currently production is dominated by molluscan shellfish, although salmon and shrimp are also important, as well as smaller quantities of other marine species. The following table indicates the quantity and value of U.S. aquaculture production and imports of three of the main seafoods consumed in the U.S. (from the U.S. Department pf Agriculture (USDA) Census of Aquaculture, 2005 and National Marine Fisheries Service Annual Summary of Imports and Exports of Fishery Products, 2007).

Marine species		thousand pounds	million US$
Oysters, clams, mussels	U.S. production	268,164	170.4
	Imports	80,416	125.3
Salmon	U.S. production	20,726	37.4
	Imports	521,293	1,600
Shrimp	U.S. production	8,037	18.7
	Imports	1,223,434	3,896

Shellfish is currently the most important and robust sector of commercial marine aquaculture in the U.S. The potential for additional growth is high despite constraints associated with food safety, water quality, user conflicts, and site availability. In addition, seafood import statistics suggest that there is tremendous potential for the broader marine aquaculture sector based on the culture of marine finfish in cages and land-based recirculating systems, and on the culture of marine shrimp in intensive, biofloc-based systems.

Workshop Structure and Organization

A two-day workshop sponsored by the National Institute of Standards and Technology (NIST) and the National Oceanic and Atmospheric Administration (NOAA) was held in Orlando, Florida from 13-14 February, 2008. The workshop, which attracted over 125 participants, served to provide a forum and focus for a broad range of input from knowledgeable and experienced participants from among the community of aquaculture producers and those providing technology and services to producers, academics, and representatives of relevant government agencies and non-governmental organizations. The goals of the workshop were to identify and prioritize the critical technology gaps and, if appropriate, identify associated specific measurement barriers that constrain technological innovation in the development of sustainable marine aquaculture in the United States.

Four types of marine aquaculture systems were examined: coastal production of shellfish, cage culture of marine finfish, land-based production of marine finfish, and biofloc-based production of marine shrimp. These systems were selected on the basis of their potential for large-scale sustainable development in the U.S., the potential competitiveness of their products in a global seafood market, and technological innovations in research and development that are currently led by the U.S.

For each marine production system, a preliminary technology roadmap that charts the development of a competitive and sustainable marine aquaculture sector was prepared for review before the workshop. Marketing, economics, financial feasibility, and risk analysis provided focus on the technological barriers that are directly related to commercial competitiveness. Each roadmap addressed the following questions:

- What is the technology at issue?
- What are the short-, medium- and long-term opportunities for technological innovation that should be considered?
- What are the technological barriers to the innovation?
- What is the economic significance of the innovation that can improve U.S. marine aquaculture competitiveness?
- How can improvements in performance be measured and to what extent are measurement problems part of the technological barrier?
- What are the potential solutions to the measurement part of the technological barrier?

Innovative technologies were identified and described with the goal of spanning and integrating among all aspects of aquaculture production, including:

- species selection, broodstock development, and genetic improvement
- hatchery, fingerling and adult husbandry
- nutrition, feeds, growth, and product quality
- disease diagnostics and health management
- production system design and engineering
- environmental standards and waste management, and
- harvesting, processing and marketing

In break-out sessions during the workshop the roadmaps were discussed, additional input collected, and participants encouraged through facilitated discussion to identify and prioritize impediments to commercialization. The output from the break-out session was a list of technology, knowledge, and implementation gaps that constrain innovation and competitiveness of each of the targeted sustainable production systems. Another break-out session focused on defining potential solutions to technology gaps and issues raised in the first break-out session. Participants were encouraged to identify and define the measurement needs that impede research and development of the technological innovations that foster competitiveness. Workshop participants prioritized output into short-, medium-, and long-term needs through a combination of individual indications of importance and consensus-building discussion to rank the most important areas. In the wrap-up session, break-out group leaders summarized findings in a plenary session and solicited additional input from participants. Participants were also given opportunities to provide additional input during several rounds of post-workshop review of roadmaps and this document.

A sustainable and competitive marine aquaculture sector in the United States must overcome numerous technical, regulatory, and economic barriers to innovation and commercial development. Although the workshop focused on technology innovation and measurement needs, the importance of the enabling environment – including regulatory streamlining and stability, the availability of investment capital for aquaculture businesses, and the overall policy environment – were identified as no less critical to the success of marine aquaculture development.

This document identifies priority areas for future research and development investments that target the most critical technology gaps and measurement needs, the solutions of which can lead to improved competitiveness and large-scale development of the marine aquaculture industry in the U.S. Accompanying this document are roadmaps that detail the research needs for four marine aquaculture production systems.

Priority Research Needs

Some of the research needs to overcome technical barriers are common to multiple technology platforms. For example, research on feeds to improve the environmental sustainability and culture performance of fish and shrimp aquaculture will be beneficial irrespective of specific technology platform. Other research needs are specific to particular culture systems. The cost-effectiveness of investment in research can be maximized by investing in priority areas that are relevant to multiple technology platforms.

Many of the technology areas that are described here apply broadly to aquaculture in general, but the specific needs of each area with respect to the four technology platforms are emphasized. Cross-cutting research areas include: genetic improvement, feeds and nutrition, health management, reproductive control, larval production, environmental monitoring and management, waste treatment, and system engineering. Research needs in economic performance and product quality and safety were also identified. The following were identified as high priority areas. Ordering of priorities varies somewhat with technology platform, but in general research needs are presented in order from higher to lower priority. A sustained, coordinated, and well-supported effort will be necessary to yield the benefits from discoveries and technology development.

Genetic Improvement

The genetic basis for growth, feed conversion, disease resistance, processing yield, and other commercially important production traits is poorly understood and represents a barrier to improved production performance. Selective breeding programs should continue to emphasize traits of commercial importance, especially growth rate, feed conversion efficiency, and disease resistance. Long-term advancement of improved culture performance of shellfish, marine finfish, and shrimp requires genetic improvement programs based on the application of conventional selective breeding (selection, crossbreeding, hybridization) aided by molecular and other genetic tools.

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Some relevant molecular tools are available, but are only moderately well developed and applied to genetic improvement of a limited number of commercially important species. Other tools have not been applied to the genetic improvement of species with commercial potential. Yet other much-needed tools with specific relevance to genetic improvement of existing and emerging species with commercial potential have not been developed. Examples of molecular tools include specific microsatellite and single-nucleotide polymorphism markers, DNA microarrays, quantitative trait loci maps, expressed sequence tag libraries, and whole genome sequences.

Although genetic improvement of all cultured species can lead to substantial gains in productivity, it was not identified as a priority area for marine finfish at this time. Compared to freshwater finfish, the culture of non-salmonid marine finfish is relatively new and fish captured from wild populations are used as broodstock. For shellfish and marine shrimp, the specific goals of research programs in genetic improvement are:

Shellfish: Establish selective breeding programs for commercially important and emerging shellfish species and continue to support current breeding and genetics research. Develop new molecular and other tools to elucidate the genetic basis for commercially important production traits (e.g., improved meat-to-shell ratio, resistance to disease, heat or salinity stress).

Marine Shrimp: Continue to invest in robust selective breeding programs for penaeid shrimp. Develop new or use existing molecular tools to understand the genetic basis of shrimp production performance and disease resistance, and apply discoveries to improve the efficiency and genetic gains of selection programs. Develop methods for monosex female production.

Nutrition, Feeds, and Feeding Practices

Feed typically represents the largest variable cost item in commercial aquaculture for systems where animals are fed. Feeds and nutrition are critical priority areas for marine finfish and marine shrimp technology platforms, and for shellfish hatcheries. Identification and evaluation of dietary protein and lipid sources suitable as alternative ingredients to fishmeal and fish oil in aquaculture feeds is a pressing research need, particularly in the context of rapidly rising commodity grain prices. Diet formulations must be improved to increase the efficiency of the fishmeal and fish oil resources used in feeds. There is also a critical need to develop high-efficiency, low-polluting diets that are optimized for species, life-stage, and culture system. Research is needed to evaluate finishing diets that can be used to affect the nutrient composition, especially the fatty acid profile, of cultured seafood. Research on attractants and diet palatability is needed. Basic nutrition research on the nutrient requirements of different life-stages of most species of marine finfish with culture potential is required. Research and development efforts are needed to evaluate feed delivery systems, including information-intensive or “smart” systems, remotely operated feeding systems, and feeding regimes or protocols to realize the production potential of genetically improved finfish and shrimp. Finally, the overall environmental impact (i.e., ecological footprint) associated with feeding requires additional review, followed by periodic re-evaluation.

Technology gaps related to nutrition and feeds of shellfish apply during the hatchery phase and are addressed in the section on larval production below. Following are the specific goals of research programs in the nutrition of marine finfish and shrimp.

Marine Finfish: Improve the efficiency of feed formulations. Evaluate diets with fishmeal and fish oil from fish processing by-products. Develop high-performance, cost-effective diets with protein sources that are alternatives to fishmeal and fish oil. Identify nutrients in fishmeal not present in other ingredients. Understand the link between broodstock nutrition and gamete quality. Improve understanding of larval digestive physiology. Improve diets specifically manufactured for optimum performance in recirculating systems. Understand the effect of diet on recirculating system performance. Evaluate the broader impact of feed use in terms of ecological footprint (e.g., Life-Cycle Assessment).

Marine Shrimp: Improve feed formulations that maximize the efficiency of fishmeal, minimize the ecological footprint of all ingredients, and promote water quality. Integrate formulations with contributions of natural productivity and maximize the benefits from suspended solids (biofloc) to shrimp growth. Improve inventory control and optimize feeding efficiencies.

Health Management

High-density confinement and other environmental stressors, weak control over the type and density of pathogens, and limited options for practical disease control are factors that make health management and disease control a major concern in all forms of marine aquaculture. This area is a priority for all technology platforms. The role of common stressors or combinations of stressors in aquaculture production systems on the immunity and health of cultured animals is poorly understood. Further, understanding of the genetic basis for the relationship between immunity and health is lacking. Probiotics and immunostimulants represent alternatives to antibiotics, but realization of the full potential of these materials requires additional research to understand the underlying mechanisms that influence efficacy. Research is also necessary to establish protocols and standards for practical application of these materials. Development of new vaccines, particularly those targeting emerging diseases, requires an ongoing research effort. New tools and application of existing tools are needed to monitor pathogens and disease outbreaks in aquaculture production systems, including shellfish growing areas. The effects of hatchery methods, larval nutrition, and water quality on the health of cultured juveniles require additional research effort. Finally, evaluation and refinement of biosecurity protocols to prevent the exchange of pathogens between aquaculture facilities and the environment is needed

The specific goals of research programs in health management for production systems used to culture shellfish, marine finfish, and shrimp are:

Shellfish. Develop real-time diagnostic tests for important pathogens of shellfish. Develop field tests for stress indicators and other measures of shellfish condition. Develop cost-effective vaccines or disease treatments for shellfish. Explore water treatment measures to improve larval and juvenile survival and growth in hatcheries.

Marine Finfish. Identify the genetic basis of fish health. Develop sensitive diagnostic tools to measure fish stress and health. Assess probiotic approaches to enhance fish growth and health and improve understanding of the underlying mechanisms related to efficacy. Improve vaccine development and delivery efficiency. Develop and evaluate rapid diagnostic tools for assessment of pathogens, particularly *Vibrio* species, especially during fingerling transfer to cages. Develop management techniques for control of sea lice and gill parasites. Develop techniques to manage the effects of harmful algal blooms.

Marine Shrimp. Improve understanding of the factors affecting shrimp health and fitness. Develop diagnostic tools that permit rapid assessment of stress and disease. Develop standard biosecurity protocols, including pathogen monitoring and disease control systems. Establish protocols for management response to early warnings of stress or disease.

Reproductive Control

Control over reproduction to achieve consistent, year-round spawning and the production of high-quality gametes and larvae are priority areas for shellfish, marine finfish, and shrimp. The identity and role of natural spawning cues and pheromones on fish reproduction requires further research. The role of the endocrine system on reproduction must be better understood to enable predictable volitional or induced spawning. Additional research is required to evaluate the role of broodstock husbandry and nutrition on the number and quality of gametes and offspring. For shellfish and marine finfish, mass production techniques that will reliably result in the reproductive isolation of cultured stocks from wild populations must be developed and evaluated.

The specific goals of research programs in reproductive control for shellfish and marine finfish follow. Control over reproduction is not seen as a priority area that constrains the development of commercial marine shrimp aquaculture in the U.S.

Shellfish. Develop improved methods for the reliable mass production of sterile animals to minimize or eliminate genetic interactions between wild and cultured populations of native shellfish. Create tools to assess maturation and potential reproductive performance in broodstock.

Marine Finfish. Improve understanding of endocrine regulation of reproduction and spawning. Establish protocols and evaluate techniques for consistent, year-round production of juveniles. Optimize gamete quality and supply. Evaluate methods for assessing and controlling gamete quality. Understand the link between broodstock nutrition and gamete quality. Improve broodstock performance through species-specific selective breeding programs. Develop reliable and effective methods of sterilization as a means to mitigate potential effects of escape.

Production of Larvae and Juveniles

Almost all culture systems require the production of juveniles in hatcheries, although shellfish aquaculture as currently practiced in some areas remains dependent to a varying degree on natural recruitment. In the future, aquaculture will require the consistent and controlled production of large quantities of healthy juveniles with high performance potential. Hatchery technologies must be engineered to reduce production variability and to allow for controlled production under diverse conditions. The quality and number of fingerlings required (i.e., large batches) are major constraints on the development of offshore cage culture of finfish. Broodstock, hatchery, and nursery operations must be established to meet the increasing demand for larvae and juveniles. Standardized stress tests are needed to gauge juvenile quality. Research is necessary to better understand larval digestive physiology and larval diets, including live foods and microdiets that replace live foods. Research is also needed to improve understanding of the species-specific physical requirements (e.g., water flow, light) for larval rearing.

The specific goals of research programs in larval production of shellfish, marine finfish, and marine shrimp are:

Shellfish. Establish the capacity for real-time monitoring of larval and juvenile condition, live food quality, and biosecurity in shellfish hatcheries. Assess water quality management and other techniques that minimize, eliminate, and control specific pathogens and contaminants in algae and shellfish larval production systems.

Marine Finfish. Establish species-specific criteria for physical and biological requirements for hatchery production of juveniles. Establish standards for larval and juvenile quality. Improve tailored microdiets to replace live foods, along with supporting probiotic regimens. Increase the level of husbandry automation (e.g., in-tank counting and grading, tank cleaning, stage-specific harvesting). Establish standard techniques for counting stocked fingerlings. Identify the species- and site-specific optimum size for transfer of fingerlings to production cages.

Marine Shrimp. Develop replacements for live foods in larval culture. Establish standards for postlarval quality and fitness. Develop non-invasive methods to accurately count post-larvae and juveniles.

Food Safety and Product Quality

Food safety is not only a critical priority area for marketing shellfish, but is an important issue in the marketing of all cultured seafood. Most shellfish are marketed as a fresh and live product so the real or perceived risk of consumption of shellfish that are contaminated with human pathogens is a serious impediment to further expansion of consumer markets. Other potential contaminants of concerns are marine biotoxins, *Vibrio* and other marine bacteria, viruses in growing area waters, and biotoxin and pathogen accumulation between harvest and consumption. Sensitive, standardized, and high-throughput methods are needed to allow expansion of testing for microbial contaminants, organic and inorganic pesticides and chemicals, antibiotic and other drug residues, and other contaminants. More rapid and cost-effective tools are needed to detect and quantify human pathogens in shellfish and natural waters, and harmful algal blooms and their toxins that are present above established food safety or toxicity thresholds. Research is necessary to develop diagnostic tests for human pathogens in shellfish, especially *Vibrio* species. Further, there is a need to define safety standards and action thresholds with respect to microbial pathogens and to develop the tools for risk analysis. In the absence of tests for specific pathogens, there is a need to establish indicators that can serve as proxies for food safety pathogens that are difficult to detect and measure directly. Collectively, these tests will provide the basis to assure consumers of the safety of cultured seafood and provide a competitive marketing advantage to U.S. growers who produce seafood under stringent regulatory oversight of food safety. In the realm of product quality, tests are needed for nutritional and flesh quality in shellfish, finfish, and shrimp. Tests to identify cultured seafood can aid in product traceability, market branding, certification programs, and differentiating cultured from wild populations. Methods for improving shellfish product quality (e.g., cleaning, sterilization) using ozone or pressure need further evaluation. Similarly, methods should be developed that avoid potential problems and remediate product quality of shrimp and shellfish with off-flavors that could be associated with recirculating systems. The relationship between feed composition and the nutrient composition (e.g., fatty acid profile) of aquaculture products needs evaluation and refinement.

The specific goals of research programs in food safety and product quality for shellfish, marine finfish, and marine shrimp are:

Shellfish. Develop and refine rapid test methods for detecting human pathogens, marine biotoxins, and environmental contaminants in water and shellfish. Establish uniform standards for infection, toxin, or contaminant thresholds. Evaluate indicators that can serve as proxies for pathogen measurement. Establish alternatives to fecal coliform bacteria as an indicator organism. Provide practical product quality measurement tools for processors and shippers of shellfish products.

Marine Finfish. Develop diets and feeding practices to minimize contaminants and optimize the fatty acid profile of the final product. Develop alternative feeds to minimize the risk of concentration and accumulation of environmental contaminants in the final product. Develop systems to monitor flavor quality in fish cultured in land-based recirculating systems.

Marine Shrimp. Develop products that can provide added value or some other premium quality over competitive products and can be distinguished in the market through branding or labeling. Examples include fatty-acid enrichment, organic certification and marketing live or fresh-never-frozen shrimp.

Environmental Performance and Impact

Monitoring and managing the beneficial and adverse environmental effects of aquaculture are high-priority areas. The application of cost-effective monitoring tools is needed to demonstrate compliance with discharge permits and performance standards. Research is necessary to further evaluate interactions between aquaculture and the environment. In particular, standard approaches are needed to assess environmental carrying capacity of local culture areas during preliminary site assessments. These techniques should also consider the cumulative effects of multiple facilities.

With cage culture, carrying capacity refers to understanding the near-field solid waste assimilation capacity of sites and the far-field effects of dissolved nutrient waste release. With shellfish culture, carrying capacity refers to the relationship between primary production, hydrodynamics, and shellfish production. Research is also needed to assess and optimize the environmental effects of shellfish harvest methods and other farming practices. Some of the specific environmental impacts and risk sources that require further investigation include benthic impacts and site remediation, disease transfer between wild and cultured populations, and the effect of escaped fish and shellfish on wild populations.

Land-based systems pose different types of environmental impacts that may need to be monitored and managed, such as footprint associated with the production of feedstuffs and feed manufacture, energy use, effluent reuse, and waste disposal. Environmental performance should be evaluated in terms of standardized sustainability metrics, which are currently lacking.

The specific goals of research programs in environmental management for coastal shellfish aquaculture and cage culture of marine finfish and land based culture systems are:

Shellfish. Characterize the effect of farming methods on the environment, indexed to reference sites. Develop and evaluate mechanized harvest methods to increase management efficiency, reduce labor costs, and minimize environmental impacts. Develop standard geo-referenced and relational databases that integrate environmental monitoring with shellfish production data to track shellfish from broodstock and larval culture through the production and supply chain.

Cage Culture of Marine Finfish. Develop cost-effective ways to assess sites and evaluate environmental performance of cage aquaculture that can predict the potential for adverse impacts (e.g., benthic, disease transfer, escaped fish) and beneficial effects (e.g., habitat creation). Evaluate the suitability of easily measured indicators or indices of the environmental effects of aquaculture on the marine environment. Further develop and validate models of environmental performance and carrying capacity.

Land-Based Culture of Marine Finfish or Marine Shrimp. Develop standardized sustainability metrics and explore methods to better characterize the ecological footprint of land based recirculation systems. Issues such as efficiencies and costs of manufacture and transportation associated with feeds formulated for these systems, efficiencies of energy utilization per unit production, effluent and waste generation per unit seafood production and sustainable disposal alternatives should be addressed.

System Engineering and Life-Support Systems

Some future marine aquaculture systems will be intensive, and therefore rely increasingly on engineering for critical life-support and waste treatment services, mechanization of management operations, and reduction of risk. Research is required to improve biofiltration and waste treatment technology for land-based marine finfish and shrimp production systems and water treatment processes for shellfish hatcheries. Further elucidation of design specifications for waste treatment and life-support systems according to species and life-stage is needed. Fundamental research on microbial processes and their relationships with water quality and target crop performance is also required. Establishment of metrics to assess changes in the efficiency of biophysical resource use can guide management improvements that enhance economic competitiveness.

In general, engineering needs are specific to culture system, species, site, and facility. The specific goals of research programs in engineering are:

Shellfish. Improve hatchery and nursery technology and culture techniques. Develop cost-effective real-time water quality monitoring and control processes for water intake and holding systems in hatcheries. Improve mechanization or automation of harvesting, predator deterrence or exclusion, biofouling control, and other operations during grow-out. Explore alternate and non-destructive predator protection and exclusion methods. Develop processing, packaging, transport, and storage techniques to maintain product quality and food safety and minimize ecological footprint.

Cage Culture of Marine Finfish. Evaluate improved materials, cage designs, and construction techniques to reduce the risk of fish escape from containment breaches caused by adverse weather, predators, and human error. Establish performance criteria and standards for containment technologies (e.g., structure, integrity). Develop highly mechanized, remotely operated systems (e.g., feeding, biofouling control). Develop generic automated monitoring and control systems for cage management operations – especially feeding, depth control, fish inventory assessment, and cage biofouling control – to maintain an optimal environment for fish production. Develop software systems that involve remote sensing, feedback systems, and neural networks for intelligent control of cage culture operations. Evaluate on-site energy generation from waves, ocean currents, or wind. Develop deepwater mooring and containment systems, including tension-leg and single-point moorings, and untethered cage systems.

Land-Based Culture of Marine Finfish. Improve the energy efficiency, cost-effectiveness, and biosecurity of life-support, biofiltration, and waste treatment technology. Optimize microbial communities and processes to maximize waste removal and water reuse, and the efficiency of probiotic support. Improve system energy efficiency, particularly for maintaining water temperature. Establish standards and specifications for waste treatment and disposal, and life-support systems. Develop generic and standard production systems suitable for the culture of multiple marine finfish species. Increase the level of system automation, particularly for routine husbandry operations. Evaluate the co-production of energy (methane) from solid waste.

Biofloc-Based Culture of Marine Shrimp. Improve the cost-effectiveness of life-support technology. Improve system energy efficiency, particularly for maintaining water temperature. Establish standards and specifications for system engineering design, with the goal of improving production efficiency as measured by shrimp growth and production potential. Demonstrate standard management techniques to establish, manage and maintain the structure, abundance, and activity of stable biofloc communities that maximize contributions to shrimp growth and water quality management. Improve methods to collect, dewater, digest, and dispose of waste solids. Improve methods for denitrifying, desalting, and treating water to reclaim minerals for reuse.

Economics and Marketing

Better understanding of the economic performance of marine aquaculture production systems is needed to stimulate investment. Economic and financial analysis at the firm or facility level is needed, including estimation of capital requirements and production costs, return on investment, and internal rate of return. The models should also include sensitivity, cash flow, and a comprehensive risk analysis. Generic business plans and economic audits for each marine aquaculture system should be used to focus research priorities on areas that are significant to reducing risk and maximizing economic performance. A market analysis must be completed before any species is farmed or an aquaculture business developed. The marketing analysis should include estimation of supply and demand, analysis of supply chains, assessment of market depth, and evaluations of consumer attitudes and perceptions toward cultured seafood. It should also determine the potential for market strategies that can increase the demand for cultured seafood products such as grading, branding, labeling, certification, and adding value.

Although there is a general need for economics and marketing research for all species and culture systems, the specific research needs identified for biofloc-based marine shrimp culture are:

Biofloc-Based Culture of Marine Shrimp. Develop accurate, flexible, and user-friendly financial bio-economic models that include sensitivity and risk analyses. Apply studies to determine the potential size of the market for value-added products.

Biofouling Control

The colonization of aquaculture netting, equipment, and structures with biofouling organisms can reduce the growth and survival of cultured animals and increase the risk of containment failure. Research is needed on technologies and management approaches to control biofouling in marine aquaculture, particularly for culture systems with direct exposure to the marine environment. Further improvement of non-toxic and fouling-resistant materials and coatings is a critical need. Alternatively, automated and remotely operated net cleaners are needed to control biofouling in cage culture.

Inventory Estimation

Efficient feeding and other aspects of culture system management requires knowledge of the number and size of finfish, shellfish, or shrimp in a production unit. Direct population sampling is the most widespread current practice, but this is often impractical (especially in large culture units), can have a negative impact on growth or health, and may lead to biased estimations of inventory. Cost-effective and non-lethal technologies are needed to assess inventory, count juveniles at stocking, and estimate population size. Collection, processing, and integration of this information in real time allows control of feeding and water quality management operations.

Ranked Specific Priority Areas

The areas requiring research and development effort for each technology platform are prioritized on the basis of three criteria:

- **Feasibility**. An evaluation of the scientific and technical potential for overcoming technological barriers. What is technically feasible? What can be accomplished through research? How difficult is it to overcome the barrier?
- **Importance/Relevance/Urgency**. How pressing is the need? How critical to overall success is overcoming this particular gap?
- **Socio-economic Impact**. Projections of expected benefits and consequences. Are results broadly applicable or narrowly focused? What is the relative return on investment made to overcome a gap?

Priorities are described in terms of the most important goals for that area, with special emphasis on those areas with measurement needs. The priority areas are described with short phrases; more detailed descriptions of each area are provided above and in the roadmaps for each production system. Areas are listed in order from higher to lower priority. In most cases, the areas indicated are viewed as critical, high-priority needs that must be addressed in the short to medium term.

Coastal Shellfish Production
Coastal Shellfish Production

- food safety and product quality
- reproductive control
- genetic improvement
- database management and tracking (traceability)
- shellfish health and condition
- farming methods
- larval and live food production

Cage Production of Marine Finfish

Issues related to species selection, genetic improvement, and hatchery production of larvae and juveniles were addressed by the land-based marine finfish group and are not discussed here. However, they were identified as high priority technology gaps that must be addressed for the development of a sustainable and competitive marine aquaculture sector based on the cage culture of marine finfish. The priority needs for cage culture of marine finfish are:

- assessment of environmental performance
- nutrition and feeds
- cage integrity
- fingerling transport and transfer
- disease diagnosis
- integrated, self-regulating, and autonomous operational control

Land-Based Production of Marine Finfish

Given the diversity of marine finfish species considered as suitable candidates for aquaculture, criteria for selecting among candidate marine finfish species with commercial culture potential are needed. A decision matrix that applies these criteria can be used to evaluate and prioritize candidate species. The priority research needs for land-based marine finfish culture are:

- life-support systems
- induced spawning
- larval rearing
- nutrition and feeds
- fish health and stress

Biofloc-Based Production of Marine Shrimp
Production of Marine Shrimp

- production system engineering and design
- suspended solids (biofloc) management
- waste management and treatment
- genetic improvement
- feeds and feeding
- health and biosecurity
- value-added products
- bio-economic models

Measurement Needs

The measurement needs for marine aquaculture can be divided into two overlapping categories. In one category are measurement needs to advance aquaculture science. These measurement needs require the development or application of sophisticated and advanced scientific and engineering tools and techniques. Advances in genetic improvement, health diagnostics, stress and digestive physiology will require development and application of these new tools. In another category are the measurement needs for the operation and management of commercial facilities, particularly as part of monitoring and control systems. Measurement tools for commercial facilities must be robust and cost-effective.

Sensors

Sensors have been widely used in aquaculture, particularly in monitoring water quality. Ideal sensors in aquaculture would be low-cost, robust, resistant to biofouling, self-calibrating, permit remote operation, and provide measurements in real time. Sensors for aquaculture can be mechanical, chemical, thermal, biological, optical, and acoustic and used for detection, monitoring, and control. Sensors can be used to measure the basic physical, biological, and chemical components of system function. The value of sensors increases with connection to control equipment that manages life-support systems or automates husbandry operations. Sensors are available to measure temperature, salinity, dissolved oxygen, and water currents, although wider use of some sensors is constrained by high cost and uncertain reliability. Sensors to measure or estimate phytoplankton and microbial biomass and activity need improvement. Sensors (e.g., video, sonar) and image analysis can be used for biomass estimation, inventory control, equipment inspection, environmental observation, and farm security. These sensors can be used as components of feeding systems in cage culture. In some cases, sensors exist, but cost reduction is needed for routine application.

Analytical Techniques

Most research laboratories have well-developed analytical capability, but most commercial facilities have only the most basic analytical equipment. Technology-intensive marine aquaculture is also knowledge- and information-intensive, increasing the need for enhanced analytical capability using new tools and techniques. Some of the research addressing technical barriers will need new tools or application of tools that are used elsewhere. The value of many techniques can be improved by increasing accuracy and precision, reducing cost, improving simplicity, and increasing the timeliness of results.

Standard analytical techniques are needed to measure:

- biochemical and physiological indices of shellfish, finfish, and shrimp, including those of the endocrine and immune systems, and changes in response to stress
- gamete quality, especially egg biochemical composition
- microbial activity
- nutrient bioavailability from feeds
- fatty acid profiles of diets and cultured seafood products
- organoleptic quality of cultured seafood

Diagnostic Tests

Most diagnostic tests in aquaculture have been applied in research settings, not as simple field kits employed at commercial facilities. Diagnostic tests should be accurate, sufficiently sensitive, cost-effective, non-destructive, rapid, and preferably provide timely results to guide management decisions. Real-time polymerase chain reaction (PCR) is an example of such a test, although it is cost-prohibitive in a commercial setting and requires a skilled technician.

Diagnostic tests are needed to:

- confirm the presence of important human pathogens and biotoxins (e.g., paralytic shellfish poisoning toxin) in shellfish or water at culture sites
- evaluate sources of microbial contaminants that impact shellfish growing areas
- evaluate and quantify contaminants in cultured seafood
- identify and quantify the most important pathogens of shellfish, finfish, and shrimp, particularly to demonstrate disease-free status (e.g., specific pathogen free (SPF) for certification of juveniles for transfer and stocking
- evaluate general health status (i.e., immunocompetence) of cultured animals
- evaluate flesh quality (freshness, organoleptic quality, fatty acid profile)
- identify or mark fish, shellfish, or shrimp to be able to trace product through the supply chain or to evaluate the effect of escaped culture animals on wild populations

Metrics or Standards

Establishing standards has been critical to the success of many industrial sectors of the economy. In aquaculture, few technology standards exist and many system designs are idiosyncratic. Metrics and standards are needed for many aspects of marine aquaculture production and marketing.

Standards are needed for:

- infection thresholds (i.e., action levels) of fish or human pathogens
- contaminants, such as pesticides, metals, organic compounds, drug and anti-biotic residues
- organoleptic quality (flavor, texture, “freshness,” shelf-life)

Standard methods and metrics are needed to:

- quantify culture system performance, particularly efficiency measures and environmental performance
- assess broodstock readiness to spawn (e.g., with gene chips that measure the activity of genes for hormones that control egg maturation) and performance
- quantify fingerling and shrimp post-larval quality (e.g., stress tests) and performance
- prevent diseases, especially in hatcheries and recirculating systems (i.e., biosecurity)
- evaluate feed ingredient digestibility

Models

The value of information from primary research can be improved by integration into models. Models can be constructed in a variety of domains: 1) physical, such as hydrodynamic models of ocean currents or shallow intensive tanks; 2) ecological, such as models to estimate waste assimilation capacity, nutrient dynamics in recirculating systems, and shellfish and primary production; and 3) economic, such as models for culture system performance, business, and market demand. Some models may be constructed and apply across multiple domains. The most useful models will be 1) developed into operational tools to forecast conditions in each domain, 2) integrated into monitoring, control, and decision-support system software, or 3) applied as a tool in environmental regulation.

Non-Technical Barriers

Although the focus of the workshop and this document is on the technical barriers to innovation in marine aquaculture, other factors play roles of varying importance to technology development and the establishment of commercial marine aquaculture.

Regulations and Policy

The process of obtaining approvals and permits for coastal aquaculture projects is a major impediment to the development of marine aquaculture in the United States. Permits from a spectrum of federal, state, and local agencies are required for marine aquaculture, and the permitting process is often difficult, time-consuming, and costly. Permitting remains an uncertain, uncoordinated, unstable, and inconsistent process, indicating that clear guidelines are needed. Permits regulate the selection of sites, the species that may be cultured, and on-site operations. Constraints on siting limit the expansion of shellfish aquaculture, particularly for small-scale producers, and offshore cage culture projects. The proposed National Offshore Aquaculture Act seeks to streamline the permitting process for federal waters, but congressional approval remains pending. There is a need for comprehensive nearshore planning (through the Coastal Zone Management Act or other mechanisms) that includes zoning for aquaculture, including marine technology parks. There is also a need to transition from individual to general permits under the National Pollutant Discharge Elimination System and the U.S. Army Corps of Engineers Nationwide Permit 48 for shellfish aquaculture. Efforts to educate regulators and assist permit applicants with regulatory clearance are needed.

User Conflicts

Some members of the public hold negative perceptions of the practices and products of aquaculture. Coastal areas are used for a variety of commercial and recreational activities that inevitably conflict with aquaculture projects. Increasing coastal population and the accompanying transition to an increasing proportion of users who are not dependent on the marine environment for their livelihood have given rise to objections to siting aquaculture facilities in productive nearshore areas. Objections are raised to the privatization of what is understood to be open-access resources. To foster good relations, the public should be provided with science-based information that describes the benefits of U.S. marine aquaculture, industry practices, and aquaculture-environment interactions. A better understanding of market and nonmarket benefits and costs associated with marine aquaculture is needed to address necessary tradeoffs among stakeholder groups.

Financial

Some types of modern commercial aquaculture are capital intensive and so the availability of investment capital and interest rates on borrowed capital constrains economic development. A thorough risk analysis can guide investment and financing decisions. Business and marketing plans with a comprehensive economic and financial analysis, including consideration of market dynamics and uncertainties, are needed. Financial information provided by commercial producers is necessary to assess economic performance, develop business plans, and conduct market analysis. New and existing producers need training in business management skills. Strong public sector investment in research to develop state-of-the-art knowledge and evaluate best practices can serve as an incentive for potential investors. A favorable and incentive-driven investment climate for marine aquaculture remains a daunting task and is becoming more challenging in the current economic environment.

Research

A major constraint to enhancement of the technical competitiveness of marine aquaculture in the U.S. is the lack of long-term vision and poor coordination of private, state, and federal research activities and infrastructure. This barrier can be addressed through strategic planning and coordination among relevant agencies, especially NOAA and USDA. Strategic planning can be used to leverage funds in targeted areas and improve the likelihood of realizing success with competitive funding opportunities. With few exceptions, there is no dedicated funding stream for long-term marine aquaculture research projects. Rather, research is largely supported by a fragmented array of short-term grant programs. Although increased long-term funding levels can improve the competitiveness of marine aquaculture, more efficient use of existing funding and limited portfolios to solve practical problems that are relevant to the needs of commercial aquaculture development are also needed. Funding for aquaculture research and development, including demonstration projects, requires consistency, continuity, integration, and evaluation of cost-effectiveness to ensure success and attract long-term commitment by the private sector. Appropriately funded government-industry-academic partnerships in targeted integrated multidisciplinary efforts should be encouraged. Short-term, extramural funding sources (e.g., earmarks and competitive grant programs, such as the NIST Technology Innovation Program) can complement coordinated longer-term, intramural funding sources from government agencies such as NOAA and the USDA Agricultural Research Service. Available Small Business Innovation Research (SBIR) programs should also be promoted to the commercial aquaculture sector to encourage proprietary research or activities more suitable for private patents. Research should be applied with a view towards understanding effects across the supply chain; for example, how research results implemented on-farm will affect product quality and market value.

Skilled Workers

Modern, technically sophisticated marine aquaculture requires skilled workers to manage and operate marine aquaculture facilities and trained scientists to staff university and government research laboratories. Marine aquaculture will compete with agriculture and other sectors of the economy for the services of individuals with desirable skills and experience. Many prominent university-based aquaculture programs have contracted, although some programs, most notably those of 1890 Land Grant universities, are expanding. Non-degree technical programs emphasizing the practical skills desired for employment at aquaculture production facilities are lacking. Thus, a deficit of skilled and experienced workers can constrain marine aquaculture development. Support is needed for infrastructure and training programs at marine aquaculture research or production facilities operated by universities, government agencies, or aquaculture businesses. The availability of expertise within the United States to address priority marine aquaculture research needs and measurement barriers remains an open question. Marine aquaculture investigators in the U.S. have relationships with international colleagues that range from informal professional contacts to formal networks.

Technology Transfer

A formal and vigorous technology transfer program will be necessary to extend technology innovations to new and existing producers. Sea Grant and Land Grant college extension programs will be the critical agents of technology transfer and producer training. Although the National Sea Grant Program has an extension function, it is not as nearly well-developed as the agricultural extension effort supported by Land Grant universities, particularly for aquaculture. The effectiveness of any transfer program will depend, in part, on demonstration of technologies at an appropriate commercial scale to encourage adoption. Commercial-scale yield verification programs that evaluate and demonstrate improved practices and technologies with cooperating producers can accelerate technology transfer.

Roadmap Implementation

A technological advanced marine aquaculture sector will be knowledge-intensive and thus require new information and technologies to supplement and extend the current understanding of aquaculture production systems. In some cases, technology gaps will be overcome with new knowledge or tools and in other cases they will be addressed by demonstrating success in application and integration of existing knowledge or tools.

Overcoming technical barriers and increasing production efficiency requires solving problems holistically, recognizing the interrelationships among areas of investigation and across disciplines. Thus, these problems are best addressed systematically by teams of researchers, each with complementary expertise to address components of the technical barriers. This approach can increase the value of research investments. An economic audit of a production system can identify areas of greatest risk or greatest economic return and impact. Economic analysis is a critical component to guide research priorities and evaluate the cost-effectiveness of investments in research and development.

In general, the capability to address technical barriers is present in the United States among the university- and government-based research and extension communities, assisted by commercial producers. However, critical needs may not be met because aquaculture competes with other sectors of the economy for individuals with desirable skill sets. Partnerships with international colleagues on issues of mutual interest can enhance the competitiveness of marine aquaculture in the U.S.

Finally, overcoming technical barriers requires periodic assessment of progress. Clear definitions of success can be achieved by developing criteria and quantitative measures to evaluate outcomes, impacts, and progress in overcoming barriers.

Demonstrating Feasibility

The focus of this workshop was on identifying specific technical barriers that constrain the development of a sustainable and competitive commercial marine aquaculture sector. Overcoming these barriers will require strategic and careful investment in research and development by public and private sectors, perhaps in partnership. The development of a competitive marine aquaculture sector in the United States can be stimulated by establishing commercial-scale pilot systems to demonstrate and refine the economic and environmental performance of each of the main technology platforms. In the case of shellfish aquaculture, one pilot system should be established at each of the three main coastal areas where shellfish are cultured in the United States (Pacific Northwest, Mid-Atlantic, Gulf of Mexico). At least three demonstration systems should be established to evaluate the cage culture of marine finfish, and at least one each for land-based marine finfish and biofloc-based shrimp systems. Project goals, evaluation criteria, and standards of success must be clearly defined.

Obviously, establishing and operating a commercial-scale demonstration facility is costly, so creative funding mechanisms that equitably share risks must be explored. One option is a private-public partnership that is part of university-supported technology parks or business incubators, particularly for diagnostic services or high-value, specialty applications. Another variation would be to establish a private-public partnership where private-sector investors, perhaps supported by a venture capital fund, would provide funding for capital equipment (facilities and equipment). The investors would also support a general and technical management team. Public agencies would support the efforts of investigators who would provide conceptual engineering designs, generic business plans, and evaluate technology and management approaches in a commercial setting. In either case, clear agreements about intellectual property, patents, and licensing agreements must be in place.

A Roadmap for Commercialization of Advanced Technologies for the Farming of Marine Shellfish

Technical Challenges and Measurement Barriers

Technology at Issue

Advanced technologies for farming of marine shellfish.

Technological Innovation at Stake

Marine shellfish aquaculture accounts for a large fraction of the total world production of aquacultured seafood, with an annual production in 2005 trailing only cyprinids (freshwater carps and similar species). It is also extremely diverse with a wide range of species cultured, culture methods, and technological development. In the United States, molluscan shellfish accounted for approximately 1/3rd of the total domestic aquaculture production of 526,280 metric tons in 2007 (FAO Global Aquaculture Production Statistics). It is a traditional and expanding industry on the West Coast, and an expanding industry in the eastern and southern U.S. Historically oysters accounted for the bulk of the production, but in recent years other shellfish have become increasingly important. These include mussels; hard, softshell, Manila, and geoduck clams; scallops; and abalone. While U.S. aquaculture production of these species is increasing, it does not meet the domestic demand for shellfish. Nor does it provide sufficient opportunities for export of shellfish products.

The U.S. shellfish aquaculture sector, government agencies and tribal entities are faced with numerous near-term to long-term opportunities and challenges. Advances in shellfish hatchery, nursery and grow-out systems require new technologies to enhance production of currently cultured species, the culture of new species, and restoration of wild stocks. These technologies can be made possible by combined private and public sector research, education, and training efforts. Coupled with technological advancements are international and national policies and programs calling for the support and development of robust, economically effective and environmentally sound aquaculture practices. In order to meet increasing world demand for shellfish and other seafood products and to reduce rising seafood deficits, assistance is needed for technology development to enhance shellfish aquaculture production in shore-based, offshore, and land-based environments.

This shellfish technology roadmap integrates previous efforts to establish research goals for shellfish aquaculture with the combined input of shellfish growers, researchers, and public agency specialists from the workshop. Beginning in 1999 with updates through 2008, a West

Coast research cooperative, the Pacific Shellfish Institute (PSI), prepared a broad list of goals through 2015 and prioritized the research needed to achieve them. These goals and priorities were subsequently adapted by the East Coast Shellfish Research Institute to develop a coordinated research, education and training effort on the East Coast. Similar recommendations were made during an oyster research and restoration workshop sponsored by Maryland Sea Grant in 2003. These documents were circulated to research institutions, granting entities, and resource management agencies for comment.

Expert input to this shellfish roadmap was facilitated by a working group with diverse interests, professional experiences, geographic representation, and institutional membership. Working group members were provided with an outline of key problem areas and were asked to comment on and enhance the outline, and to respond to ongoing updates in the shellfish roadmap.

Economic Significance of Innovation

Technological innovation for shellfish aquaculture can take many forms. It has the potential to markedly increase U.S. shellfish production, expand export opportunities, and improve understanding of the complex interrelationship between the natural and human environment in these production systems. The recent development of geoduck clam (*Panopea abrupta*) aquaculture in the western U.S. offers an excellent case example of the economic effects of new technology. Geoduck are large (0.75 to 1 kg at harvest) and relatively fast-growing (4-5 year growout) clams with a high biomass density at harvest (90+ mt/ha [80,000+ lb/acre]) and strong market demand from Asia. The development of geoduck aquaculture is closely linked to hatchery, nursery, grow-out, harvest and transportation technologies which must be adapted specifically to create an optimized product for the producer and consumer. The geoduck aquaculture sector is expected to increase with improvements in those technologies. U.S. production is projected to be over 2,000 mt by 2010 with a farm-gate value of about $20 million (Jonathan King, Northern Economics, Anchorage, personal communication). New technology applications are beginning to drive economic development in other parts of the shellfish aquaculture sector. Examples include:

- development of intensive hatchery and nursery systems
- application of genetic tools to improve shellfish yields, survival and appearance/taste
- experiments with methods to modify the production cycle and access non-traditional growing areas (such as offshore systems)
- intensive production systems
- precision harvesting methods to reduce harvest area disturbance and increase yields
- processing methods to control product quality, food safety, and facilitate transport.

Crosscutting Non-Technical Barriers to Innovation

<u>Research Integration and Management</u>

A major constraint to enhancing the technical competitiveness of marine aquaculture in the U.S., including shellfish aquaculture on the West Coast, is the lack of long-term vision and a coordinated private, state and federal research infrastructure. The present fragmented approach is impeding the development of important shellfish research programs and uniform environmental management systems. For example, shellfish breeding programs must integrate genetic technologies with husbandry, nutrition, disease management, and production systems in a long-term strategy to improve the efficiency and yield of shellfish farming. While the West Coast has had the benefit of two long-term research projects on genetic improvement of Pacific oysters, both of which have produced new knowledge, limited progress has been made towards applying that knowledge to commercial breeding. The industry continues to grow wild animals, with only rudimentary knowledge of yields, production efficiencies, and environmental effects. This is not necessarily a result of specific technological gaps but is more likely caused by a lack of integration of existing research findings with commercial production methods.

Regulatory, Siting, and Public Policy Issues

Progress in key regulatory and policy areas is critical to open opportunities for application of new technologies in aquaculture. For example, provisions of the Coastal Zone Management Act encourage states to do comprehensive nearshore aquaculture planning. NOAA is promoting aquaculture development in the Exclusive Economic Zone and indicating the need for further growth in nearshore waters. However, without a comprehensive state-level planning process, user conflicts and water quality issues will impede expansion of shellfish aquaculture.

Economics, Training, Markets, and Pricing

These largely social issues are essential components in marine aquaculture development. Specific cross-cutting examples include a marketing strategy to increase demand and price for species currently under cultivation and identify market opportunities for new species; educating the general public, consumers, waterfront owners, resource managers, boaters, and others regarding the benefits of shellfish, shellfish culture, and the industry's need for a clean healthy environment; and increased support for formal undergraduate and graduate training in marine aquaculture centers and laboratories at community colleges, universities, tribal and other research facilities. Other common areas of interest are country-of-origin labeling, product branding, organic labeling, advertising tools, specialty and value-added products and markets, business training for new entrants and existing farmers, investment capital at reasonable rates, and improved economic metrics for production volumes and values.

Technology Transfer

There are many examples of currently available technologies in the scientific literature and in various locations around the world, which are not being employed by the U.S. marine shellfish aquaculture sector. There is a strong need to develop more effective methods of transferring the most efficient methodologies available in a manner to encourage adoption by the industry. This requires extension and outreach efforts including demonstration at an appropriate scale to convince producers or processors to adapt efficient technology. This effort requires new and traditional extension and outreach methods.

Technical and Measurement Barriers to the Innovation

Despite the high potential for growth of shellfish aquaculture in the U.S., significant technical gaps and impediments remain. These are organized according to stages of the production cycle and by tasks or operations within each stage. Listed first are those which are cross-cutting with other marine aquaculture sectors. These are followed with examples of technologies and processes specific to the shellfish aquaculture sector. A summary of these key technologies is provided in Table 1.

Cross-Cutting Measurement Challenges

Many of the technological aspects of aquaculture development have broad cross-cutting measurement requirements. Specific examples include:

- multiculture / multitrophic systems – production and yield measurements
- broodstock integrity and grow-out performance – identification and markers
- health management, disease control / prevention, and biosecurity – disease and contaminant monitors and detectors
- feed supplies – monitoring and production of balanced non-algal diets that are economically feasible
- ecological carrying capacity and sustainability (environmental footprint) – productivity measurements
- temperature, salinity, light, pH, chlorophyll *a*, ammonia, nitrite, nitrate and phosphorus concentrations, and other environmental parameters – water quality measurement devices that are designed for continuous operation, provide reliable and stable operation over time, are cost-effective, and robust
- water management for hatchery and nursery systems – flow control, water quality maintenance
- energy, product, and materials management – monitoring heat reclamation and energy use

Genetics, Breeding, Larvae and Seed Supply

While most shellfish produced in the U.S. originate from wild sources of seed, hatcheries and controlled nursery systems are increasingly playing a greater role in commercial and restoration aquaculture. These facilities give producers greater control over sources of broodstock, allow selection for favorable characteristics, and help stabilize seed supplies. Nevertheless, shellfish hatcheries are at an early stage of development, with many elements needing technological improvement.

Important methods currently at a very early stage of development are: 1) the use of DNA microarrays to study the effects of certain treatments, diseases, and developmental stages on gene expression in cultured shellfish, and to assist breeding programs in assessing genome content in selected animals; 2) sterilization methods, including triploidy, coupled with breeding procedures which effectively predict the in-field production characteristics of sterilized animals vs. non-sterilized individuals; and 3) suitable trace-back tools to provide improved growth and survival performance guidance for breeding programs, and to enhance the abilities of hatcheries to produce the highest quality larvae and seed.

Genetics and Breeding

Integration and Coordination: Improved tracking procedures or methods are needed throughout the production cycle. This system should be able to track shellfish production from spawning to consumption and would ideally include information on parental genetics, performance traits in the hatchery and the field, environmental conditions, and grow-out technique used. This kind of farm-level data is critical in a number of ways. It would provide, for example, de facto field trials of various stocks, strains, and families in a variety of production environments and tracking data to quickly identify and isolate both shellfish and human disease issues. It would also provide long-term data to evaluate the impacts of selective breeding and improvements in husbandry technology.

In addition to production tracking systems, a publicly-financed research hatchery could produce large arrays of genetic families and impose various experimental conditions (e.g., temperature, food level) using highly automated systems. This would allow a major scale-up of breeding efforts, moving beyond the current limitation of about 50 families. Something on the order of a few hundred small, flow-through larval tanks would be appropriate. Such a facility would also require expanded nursery and grow-out systems.

Controls on Reproduction: There are two major constraints to controlling reproduction in shellfish. First, a better understanding and application of triploidy in species other than oysters is needed, especially when native species are cultured in proximity to wild populations. This is critical because, unless there is a way to prevent cultured shellfish from interbreeding with wild stocks, a complex system of growing only non-improved locally-derived stocks may be necessary to prevent translocation. This would create a complete roadblock to genetic improvement through selective breeding if domestication selection produces genotypes that are inferior under natural conditions. The application of triploidy for isolating aquaculture stocks from wild congeners can amplify efforts to increase stock improvements in cultured species by eliminating or reducing genetic risk issues. The best way to assure that this does not occur is to prevent interbreeding altogether by using sterile animals for culture. Measures of success for different methods of producing sterile animals are needed, including the stability of sterility.

Triploidy may not be the only approach, but has proven effective with oysters. Other methods to prevent reproduction in cultured shellfish that require further investigation include genetic manipulation to knock out key genes involved in sexual maturation, development of all-female lines in species with genetic sex determination, and selective breeding for delayed maturation and fast growth so animals can be harvested before reproducing.

The second issue is how to conduct selective breeding for triploids or other non-reproductive end products. Because triploids are sterile, it is impossible to use the best-performing animals as broodstock. Also, it is unknown whether it is best to carry out selection on diploids and/or tetraploids in order to improve triploid performance. Therefore, large collections of genetic material in diploid and tetraploid forms must be available to find the best combinations. Other approaches to reproductive control may have other unknown implications with respect to selective breeding for genetic improvement.

Germplasm Collection and Preservation: Critical to maintenance of selectively bred shellfish is the need to facilitate the transfer of genetic materials in ways that do not involve moving whole animals, is not subject to intensive disease testing and quarantine requirements, and does not require the maintenance of a large-scale broodstock repository. This could be facilitated by understanding how to freeze, store, and distribute cryopreserved sperm, eggs, and embryos that have been certified as disease free and thus are not restricted in terms of transport. For model organisms such as *Drosophila* and *Arabidopsis*, there are large collections of lines and crosses that researchers can obtain at nominal costs. Such collections are used for basic scientific research or as sources of novel genes for selective breeding. With shellfish, lines of oysters have been produced in France that are resistant and susceptible to summer mortality (a disease affecting oysters). At this point, the only way these animals can be imported into the U.S. is to go through a multi-year process of growing a generation in quarantine and conducting an expensive suite of disease tests. Frozen embryos certified as disease-free could be made available to U.S. producers within a much shorter time.

Heritability Estimates: Heritability is often misunderstood because it is a characteristic of a specific population and not the whole species. Furthermore, genetic correlations among multiple traits may be more important than single-trait heritability because these can complicate multi-trait selection or produce unexpected results if selection is based on single traits. An efficient way to estimate heritability and genetic correlations with reasonable precision is needed. Reasonable estimates of genetic correlations require a half-sib mating scheme involving at least 50 half-sib families (i.e., 150 full-sib families). Current hatchery limitations make this extremely difficult. The other option is to mix families and sort them out using molecular markers, but this can be expensive. One way to minimize these expenses would be to develop some kind of standard set of multiplexed marker loci that allows inexpensive and rapid genotyping of enough markers to allow parentage determination at low cost.

Inbreeding: Inbreeding is typically avoided, but depending on the approaches to genetic improvement, it can be desirable. Specifically, if cross-breeding to obtain heterosis (“hybrid vigor”) is indicated as the best alternative, then a large array of highly inbred lines is needed to construct and test hybrid combinations. This will require the creation of a very large set of inbred lines.

Molecular Markers, Mapping and Genomic Enablement: A better DNA microarray is needed for Pacific oysters and other shellfish species. A microarray has been produced for Eastern oysters; however, it is not very useful for other species. The Eastern oyster array contains a limited number of Pacific oyster genes, and many of those are not fully described or annotated. A reasonably priced, high-quality, high-coverage microarray would go a very long way toward improving understanding of how oysters and other shellfish interact with pathogens, physical stress, and pollution.

Genetics and Breeding Technology Gaps: Information on the performance of improved molluscan stocks is difficult to obtain and expensive to produce. Improved systems for evaluating the performance of lines or stocks of bivalves under field conditions are greatly needed. This will require better husbandry systems that control for density-dependent interactions between individuals and enable evenly distributed availability of suspended foods to test animals – both factors that contribute significantly to variability in performance. Reducing the time needed to obtain a production “signal” is greatly needed as a means to reduce costs and time between subsequent generations. Both selection and crossbreeding approaches to stock improvement would benefit from research on systems that enable faster and more accurate measurement of individuals or stocks at the larval or seed stage that serve as predictors of adult performance. The development of microarrays may be very useful in this regard. Marker-assisted selection programs remain elusive but equally valuable as a means to evaluate stocks routinely and help predict production characteristics based on analysis of broodstock. Further development of the genetic tools needed to elucidate the genetic basis of economically important traits and enable genetic-level selection in a variety of cultured shellfish species is needed.

The development of industry-supported programs that enable the shellfish sector to learn about and incorporate genetic improvement are in great need of support. Genetic improvement programs need coordinated baseline data for evaluation of strains, integration of environmental and production data, and tracking of geo-located data at all levels. Genetic improvement has largely focused on Eastern and Pacific oysters and needs to be extended to other mollusk species.

Genetics and Breeding Measurement Issues: A key issue to monitor is how improved stocks are utilized by industry. Without industry participation, stock improvement programs should be a secondary objective for funding agencies. It is critical to demonstrate to industry that stock improvement can increase profitability, and outreach should be scaled up to enable growers to utilize improvements. Modeling of the Australian oyster industry would be a useful approach for U.S. growers. There is a need to better apply the Land Grant university agricultural experiment station model to shellfish aquaculture.

Other measurement needs include 1) cost-effective genome sequencing tools for key commercial shellfish species; 2) adaptation and application of current geographic information system (GIS) technology for product tracking coupled with technical support at the industry level and centralized data collection; and 3) measures of the social acceptability of applied technologies.

Broodstock Maturation Systems

Broodstock can be held in controlled environments in hatcheries to stimulate the growth and development of reproductive products. The goal of broodstock maturation systems is to accelerate the spawning cycle and/or facilitate spawning independent of the normal seasonal periods.

Systems Engineering: Broodstock systems are typically placed inside larval culture systems with modest control of water quality and management of water flows. Measurement requirements are the same as described below for larval culture systems. Automation of the control and operation of these systems will greatly reduce the required labor.

Feeds and Feeding: The feed requirements for broodstock are different from larvae and juveniles (markedly so for abalone). Typically feeds are live microalgae, but prepared diets are also used. Availability of balanced, prepared diets for shellfish is a major impediment to development of large-scale holding systems.

Reproductive Performance: Reproductive performance is linked to fecundity, fertilization rates, and hatching rates. Significant measurement issues include identifiers of gamete maturation, sex type, and spawning indicators.

Health and Prevention of Disease Transfer: Disease in broodstock can be associated with the use of diseased wild shellfish or through the introduction of disease organisms in the culture system. Diseases may be transferred through the culture system and/or reduce reproductive performance of broodstock. Non-technical options include improved screening standards for Reportable Diseases and tools to measure broodstock health.

Broodstock Maturation Technology Gaps and Measurement Issues: The development of hatchery-based systems to supply molluscan larvae and seed that are characterized by a "high health" certification, genetic improvement of larvae and seed (for a variety of production traits), and widespread availability remains an elusive set of goals for shellfish aquaculture worldwide. Few broodstocks used in the industry have an associated genetic-performance history. Information on all stocks used for seed production should be fully pedigreed with associated performance information for phases of grow-out that is comparable to the disease history information that is much more widely available today. Further, little is typically known about reproductive parameters associated with broodlines. Age at first reproduction, level of reproductive effort and output, gametogenic response to environmental cues and predicted sex ratio in both broodstocks and progeny are all likely under some genetic control but are not known for most broodstocks utilized. Most information for suspension feeding bivalves is available for commercially farmed oysters only.

Nutrition of broodstock animals is not well understood with specific reference to the interplay between nutrition and maturation, environmental cues (e.g., temperature, light, salinity) and the onset of maturation processes (e.g., glycogen storage and/or gametogenesis). Information on endogenous factors (e.g., hormonal controls) influencing the onset of gametogenesis in bivalves of commercial importance is needed, as is better information on nutritional needs (e.g., sterols and other constituents of microalgae that are not well understood with respect to maturation processes in suspension-feeding bivalves).

Other technology gaps and measurement issues include: 1) hatchery and nursery culture methods for broodstock maintenance, and larval and juvenile rearing; 2) rapid methods to assess and monitor algal nutritional quality and improve feed delivery; 3) real-time monitoring of bacterial flora in culture systems; 4) low-cost sterilization or treatment of culture water that does not affect water quality; 5) tools to determine or measure food composition and performance of algae and manufactured diets (also directed at biosecurity issues); 6) development of measurement parameters to determine environmental conditions that allow selection of specific organisms in algae production; 7) technology to selectively eliminate specific organisms in a mix of algae (such as acoustic tools, probiotics); and 8) non-invasive and cost-effective methods for rapid determination of reproductive condition.

Larval Culture Systems

Systems Engineering: Larval culture typically employs complex systems for water filtration, purification, and heating. Most aspects of these systems are similar to those employed for flow-through finfish culture, with the exception of the use of water-borne feeds. Recent experiments to intensify culture systems have demonstrated the need for sensitive real-time tools to monitor feed quality, feeding rates, and other biological indicators. Methods of measuring and/or managing fouling in all shellfish culture systems are also needed.

Husbandry: Management and monitoring of larval growth, metamorphosis, and survival are often the most labor-intensive aspects of hatchery operations. Most shellfish hatcheries use live microalgal feeds grown in batch or continuous incubators. Some prepared feeds, such as packaged microalgae concentrates, may be used. Similar to the health management and disease prevention requirements for broodstock, the susceptibility of shellfish larvae to a wide variety of viral, bacterial, and protozoan diseases places a significant burden on hatchery operators. Larval transport does not pose any significant measurement challenges other than a need to ensure that transport temperatures and durations do not exceed expected ranges. There are needs for automated methods to clean, feed, measure feed concentrations, count larvae, and other parameters in husbandry systems.

Larval culture systems technology gaps: The availability of adequate supplies of larvae and seed when growers need them has been virtually impossible to achieve on a consistent basis. This calls for the need for better production systems that focus on bottlenecks, including better information on broodstock maturation cues, larval husbandry, and nursery system development. Often, live algal food supplies are limiting. This severely limits the ability to consistently rear larvae and early-phase seed to a size or age when survival improves. Replacement of algal feed with cost-effective, balanced diets of the correct particle size formulated from prepared ingredients would eliminate many of these problems. Primary research and rapid technology transfer of information on bivalve nutrition on a species-specific basis is greatly needed. Water quality and water treatment options have improved but there is no technology in place that enables consistent monitoring of water quality in real-time for the pathogenic bacteria, viruses or water pollutants that may have profound consequences for viability of embryos, larvae and small seed. Probiotic approaches are under study in a variety of locales for bivalve systems but they have not yet been applied commercially on a large scale. Commercially available probiotic water treatments are largely ineffective for bivalve systems.

Larval culture systems measurement issues: Important measurement parameters are growth rates, larval quality, and larval quantification. There is a critical need for measurement parameters associated with key genetic information that is obtained in part by having pedigreed lines of broodstock. Key measurement tools should assist in feed management, health and pathogen monitoring, disease prevention, monitoring the utility of probiotic and antibiotic applications, and assessing larval settlement, induction and synchrony.

Prepared feed must be the correct size for effective utilization by shellfish. Low cost and easily used instrumentation to measure feed particle size and feed concentration in water are needed. Methods to measure feed constitutions and determine if each feed particle contains the complete balance of nutrients are needed. Easy to use, cost-effective instruments and methods to determine algae species composition, particle size of algae, and algae concentration in water are needed.

Nursery Systems

Nursery systems associated with larval hatcheries usually consist of downwelling and/or upwelling technologies that are put in place when larvae reach the pediveliger stage, or larval phase when individuals are competent to settle and metamorphose. These may consist of systems with a small volume and flow-through capability (e.g., soft-drink bottles) where feed and water are supplied continuously or semi-continuously under temperature controlled conditions or larger systems that rely on setting tanks and screens and larger volumes of water and feed. Invariably, as seed grow, space becomes limiting and feed costs increase significantly. Outdoor nursery systems typically rely on upwelling tanks and/or raceway systems. Depending on the value of the species cultured, hatchery operators carefully monitor the volume of seed that can be produced with the algal production capability of the facility. Increased use of floating upwelling systems is usually warranted because costs for live or artificial supplemental feeds are high and increase dramatically with size of bivalve seed.

Water quality for nursery systems containing newly settled individuals must be assiduously monitored. Water treatment is phased to accommodate the needs of the species cultured. Treatment options can include primary filtration, ultraviolet sterilization, carbon treatments, passage of seawater through biological media and foam fractionation to remove proteins, toxins and other metabolites that may be harmful to newly settled seed. This phase of culture is typically the point where high losses are seen in most if not all bivalve and gastropod hatchery facilities. Oyster nursery systems benefit from the use of spat-on-shell technologies because spat can often be placed into the natural environment with adequate predator protection quite soon after settlement. Clams, mussels, and other commercially valuable species (e.g., abalone) typically require a longer nursery phase.

Nursery Systems Technology Gaps: Critically needed are alternatives to removing most particulate and biological constituents of seawater prior to addition of cultured algae and use for nursery phase animals. Systems that can grow large quantities of algae without bacterial contamination are needed. Reliance on commonly cultivated microalgal species for use in nursery culture systems should be replaced by using native algae that is produced on site in tanks or closed systems. Research is needed on the nutritional value of uncommonly cultivated microalgae for use with bivalve and gastropod nurseries. Control of bacteria and/or toxins in high-density nursery culture is needed. Probiotic approaches better knowledge of the interplay between water quality, seed health and viability are needed.

Direct seeding of pediveligers onto suitable beach substrates, as has been examined for Pacific oysters and Manila clams, should be further examined to reduce costs. This approach may have significant utility for shellfish restoration efforts.

Nursery Systems Measurement Issues: A database that monitors larval and seed output on an annual basis is needed to measure progress toward eliminating or reducing variability in larval and seed supplies from nursery systems. Seed production, availability, species diversity, survival and growth are all factors that can be measured that will help gauge improvement in these systems as a result of increased attention though research and development.

Instruments noted under larval culture above for measuring feed composition, particle size, nutrient content, and concentration in the water are needed for all stages of growth for all cultured shellfish species.

Grow-out Systems

All shellfish, with the exception of abalone (grown in land-based tanks or raceways), are raised to market size using variations of on-bottom or suspended open-water culture systems. Bottom culture of shellfish is often seen as a traditional enterprise, and is (with geoducks being a recent exception) widely viewed as environmentally acceptable aquaculture. Bottom cultured animals often exhibit varying growth, shell shape and other characteristics. They can be markedly influenced by sediment composition, organic content, and other variables. For example, Manila clam shells are often darker or less well marked when grown in fine-grain sediments, or oysters may exhibit higher mortalities when the underlying sediments become increasingly anoxic. Therefore determination of sediment characteristics and sediment and water column chemistry is a valuable measurement tool for the shellfish farmer.

Off-bottom culture is a preferred method in many areas of the world, and is common in the U.S. for mussel and oyster culture. For oysters, this method gives the grower greater control over shell shape, and sometime shell color. It also facilitates the production of a more uniform or consistent product size and can allow continuous product harvest. A primary advantage of controlled or containerized culture systems is that they improve the capability of growers to manipulate the production system and improve the quality of their product during grow-out. For example, in protective containment, geoduck clams can have better meat coloration and texture, faster growth, and a higher market price than wild harvested animals.

Until recently there has been little effort to identify optimal configurations and construction features of shellfish grow-out systems. The systems are typically configured to the maximum extent (or maximum permitted) of available and accessible water surface or bottom areas. Recent efforts to model carrying capacity and ecological interactions in these systems have also provided insights on methods to optimize production and monitor associated environmental parameters. Land and resource use conflicts, and urban growth are increasingly influencing the type and intensity of environmental monitoring required of shellfish farmers.

Grow-out Systems Technology Gaps and Measurement Issues

- accurate real-time and low-cost instruments for measurement of a variety of water quality parameters (e.g., temperature, salinity, dissolved oxygen, pH, pCO_2/TCO_2, ammonia, chlorophyll *a*, and certain contaminants) in intertidal environments at the sediment-water interface
- practical field-deployable tools to measure biological activity – photosynthesis, respiration, nitrification/denitirification, bacterial and algae productivity, sediment organic content, and animal abundance, diversity, and seasonality

1. low-cost instruments that measure wave height, tidal surge and flow and other physical parameters that effect shellfish production over growing areas; little is known about how these physical factors interact to provide the desired food to shellfish growing on natural bottom or in the water column

- simplified tools to assess and manage shellfish production and the associated biological community -- phytoplankton/macroalgae/seagrass/harmful algal blooms, bacteria (including *Vibrios* and pathogens), animal competitors and predators

- procedures to examine the relationships between environmental variables and key production characteristics, and contribute to the development of predictive models
- environmental/crop monitoring and modeling tools that integrate water quality reporting with husbandry and production
- inventory and growth monitoring and modeling
- direct measurement of production carrying capacity of suspended and bottom culture systems
- application of underwater video or other observational methods to assess shellfish behavior, phytoplankton (flow cam), other flora and fauna (i.e., fish, shrimp)
- improved methods to monitor animal physiological state (such as hormone production, respiration rate, excretion, stress indicators) under field conditions
- veterinary health monitoring; measures of the condition and health of shellfish
- shellfish condition and disease detection measures that are rapid, non-destructive, cost-effective and automated
- enhanced technology transfer from existing applications.

Harvest Systems

Harvest systems include materials/product handling systems and tools to enhance/ensure product quality and food safety, and to minimize environmental effects. Material/product handling is not so much a measurement issue as a material design problem. Efficient, robust, and cost-effective materials handling systems are needed to reduce labor costs. These may include improved product containment methods which reduce both the handling effort and damage to harvested shellfish. Some harvest practices are under great environmental scrutiny and consequently have significant measurement requirements to assess sediment alterations and harvest-induced turbidity. These practices would benefit from observations aimed at reducing or minimizing environmental effects.

A key issue affecting bivalve grow-out systems revolves around food safety at harvest. Bivalve shellfish are usually grown in estuaries and are typically associated with streams and rivers draining large upland watersheds. These watersheds may be undeveloped, but more often, receive some form of human inputs that can increase pollutant loads to estuaries. Shellfish, being filter-feeding animals, can concentrate a wide variety of potentially harmful materials including pathogenic bacteria and viruses, protozoa, biotoxins, heavy metals and organic contaminants. Much effort in terms of shellfish health and safety is focused on management of potential human pathogens. Primary pathogens are monitored by indicator organisms to characterize the likelihood of pathogenic enteric bacteria and viruses – such as *Salmonella* and Norovirus (formerly "Norwalk-like virus"). Other methods are used to detect marine *Vibrio* bacteria, protozoa, biotoxins, heavy metals and contaminants. In order to prevent disease outbreaks and protect human health, a complex suite of measures is in place to control harvest and processing practices, monitor and maintain growing waters, and manage international and interstate transport and movement of shellfish and shellfish products. In shellfish growing areas of the U.S., farmers and harvesters are currently responsible for adhering to monitoring guidelines to handle and track live and fresh shellfish products. Growers may be forced out of business or find their markets restricted if their farm area is closed to harvest by a public health agency due to bacteria or other form of contamination.

Harvest Systems Technology Gaps and Measurement Issues

There is a strong incentive for developing reliable and cost-effective methods to determine the presence of harmful bacteria, viruses, heavy metals, and marine biotoxins in shellfish and growing waters prior to harvest. For example, tools to differentiate economically and quickly between safe and pathogenic *Vibrios* are presently lacking. Because of the potential negative economic impacts of *Vibrio* outbreaks and the uncertainties involved in the detection of pathogenic strains, the development/improvement of rapid and field-deployable diagnostic abilities has ranked among the highest priorities for U.S. shellfish growers for several years. Similarly, diagnostic and measurement tools have been recommended for other important bacterial pathogens, heavy metals, and biotoxins. An ideal measurement system would provide field deployment capabilities with real-time results, have a non-technical user interface, use pre-calibrated unit-use packaging, be compatible with water and tissue analysis, and have multi-analyte flexibility (e.g., HAB toxins; water contaminants, including bacteria, viruses, and pollutants).

There is need for instrumentation to reliably and continuously monitor environmental variables. Desired sensors must be stable over time, reliably measure what the operator thinks they are sensing, be robust, require recalibration only after an extended time of use, be cost effective, and usable by farmers and their employees. Similar instruments are needed for monitoring the size and concentration of particles in the water, including algae, prepared feeds, organic debris, and other particle types. Instruments and methods to monitor growth rate, shellfish movement on the bottom or in growing containers, and to monitor stress in shellfish are needed.

Other technology gaps and measurement issues include: 1) methods for the early detection of contamination allowing expansion of shellfish harvest areas and reducing shellfish harvest area monitoring costs; 2) rapid test procedure(s) to detect/monitor human pathogens in water and in the product; 3) ability to quickly differentiate pathogenic and non-pathogenic strains; 4) pathogen indicators other than fecal coliforms; 5) improvements in harvest efficiency through the use of crop mapping and incorporation of global positioning systems and geographic information systems technology; 6) environmentally friendly mechanization, material handling, predator deterrence and exclusion, 7) better assessment of allied technologies for possible technology transfer; 8) policy issues are important, especially the baseline socially acceptable farming practices; 9) better standards of human health infection thresholds; 10) the lack of approved real-time technology to measure specific pathogen or proxies to pathogens with sufficient relevant cost-effective precision and accuracy; and 11) effective measures of indexed ecosystem structure to characterize biological community structure, and net effects of farming methods.

Processing, Packaging and Transport

Shellfish are highly perishable and there are a variety of methods to maintain or improve shelf life, and reduce or minimize the loss of flavor and texture during storage. Processing of shellfish has until recently been limited to packing of a fresh product, or production of canned, smoked, or dried products. A growing number of shellfish are now treated with a variety of processing methods, primarily to add value, and improve product quality and ease of use. All of these methods fall into the general category of post-harvest processing. Post-harvest processing (PHP) methods available to shellfish producers include:

- fresh and raw processing -- Shellfish are consumed live and/or raw; temperature control and rapid transport from the shellfish growing areas to the market are necessary to maintain the highest quality. New processing technology and product handling systems for processing plants are good areas of focus. Cleaned and byssus-free fresh mussels are often sold in Europe in non-odor, non-drip plastic bags – either Modified Atmosphere Packaging or vacuum packs which greatly enhance product quality and shelf life.
- Individually Quick Frozen (IQF) -- Freezing shellfish to extend shelf life was first applied in 1989; and, presently, there are many facilities using this technique for oysters and other shellfish. The largest of the IQF facilities frequently employ cryogenic freezing to accelerate the freezing cycle.
- Heat – Cool Pasteurization (HCP) -- Initially developed in 1995 for oysters by a private firm in Louisiana, HCP involves submerging fresh unshucked oysters into warm water followed by immediate cold water immersion. This process reduces *Vibrio* and results in a raw product with a fresh taste, good shelf life, high yield, good appearance, and low processing cost.
- Irradiation -- Effective in reducing to non-detectable levels the presence of pathogenic *Vibrio* in shellfish but high doses are required for the reduction of viral loading. Reports of irradiation affecting shellfish taste, appearance, and shelf life appear to be associated with high dose levels. Advantages of irradiation may be outweighed by the limited availability and high capital cost of large-scale processing facilities, reduced efficacy for viruses, and consumer reluctance to purchase irradiated food products.
- High Hydrostatic Pressure (HHP) -- Pioneered in the prepared meat and juice industries, the application of HHP to bivalve shellfish was approved in 1999. HHP is now utilized commercially on the U.S. Gulf and West Coasts primarily to process oysters. At moderate pressures of up to 300 MPa or approximately 44,000 lb/in^2, it facilitates the oyster-shucking process and extends the shelf-life of raw shellfish due to the reduction of spoilage bacteria. Higher pressures are also effective inactivating the hepatitis A virus and possibly other pathogenic viruses. HHP has largely been used to process Eastern and Pacific oysters; however, it is equally effective for hard clams (to shuck and pasteurize the product) and non-bivalve shellfish (lobster and crab) destined for the raw market.

Processing, Packaging, and Transport Technology Gaps

Processing and packing methods can have a major effect on shellfish meat quality. For example, the typical U.S. oyster freshwater pack (Japan packs in saltwater) can result in a pH shift, product degradation, and browning of meats. Altering water packing or washing phases could have a positive effect on shelf life. Product shrinkage is also a serious problem for packers and retailers. Reducing shrinkage could provide a fresher and more uniform product. There is an immediate need to review meat-washing technologies and evaluate whether shelf life and/or quality could be extended by changes in processing and packing methods.

Application of energy monitoring and conservation to the shellfish processing can lower costs and improve efficiencies. Electrical, propane, natural gas, gasoline, and diesel fuel are all used in processing and little effort has been applied to reduce these fuel inputs by conservation, more efficient process, and recycling energy streams (e.g., heat lost in steam).

Shellfish growers have little control over commercial trucking regulations and temperature recording devices do not always tell the whole story in palletized shipping and may, in fact, give false readings. Improved packaging that holds loading temperature targets may be the most effective method for ensuring freshness and quality in the near term.

Technology gaps for processing also include the need for: 1) continuous HHP processing, 2) low-cost non-radioactive irradiation and/or high pressure processing equipment accessible to small-scale producers, 3) sustainable and environmentally acceptable packaging (recyclable containers, recyclable insulation, returnable containers), 4) improved shellfish depuration (where legal), 5) time control to maintain harvest temperatures, 6) improved process efficiencies, especially to move away from batch processing, 7) a low-cost oyster shucking machine, 8) alternative methods to ensure pathogen elimination using, preferably, PHP that does not kill the animal, 9) improved en-route temperature monitoring systems, radio frequency identification (RFID) tags, barcode tags, and external temperature labeling.

Processing, Packaging, and Transport Measurement Issues

Measurement needs for processing, packaging, and transport include:

- instruments that easily and rapidly determine freshness of processed shellfish (electronic quality “sniffers”) and are correlated with consumer preferences
- measuring quality freshness by employing a pH shift recording device within the package as an alternative to the current standard sell-by-date
- methods and instruments to monitor contaminants, including metals, bacteria, toxins etc., and evaluate nutrient concentrations in processed and/or packaged shellfish
- cooling methods/kill curves for non-lethal reduction bacterial loads in shellfish
- effective measures of growth rates/loading for different pathogen type and between processed shellfish species
- alternative monitoring guidance to reduce pathogen loads during transport
- non-contact instruments to determine and automatically sort shellfish in the shell or meats by size or quality factors.

Table 1. List of technology actions and goals for marine shellfish culture

Category	Technology	Goals
Genetics and breeding		
Integration and coordination	Adult performance	Ability to predict from young animals
Triploidy, etc.	Sterilization methods	Offer increased yield with limited wild stock effects
Germplasm preservation	Long-term germplasm storage	Allow ready access to germplasm
Heritability estimates	Genetic markers	Low cost and standardized for multiple species
Inbreeding studies	Mass rearing of multiple families	Increase breeding capacity
Molecular markers, mapping	DNA microarrays	Improve performance in multiple species
Information systems	Database development	Enhanced tools to evaluate breeding performance
Broodstock maturation systems		
Systems engineering	Broodstock maintenance	Automate holding and feeding
Reproductive performance	Reproductive parameters	Rapid non-destructive determination
Feeds and feeding	Feed requirements and interactions	Measure and predict feed performance
Health and disease prevention	Health and condition during holding	Real-time and accurate diagnostic procedures
Larval culture systems		
Systems engineering	Larval maintenance	Automate rearing and feeding
Husbandry	Culture density	Methods to optimize density, growth, survival
Feeds and feeding	Feed production and consumption	Measure and predict feed performance
Health and disease prevention	Health and condition during holding	Real-time and accurate diagnostic procedures
Nursery systems		
Systems engineering	Juvenile maintenance	Automate rearing and feeding
Husbandry	Culture density	Methods to optimize density, growth, survival
Health and disease prevention	Health and condition during holding	Real-time and accurate diagnostic procedures
Growout systems		
Systems engineering	Culture systems	Production automation and trace back tools
Information systems	Database development	Trace-back tools to evaluate performance
Husbandry	Environmental monitoring	Real-time, reliable and low cost measurement tools
Health and disease prevention	Health and condition during growout	Real-time and accurate diagnostic procedures
Harvest Systems		
Systems engineering	Harvest methods	Improved mechanization to reduce impacts
Harvest assessment	Environmental monitoring	Real-time, reliable and low cost measurement tools
Product quality and safety	Status of product at harvest	Rapid, real-time and accurate procedures
Human health standards	Human pathogen/toxics	Improved monitoring tools / different indicators
Processing, Packaging and Transport		
Systems engineering	Processing	Further automate process systems
Systems engineering	Processing and packaging	Product "sniffers" and other detection methods
Systems engineering	Packaging -- public health	Rapid/tamper-resistent, real-time measurements
Systems engineering	Transport	Improved methods to monitor quality

Shellfish Culture Sub-group Members

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A Roadmap for Commercialization of Cage Production of Marine Finfish

Technical Challenges and Measurement Barriers

Technology at Issue

Technology for production and environmental management of sea cage farming of marine finfish

Technological Innovation at Stake

In order to meet increasing demand for seafood and reduce rising trade deficits, the U.S. needs to enhance aquaculture production in land-based, nearshore and offshore sectors. Technologies and production methods for nearshore sea cage culture of a few species of finfish (e.g., salmon, trout) are well developed, however, suitable sites in protected waters are limited, and further development has been impeded by environmental concerns, disease and parasites, containment breaches, and multiple use conflicts. Technologies to improve environmental performance, create more secure containment barriers, manage fish health (diseases and parasites), reduce production costs (feed, labor) and produce new species for culture may result in expansion of nearshore cage culture. There is tremendous opportunity for expansion of cage culture in open ocean waters, however, the technology suitable for high energy ocean environments is in an early stage of development, and farms operating in exposed waters are small, production costs are high, and economic risk is not well known. Development and integration of technologies to a high level of automation for conducting routine operations is needed for offshore farming to expand. In addition, additional data on environmental effects of ocean farming at a commercial scale (e.g., 2-5,000 MT annual production) are needed in order to overcome impediments due to environmental concerns, and to inform the policy and regulatory framework for domestic offshore farming.

Economic Significance of Innovation

Restoring U.S. nearshore cage production to its 2001 peak would add approximately $80,000,000 in farm gate value to the existing sector. Additional production beyond that amount may or may not be possible due to space constraints. If technology for large scale offshore production could be achieved, (e.g., 50 U.S. farms each producing 5,000 MT) the farm gate value would be in the $1.5-2 billion by 2025, and perhaps double or triple that mount by 2050. In addition, technologies for offshore farming developed in the U.S, would be highly sought after internationally.

Technical Barriers to the Innovation

This cage culture roadmap addresses technology gaps in the production cycle from the point when juveniles are transferred from land-based facilities to sea cages in nearshore or offshore locations. While prior production stages are critical to the supply of healthy seed stock, the assumption was that those stages would be covered by the land-based finfish culture sub-group, as for the most part, these production stages take place primarily in land-based systems. The technology gaps are organized according to stages in the production cycle and by tasks/operations within each stage. As some technology gaps apply to different stages of the cycle, or for more than one purpose, they may be listed more than once. In addition, those that are cross cutting with other aquaculture sectors are tagged with a "C" and measurement technologies with an "M". A summary of technology areas, goals prioritized by the breakout group, and technology gaps for marine cage culture of finfish is provided in Table 2.

It should be emphasized that addressing each of the individual technology gaps is important, however, integration of these technologies into "intelligent" fully automated farming systems must be achieved to realize production goals.

It should also be noted that all the workshop participants agreed that government sanctioned, publicly supported programs and demonstration facilities to develop, demonstrate and evaluate offshore technologies and farming practices at commercial scale are needed to reduce private sector financial risk, and to generate economic and environmental data to stimulate private sector investment and inform a rational regulatory framework.

Fingerling Transport and Stocking

Technology for transport of juvenile fish is well developed for nearshore culture, however, since transit time to offshore cages will likely be longer, additional care must be taken to insure the fish are not overly stressed. Therefore, it is important that fish are in optimal condition (health and nutritional status) prior to transport, and that the size at transport to offshore cages is appropriate for the species and the in-cage conditions (e.g., current velocities, mesh size). Transport procedures, nursery cage and growout systems that facilitate secure and efficient transfer and stocking, minimize stress and mortality of fingerlings are needed. Appropriate standards for fingerling quality need to be established to inform growers of the level of risk to the stock during and after transport. In addition, it is often difficult to count post-transfer mortalities of juveniles, therefore, technologies to count mortalities of very small fish are needed.

Growout

Engineered Systems (labor reduction, safety, integrity of infrastructure)
On-site energy generation (e.g. wind, wave, tidal) to power farms (e.g. lights, feeders, instruments) could help control costs, in addition to reducing the risks of fossil fuels spills which can affect the profitability and sustainability of sea cage farming. Technology that can capture natural energy available at coastal and ocean sites would reduce farming costs, improve safety and insure long-term sustainability. Technologies must be properly scaled and affordable.

Self-cleaning or non-fouling containment barriers are needed. Biofouling increases weight and drag on cage and mooring systems and reduces the flow of oxygenated water through the containment volume. In addition, biofouling communities may harbor parasites and disease causing organisms that can affect fish health. Coatings commonly used to reduce biofouling contain toxic substances (e.g. copper) and it is unlikely that the use of these coatings will be allowed in the future. Current methods of biofouling removal require divers, which is both costly and dangerous. Changing nets during production cycles, another common practice, is also labor intensive, and creates increased risk of escapement. Biofouling control, either through the use of non-toxic antifouling materials or coatings, or automated (robotic) cleaning systems would improve both profitability and worker safety.

Lower cost but sufficiently robust submersible cages for open ocean/high energy sites are needed as sea conditions at exposed oceanic sites prohibit the use of surface referenced cages. Currently available submersible cages are more costly per unit volume than surface cages. Reducing costs and increasing the volume of submersible cages without sacrificing structural integrity would improve profitability of farming at open ocean sites. Performance standards for assessing the structural integrity of cages are needed.

Deep water moorings and/or cage systems are needed as offshore waters present challenges due to wind and wave conditions. There is also the challenge of mooring cages in deep water (e.g.> 100 m) where the mooring line scope typically used for multi-anchor grid systems would require a very large seafloor footprint and incur a large up-front capital cost as well as high maintenance costs. Mooring options for deep water include tension leg, single point and untethered cages, however, none of these options have been demonstrated for large scale offshore farming. Single point mooring systems and untethered cages have the added benefit of dispersing organic wastes over a larger area, thereby reducing the potential for benthic impacts.

At many deepwater and oceanic sites, a seasonal thermocline can develop, creating temperature differentials through the water column of as much as 10°C. Since temperature affects feeding, growth and metabolism of the fish, it is important to position cages at depths with optimal temperature for stock performance. In addition, the ability to raise and lower a cage at a controlled speed reduces stress on fish (temperature and pressure acclimation) and provides greater opportunity for live marketing of fish with pressure sensitive swim bladders. Therefore, precision depth controls for submersible cages would be an important advance.

Technology is needed to remotely observe the behavior (swimming, response to feed delivery) and condition (parasites, health) of stock relative to real-time environmental conditions (temperature, oxygen, current velocity).

More secure containment barriers materials are needed as currently used materials consist primarily of woven synthetic netting which is susceptible to wear and tear, can be breached by accidents (e.g. boat propellers and other equipment), predators and in some cases by the cultured fish (e.g. cod) and lead to escapement. Alternative materials must be developed to reduce the risk of escapement.

Another gap is the lack of remote barrier integrity monitoring systems. Breaches in the containment barrier, particularly small holes or tears, can go unnoticed, allowing fish to escape. Remote methods of inspection (e.g. robotics) or alternatively breach alarms are needed to alert farm managers that action to correct the breach is required.

Robotic devices to perform routine tasks would reduce labor costs and improve worker safety. Remote communication and control of these devices would also reduce the need for site visits to farms, further reducing operational costs.

Wireless broadband data communication among surface nodes and to shore could significantly improve operations. Real-time remote observation of stock (video, acoustic data) requires greater bandwidth than can be delivered by today’s affordable wireless technologies. Low cost, reliable technologies are needed to transmit large amounts of data in real-time over distances up to 20 miles.

A system for alerting growers to mortality events and enumerating mortalities would be a critical improvement for fish health management, and could reduce the risk to containment system breaches from predators/scavengers attracted by dead fish. Technology that could enumerate mortalities in real or near real-time would alert managers to any health problems and allow for prompt removal without the need for costly inspection dives.

Integrated, “intelligent” farming systems with automatic feedback /neural network programming would be am important advance for the sea cage systems of the future. Automated systems with artificial intelligence capability for decision making that can integrate observations (stock and environment) with operations (e.g. feeding, harvest, grading) would greatly reduce production costs and labor requirements.

General Husbandry

Diagnostics and treatments for diseases and parasites of new/emerging species are needed. Current knowledge of diseases and parasites to which many of the new species may be susceptible is minimal, therefore research into the diseases/parasites that affect these species in the wild, followed by rapid and reliable diagnostics and vaccines or other treatments for cultured fish are needed (C).

Precision depth control of submersible cages and remote monitoring of stock and environmental conditions would be important advances to promote general husbandry and management (see more detailed description in growout engineering section above) (M).

Breeding programs based on "native stock" that will enhance the culture performance of the selected species and the possibility to produce sterile fish or mono-sex stocks that will reduce or eliminate in-cage spawning are needed to address concerns over the effects of escapes (including those resulting from in-cage spawning) on native fish (C).

In-cage biomass measurement linked to feeding programs could greatly increase feeding efficiency. The amount of feed delivered to a cage is based on a percentage of the total biomass in the cage, therefore accurate measurement of total biomass is needed so that fish are not overfed (wasted feed) or underfed (sub optimal growth). Technologies to estimate the biomass of individual fish exist, however, technologies that can provide accurate counts of fish in a cage do not. Therefore, accurate assessments of total biomass within a cage cannot be made. Clearly, as described above, a method for alerting the manager to mortality events and enumerating dead fish could also improve general husbandry and management (M).

Feeding

Development of mobile, remotely-controlled feeders would be an important advance. Extreme weather events can pose risks of damage to centralized feeding systems moored at the surface. In addition, transferring feed and fuel from vessels to moored feeders in rough sea conditions poses risks for spills and injury to personnel. Mobile feeders that could brought to safe harbor prior to the onset of heavy weather, as well as to re-fuel and replenish feed supply would help to avert those risks.

On-site remotely operated feeding systems with even dispersion within the cage(s) and equipped with full automation and video monitoring would providing for “intelligent” feedback control and manual overrides could greatly improve feed programs reducing costs and waste. Uneven distribution of feed within a cage can lead to differential growth rates of stock. Remote control and observation of programmed feeding, would improve feeding efficiency and stock performance (M).

The high cost and finite quantity of feed ingredients like fishmeal and fish oil represent challenges to profitability as well as expansion of marine finfish culture. Alternatives, including land based plants, marine plants and invertebrates, or other ingredients that are competitive (e.g. fish processing waste), from both performance (including species–specific nutrition, physiological considerations, and waste minimization) and cost standard for carnivorous marine species are needed. In addition, feed supplements that improve health and reduce stress should be developed, as should finishing diets to improve product quality (flavor, texture, shelf-life) prior to harvest and marketing (C).

As the culture of new/emerging species is commercialized, improved feed formulations and feeding regimes must be developed that increase feed conversion and reduce waste. More research is needed on the nutritional requirements of new and emerging species and on feeding regimes (frequency, speed of delivery) will be necessary to improve performance and reduce costs and waste (feed and feces). Other considerations for feed formulations include buoyancy and low effluent formulations (C).

As described in more detail above, information from in-cage biomass measurement and monitoring and enumeration of mortalities should be linked to feeding programs to increase feed efficiency (M).

Grading

Low stress in-cage grading systems that do not require divers are needed. Unequal growth rates, often exacerbated by feeding hierarchies established within a cohort can lead to poor performance by slower growers. In-cage grading in surface cages requires SCUBA diving, is difficult, labor intensive and stressful on the fish. It is all but impossible in submerged systems.

Passive grading technologies for surface and submerged systems are needed to reduce costs and improve stock performance.

Harvesting

Development of methods for improving harvesting efficiencies would be an important advancement. Non-diving technologies for rapid harvest at sea with options for live harvest or fresh killed fish are needed. Commonly used methods for both surface and submerged cages consist of "concentrate and pump" and submerged cages require divers to concentrate the fish. In addition to the labor costs and risk to divers in the cage, this method is stressful on the fish, which in turn affects flesh quality in fish destined for the fresh killed market, and survivability of fish harvested for the live market. More efficient, passive and size selective harvest methods are needed to reduce costs and optimize product quality. Technological advances to achieve this goal could include: 1) new harvest vessel design with greater live haul capacity, 2) towable harvest cages, 3) conditioning fish to respond to environmental cues (self harvest) and 4) low stress, size selective partial cage harvesting.

Feeds and Nutrition

Feeds represent the most important component of variable costs associated with marine fish production. High inclusion rates of marine fish meals and oils have been identified as significant potential impediments to large scale expansion of marine fish culture. Improved feed ingredients including land based and marine plants, invertebrates, or other novel crude protein sources are needed. Significant obstacles to formulating reduced fishmeal diets include assuring growth performance while overcoming potential problems with anti-nutritional factors. Improved understanding of nutritional requirements could reduce over-formulation, while improving growth even as expensive marine proteins and oils inclusion rates are lowered. Additives aimed at improving digestibility and gut health as well as potential application of enzymes may also have potential to improve feed performance. All of these technologies would have to be competitive from both performance and cost standards for carnivorous marine species.

Environmental Performance

Feeds and nutrition

As described above, new feed formulations and feeding regimes based on requirements of existing or new/emerging species could increase feed conversion and reduce waste improving environmental performance (C).

Benthos and Water Column

Reducing potential environmental impacts to benthos and water quality could be achieved through the integration of several technology improvements described above. These include 1) fully automated video enabled remotely operated feed systems with manual overrides, 2) remote biomass and abundance measurement linked to feeding programs to increase feed efficiency, 3) deep water mooring/cage systems, 4) self-cleaning or non-fouling containment barriers.

Rapid, reliable, affordable and ecologically relevant indicators (e.g., chemical, visual imagery) of impact to benthic communities are needed to establish performance based-standards for environmental compliance. Current methods of assessing impact are either costly (benthic community analyses), too spatially variable to be reliable or representative of actual condition (sediment sulfide, redox), or costly and difficult to do in deep water (diver surveys). Physicochemical measurements or visual imagery that are highly correlated to the condition (biomass, diversity) of infaunal and epifaunal communities are needed.

Capabilities for assimilative capacity modeling and verification including predictive modeling and assessment (monitoring) must be improved. Considerations include: 1) ability to determine both adverse and beneficial effects (M), 2) ability to measure and predict resuspension dynamics of waste feces and feed for key species or families of fishes (M), 3) understanding and predicting the rates and drivers for respiration/decomposition of organic carbon and other oxygen demanding discharges from cages (M), 4) methods to determine fish and shellfish fecal settling rates, which is a primary factor driving initial dispersion (M), 5) determination of benthic to water column coupling for flux of aquaculture wastes (M).

Fish Health

Fish health is an important environmental consideration. A few of the potential advancements described above have direct relevance to fish health. These include 1) development of vaccines and treatments for diseases and parasites of existing and new/emerging species (C), 2) precision depth control of submersible cages 3) remote monitoring of stock and environmental conditions (M). In addition, more information is needed on potential for transfer of disease causing organisms from farmed to wild fish. This has been cited as an important potential negative environmental impact from cage culture operations, however, actual empirical evidence that farmed fish are the source of the organisms affecting wild fish is lacking. Some improved means of measuring the transport of organisms from cage sites to wild fish is needed.

Containment

Improving containment of cultured fish would improve industry sustainability. Several potential technology advances that could achieve this goal were described above including 1) lower cost, yet sufficiently robust submersible cages, 2) more secure containment barriers (new materials) 3) remote barrier integrity monitoring and 4) sensing and control of robotic devices for monitoring and cleaning of cages.

Breeding programs based on “native stocks” could allow for enhanced culture performance while eliminating potential adverse effects associated with culture of non-indigenous species. Similarly, possibilities of production of sterile fish or mono-sex stocks would reduce or eliminate in-cage spawning and/or if there are escapes, eliminate potential for mating with wild fish.

Technologies for rapid, easily identifiable, low cost and low stress methods of marking farmed fish would allow for identification of the source of potential escapees.

Application of Measurement Science to Overcoming Technical Barriers

Approaches to applying measurement science for addressing bottlenecks should include clear articulation of the problem, a review of current state of the technology, identification of opportunities for technology transfer from other industries/uses, a science-based research and development process followed by demonstration and third party evaluation of technologies. An example of how a solution to a measurement technology might be developed is presented below.

Measurement problem: The amount of feed delivered to a cage is based on a percentage of the total biomass in the cage, therefore accurate measurement of total biomass is needed so that fish are not overfed (wasted feed) or underfed (sub optimal growth). Technologies to estimate the biomass of individual fish exist, however, technologies that can provide accurate counts of fish in a cage do not. Therefore, accurate assessments of total biomass within a cage cannot be made.

Measurement need: In-cage biomass measurement linked to feeding programs to increase feeding efficiency

<u>Technology Development Approach:</u>

1. Review current status of abundance and biomass measurement technologies.

   Technology to estimate the biomass of individual fish is commercially available (e.g., Vaki Biomass Counter) as are technologies to count fish (e.g.,Vaki Bioscanner Fish Counter) provided they are channeled through a pipeline or trough. While technology like the Bioscanner can provide accurate counts during transfers, it cannot provide accurate counts of fish within a cage without pumping from one containment volume to another (which is not practical, particularly for submerged cages).

2. Identify technology gap

   In this case it is the inability to get accurate counts of fish in a cage, which when combined with data on average biomass of individual fish, total in-cage biomass can be estimated and feed can be metered out accordingly.

3. Identify technologies from other sectors that may be applied to this problem

   Potential solutions include acoustic (e.g. multibeam sonar) and optical (e.g. video) technologies

4. Conduct research on the state of the science/technology for each option and select the technology that appears to have the highest potential to solve the problem. Consideration needs to be given to costs, operational requirements (e.g. operator skill level), and

practicality of the environment in which the application will be applied.

5. Adapt existing technology or build a prototype for use in scientifically valid trials –must be done in conjunction with end users, who in this case are farm managers and operators

6. Make changes adaptations based on results of trials

7. Demonstrate effectiveness/utility and submit to third party evaluation/assessment of technology, preferably at a publicly supported facility

8. Develop final commercial version of fish counting technology and 1) create programming to link to output from individual biomass estimator and 2) create user output interface of total in-cage biomass.

9. Add value by developing programming that links biomass estimation, data from in-cage sensors and cameras to intelligent automated feeding systems.

Table 2. Technology areas, goals prioritized by the breakout group, and technology gaps for marine cage culture of finfish. The number in parentheses following each goal is the # of votes cast during the prioritization exercise.

Technology Area	Goals (# votes)	Technology Gaps
Transfer of juveniles and nursery culture		
Fingerling quality	Measures of "fitness" of juveniles prior to transfer to sea cages (9)	Inability to measure condition
Transport and submerged cage transfer	Pre-transport conditioning (nutrition) and safe efficient, low stress transport methods that are species and life stage-specific (3)	Transport difficult and stressful for offshore cages
Nursery cages	Technologies for efficient deployment and demobilization (1)	Difficult to install/remove in submerged cages
Growout: engineered systems		
Integrated "intelligent" farming systems	Capabilities for autonomous (remote observation and control) operations that achieve optimal production results, maintain optimal environment for stock, inform operators of system failure (15)	Complete, autonomous farming systems for offshore waters not available
Mobile, remotely controlled open ocean feeders	Offshore feed systems that can move to safe harbor in storms and can go to port to re-stock and refuel (11)	Technology has not been developed
In-cage biomass measurement	Technology to determine stock numbers and size (10)	Technology not available
Untethered cages	Reduce footprint, cost, and potential for benthic impacts (10)	None have been developed to date
Biofouling control/management	Reduce labor/diving, reduce seafloor deposition from cleaning (8)	Non-toxic fouling resistant materials/coatings, automated remotely controlled net cleaners not currently available
Deep ocean mooring technologies	Affordable deep water mooring technologies (7)	Technology exists (e.g. oil and gas) but is too costly
Remote monitoring of stock and environmental conditions	Observe and manage feeding (5)	Technology not available for submerged cages
On-site energy generation (wind, wave, etc)	Reduce costs and emissions, prevent fuel spills (4)	Properly scaled, affordable and accessible technologies not available
Sensing and control of robotic devices	Technologies to reduce labor/diving (3)	Technologies not developed
Single point moorings (SPMs)	Reduce cost and complexity of moorings (3)	No SPMs have been developed or demonstrated for large scale farming
More secure containment barriers	Reduce/prevent escapement (3)	Need proven and affordable materials

Table 2 (continued). Technology areas, goals prioritized by the breakout group, and technology gaps for marine cage culture of finfish. The number in parentheses following each goal is the # of votes cast during the prioritization exercise.

Technology Area	Goals (# votes)	Technology Gaps
Growout: engineered systems (continued)		
Precision depth control of submersible cages	Optimize conditions for stock, improve safety and efficiency of routine operations, options for efficient live harvest (2)	Technology not developed
Low cost and robust cages (surface and submersible)	Reduce infrastructure costs (1)	Proven submersible cages too expensive; stronger surface cages are needed
Site security	Alert operators to natural and unnatural events (1)	No off the shelf technology available
Growout: feeds and feeding		
Feed formulation	High conversion, low effluent feeds, optimize buoyancy/sinking rates (14)	Needs further development
Fishmeal and fish oil replacements	Nutritious and digestible alternatives to reduce costs and improve long-term sustainability (12)	Fishmeal and fish oil replacements for carnivorous marine species in development
Use of fish processing waste	Efficient and safe use of processing waste for feeds (5)	Processing, formulation and transport systems need to be developed
Finishing diets	Diets to improve flavor and texture prior to harvest	Needs development (4)
Feed delivery	Even distribution of feed in submerged cages (4)	Current methods exacerbate feeding hierarchies
Feed supplements	Improve health, increase growth (4)	Not currently available for most species
Growout: General Husbandry		
Vaccines	Improve fish health, reduce use of antibiotics (5)	Not available for most pathogens
Predator control	Reduce predation on stock (5)	Materials, site selection to avoid/reduce predator interactions, removal of mortalities (4)
Selective breeding/sterilization	Improve growth rates, disease resistance/reduce potential for impacts from escapees (3)	Breeding programs/ broodstock lines and techniques for producing sterile offspring not developed for most species
Diagnostics and treatment	Improved fish health (3)	Diseases/parasites for many marine fish are not known, therefore, no diagnostics or treatments exist

Table 2 (continued). Technology areas, goals prioritized by the breakout group, and technology gaps for marine cage culture of finfish. The number in parentheses following each goal is the # of votes cast during the prioritization exercise.

Technology Area	Goals (# votes)	Technology Gaps
Harvesting		
Low-stress, partial cage harvesting	Improve efficiency and reduce stress on fish (4)	Methods not developed
Offshore harvest/service vessels	Ocean going vessels that can harvest/service cages in rough sea conditions (3)	Technology has not been developed
Self harvesting fish	Develop environmental cues (e.g. acoustic, visual) to direct fish into harvest tunnels/cages (1)	Methods not developed
Environmental Performance		
Environmental monitoring performance metrics	Rapid and reliable monitoring methods and performance-based standards (14)	No uniformity in standards, measured parameters or methods
Assimilative capacity modeling and verification	Match production volume to assimilative capacity (11)	Assimilative capacity and adverse or beneficial effects not well known
Disease transfer	Determine extent/severity of disease transfer from farmed to wild fish (6)	Extent/severity of the problem not well documented
Feeding	Real-time ability to control feeding in offshore cages (prevent over and under feeding) (3)	Off the shelf technology does not exist
Escapes	More robust containment barriers (2)	Materials in current use vulnerable to damage
Offshore site assessments	Standard methods for characterizing sites in the EEZ (1)	Methods do not exist

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Sub Group Members

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A Roadmap for Commercialization of Land-Based Production of Marine Finfish

Technical Challenges and Measurement Barriers

Technology at Issue

Land-based closed system production of marine finfish in recirculation systems.

Technological Innovation at Stake

Anthropogenic activities such as intensive fishing, environmental pollution and marine and coastal habitat degradation, together with emerging environmental changes associated with global climate issues, have been adversely linked to dramatic declines in marine biodiversity. Human-driven erosion of marine biodiversity has recently been projected to lead to the collapse of all currently fished taxa by 2048. Reversing this trend, restoring marine biodiversity, and meeting the ever-increasing global demand for seafood consumption will require the integration of fisheries management, pollution reduction, habitat restoration and, to a large extent, development of environmentally sustainable marine aquaculture.

Responding to the continuous decline in fishery harvests and in an effort to meet seafood consumption, aquaculture has become the world's fastest growing sector of food production, increasing nearly 60-fold during the last five decades. Currently, however, farmed marine species account for only 36% (3.2% for finfish) of the global shellfish and finfish aquaculture production and provide only 11.5% (1.1% for finfish) of all seafood products, inclusive of fisheries and aquaculture. It is clear that in order to ease fishing pressures on marine stocks, the production of marine species (especially finfish) through aquaculture must be accelerated.

Two primary obstacles impede the ecologically sustainable growth of marine aquaculture: its interaction with the environment, and the use of fish proteins and oils as aquafeed components. The future expansion of marine fish production through aquaculture will largely depend on our ability to reduce its potential risk and impact on the environment and the development of alternative animal protein sources. In the US, as well as globally, there are two emerging avenues to address the environmental concerns and to increase the competitiveness and environmental compatibility of marine aquaculture: off-shore open ocean cage culture, and land-based, recirculating mariculture. This document addresses the latter approach.

There are several benefits to land-based mariculture systems. They have minimal or no interaction with the environment and can be engineered to generate near-zero waste discharge to the environment. They can be fully bio-secure and pose little or no risk of farmed fish escaping to the wild. They can thus be used to grow native or non-native species, and potentially high performance genetically modified fish. Moreover, when land-based operations use artificial seawater, they can produce disease- and contaminant-free finfish. The environmental conditions in the systems can be fully tailored to meet the physiological requirements of the species of interest and lead to optimal performances and fastest growth to market size. They are thus generic and can accommodate any species of fish, as dictated by its economic value. They can be located anywhere, in rural or urban locations or in the immediate proximity of the market, thereby reducing the carbon footprint of the operation.

With its ample aquaculture, biotechnological and engineering expertise and resources, the US is well positioned to become a global leader in developing economically feasible and environmentally responsible land-based, recirculating finfish mariculture. Such technology can not only stand alone, but is also a necessary component to supply seed for cage culture's growing production, thereby making the mariculture industry highly competitive and an engine of economic development in this country.

Economic significance of the innovation

As noted above, aquaculture has been steadily growing and has, in fact, been the fastest growing sector in the US and world agricultural industries. During the last 10 years, global aquaculture (food fish and aquatic plants) production has expanded with extraordinary growth, reaching a total production in 2004 of 59.4 million tonnes and a value of $70.3 billion (FAO-SOFIA, 2007). Despite the industry's overall growth, the culture of freshwater species still comprises about three-fifths of global aquaculture production. The farming of marine species must be accelerated to meet the challenge of providing seafood to the growing world population, especially in the face of dwindling marine landings. The development of land-based recirculating aquaculture systems that are capable of high density production and economically viable annual output will significantly increase market supply and geographic distribution of marine finfish products.

The benefit of marine fish production through recirculating systems is that it provides year-round production in high density growout tanks with minimum environmental impact, water losses, and maximum use of land and space. Additionally, all environmental parameters are fully tailored to meet the requirements of the species of interest to guarantee optimal performance.

Not surprisingly, production costs are always the determining factor for the economic viability of an aquaculture operation. A significant expenditure is shipping cost to final destination markets, which are largely metropolitan areas. Land-based RAS systems provide unique site selection flexibility, compared to cage/offshore operations, and can offer potential advantages for distribution, market access and value-added products (e.g., freshness factor, live products, etc). The RAS alternative, though a technically and financially challenging endeavor, has great potential for secure and sustainable fish production. Moreover, RAS has been already demonstrated with several marine fish, including cod, halibut, flounder, seabream, and barramundi among others.

The adoption of land-based recirculating aquaculture systems (RAS) as a primary fish production method on a global scale is going to require demonstration of a return on investment (ROI) at a level similar to other investments with similar risk profiles. The two major sources of risk for RAS investment are production risk related to the uncertainty about system performance at full scale operation and market risk related to uncertainty about the price performance of the target species at increasing market quantities. Most aquaculture products have seen major price declines accompanying significant expansion of production (e.g., U.S. catfish industry, tilapia, Atlantic salmon and shrimp). The ability to produce a variety of species in RAS should provide some reduction of market risk. Production risk can be decreased by ensuring the system is performing at its economic optimum. Technical advances and commercial-scale pilot projects will allow potential investors to examine production costs under a range of production performance parameters and to determine the optimum operating procedures for production. It will also allow technology developers/licensors to convey the expected risk in return on investment.

Cross-cutting Non-technical Barriers to Innovation

The development of technical advantages or solutions to current limitations of marine RAS will require the combined effort of the research community (universities, state and federal research labs, etc) and the private sector (see the summary of workshop technical recommendations in Tables 3-9). It will also require concerted efforts and advancements in areas related to the economics, marketing and regulation of RAS operations. Areas of concern/focus have been identified and loosely prioritized (see Table 10 - Economics & Marketing and Table 11 – Regulations at the end of document).

Technical Barriers to Innovation

The development of more economically feasible recirculating, land-based marine finfish production systems will require addressing and overcoming many gaps in technology and performance quantification for all components of the system. Increasing the degree of containment and, as a result, environmental compatibility and bio-security, brings about bigger engineering and biological challenges and barriers.

The roadmap first addresses gaps specific to production systems (e.g., broodstock, hatchery), followed by barriers that are relevant to all components of land-based operations (e.g. microbial processes, system engineering, health management). Finally, non-system gaps are addressed, such as system economy, regulatory aspects, and others. A specific example is also given of how developing measurement technologies can help advance land-based marine aquaculture. Summary tables of ranked priorities listing the workshop technical findings/consensus and goals of future efforts and potential deliverables are provided at the end of this document. The order of tables reflects the importance of topics as prioritized by the workshop breakout group. However, for the sake of subtopic continuity, the discussion areas within the text have been rearranged. Also included is a detailed list of measurement and technological gaps in the different categories that was developed by all members of the subgroup (attached as Appendix I).

Seed Production

Juveniles for either cage or recirculating mariculture operations must be produced on-land. With the expansion of marine aquaculture in the US and the promotion of offshore aquaculture, seed production has become a major bottleneck to the growth of the industry, second only to regulatory constraints. Increasing the production volume, as well as diversifying into additional species, requires a concerted research effort. Species to be farmed in the US must be clearly identified and prioritized. Affordable, unlimited numbers of juveniles for stocking into growout systems must be available on demand and year-round for priority species. They must be top quality and disease-free. Size-specific temperature tolerances must be well understood for stocking fish into ocean systems out-of-season. Genetic selection programs, aided by advanced molecular tools, will provide the best performing fish to be used as broodstock. Transgenic technologies should be researched towards developing optimally “tailored” fish for multiple traits, to be farmed in fully bio-secure, land-based operations. New approaches to producing sterile fish should be explored to reduce the risk of farmed fish breeding with wild stocks, as well as to enhance performance.

Although much progress has been made during the last decade in developing seed production technologies, several technological and measurement gaps still exist, which will be addressed separately for the three components of juvenile production: broodstock, larval rearing and nursery.

Broodstock Management and Spawning: Broodstock fish must be managed to promote spawning on demand all year round. While this has been achieved for a number of fish species, several recent candidates for marine aquaculture in the US either do not spawn at all in captivity, reproduce very sporadically, or only spawn seasonally. In others, sperm production is impaired. Land-based broodstock operations must be contained and maintain full control over all environmental parameters, to provide optimal conditions for gametogenesis and spawning and to enable phase-shifted, year-round spawning. Ovulation and spawning must be induced at will either using environmental conditions or hormone therapies. FDA-approved spawning agents and auxillary programs (such as seed banks and selective breeding programs) must be established for industry-wide use. Hormonal and molecular indicators of reproductive and gonadal development in male and female broodstock must be developed and studied. Endocrine and genomic-based technologies need to be used to measure and assess reproductive success, maturational competence and the need for - or response to - hormonal spawning induction. Biotic and abiotic parameters contributing to gamete and egg quality must be understood and measured, and indicators and standards established, to provide best quality embryos and juveniles. Other long-term obstacles, such as poor control of maturation, lack of gamete cryopreservation technology, unreliable sex control, and unpredictable sterilization methods must also be solved. See Table 4 for additional details.

Hatchery and Larval Rearing: Mass-producing early life stages of marine finfish is a complex undertaking, as the larvae in most marine species are small in size and require live feed and a food chain for the first few weeks of their life. Moreover, several finfish (e.g., flat fish) undergo distinct metamorphosis during larval development, which requires special care. Consequently, mortality during larval rearing in marine fish is relatively high. Increasing survival rates is the main challenge in larval rearing that requires overcoming technological and measurement gaps.

In addition to survival, rates of deformity can be high in some species, which may negatively affect fish performance and marketability downstream. Standardized species-specific quality standards, as well as measurement technologies must be established for current and emerging aquaculture species. The production of live feed, including microalgae, rotifers, copepods and *Artemia*, should be optimized and standardized based on a better understanding of their biology. Detailed knowledge of early developmental processes, at the molecular, cellular and physiological levels should lead to better larval rearing protocols and increased survival rates. Biotechnological approaches should be evaluated for increased efficiency and decreased cost of producing live feeds (such as heterotrophic fermentation of microalgae), using live feed to deliver beneficial compounds (such as nutrients, enhancers of immune response and growth, therapeutics, etc.). Artificial diets to replace live feeds, based on an enhanced and species-specific understanding of digestion physiology, should also be investigated. The role of microbial communities and probiotic processes in larval growth and survival should be better understood. Measurement technologies (molecular, physiological, chemical and physical) are needed to assess live feed production efficiency, larval health, quality and developmental success, as well as to optimize feeding protocols and environmental conditions.

Automation of husbandry protocols (in-tank counting and grading methods, larval tank cleaning, stress-free harvesting, etc) should be advanced. Optimal culture environments should also be identified by species (e.g., species-specific light requirements, larval stressors, probiotic and microbial support, etc) for mariculture operations. See Table 3 for additional details.

Nursery: Post-larvae are grown in intermediate tank systems to a size at which they can be safely moved to growout tanks or cages. Many of the technological and measurement gaps in the nursery phase are similar to those addressed in the Growout Production section below. Technological issues specific to the nursery stage include better understanding of optimal rearing conditions for maximal growth, weaning of fish from live feed to artificial diets and the occurrence of cannibalism. An enhanced species-specific understanding of developmental physiology and maternal immunity transfer would also be beneficial. Increasing weaning success and reducing cannibalism in intensive systems must be based on a species-specific understanding of the digestive system and of feeding and aggression behaviors. Growth, overall performance and handling/husbandry issues are addressed in the following sections. See Table 3 for additional details.

Growout Production

Because of the ability to fully control all environmental parameters in the tanks (salinity, temperature, photoperiod), fully contained, recirculating systems have the potential to produce fish at optimal performance. Understanding the physiology and molecular basis of metabolism and growth, and the effect of environmental culture parameters on those processes, is essential to producing healthy fish with the fastest growth rate to market size. This understanding is also required to develop genomic, proteomic and metabolomic tools to measure, assess and predict the physiological robustness of processes underlying performance, with the goal of optimizing them. Biotechnological approaches should be evaluated for improving fish growth and overall performance, including growth enhancers and transgenic approaches. Measuring stress indicators is required to assess and optimize the well-being of the fish under different culture conditions, as well as to develop methods for stress-reduction when handling the fish. Efficient and harmless husbandry strategies for grading, moving and harvesting the fish should be researched and established. Reliable and cost-effective systems that incorporate automation for critical culture steps are needed. Automatic, real-time and on-line technologies should become available for constantly monitoring water chemistry and quality parameters. Automation of operations, thereby minimizing handling from larval to growout stages, is imperative. In addition, automated methods for removal and disposal of mortalities are needed. See Table 6 for additional details.

Microbial Process and Communities

The most essential component of recirculating, land-based marine systems is the microbial activity occurring in the system. The microbial communities/processes are responsible for removing dissolved and solid waste and enable water re-use and full containment. In short, the health of the microbial consortia is as intimately tied to production success as it is the health of the fish. Numerous technological and measurement gaps remain to be addressed in this area, which to date has been understudied and poorly applied in marine systems. Designing the specifications and limits of biofilters and solids separation equipment is not currently done based on strong science. Biofiltration in marine recirculating systems is a “black box” that needs to be fully characterized, understood and improved. Microbial communities/processes occurring in marine systems are unique and significantly different than those found in freshwater systems. Aerobic, anaerobic, autotrophic and heterotrophic bacteria responsible for nitrogen, phosphorous, sulfite, carbon dioxide CO_2 and sludge removal should be characterized, measured and optimized. In addition, bacteriophages that can aid in controlling water quality and disease should be identified and studied in more detail. Tools of functional and meta-genomics, proteomics and metabolomics must be utilized to characterize and measure microbial species, consortia and processes. Automatic, real-time, one-line methods must be developed to measure microbial species abundance and activity, as well as water quality parameters. The interaction between microbiota of the cultured fish, the water, and the biofilters has to be measured and understood, with a view toward attaining stable microbial systems and optimal bacterial-fish performances. The inclusion of prebiotic and probiotic approaches, both to enhance fish health and growth as well as to feed bacteria, should be used more frequently. However, identification of probiotic species and species-specific mechanisms of effects must be more intensively studied. In addition to biotic parameters, the effect of abiotic parameters (such as temperature and water salinity, as well as the type of feed and the source of water) on the microbiology of the system, must be analyzed and assessed. This will enable the optimization of cold and warm water systems, as well as a range of salinities. Microbially-mediated conversion (on a large scale) of waste products to energy is a critical component that will hasten the establishment of more environmentally and economically competitive systems. However, thus far, these conversion processes are poorly understood or unquantified.

The development of ‘green technology’ in recirculating mariculture also extends beyond seafood production. Improved economics and reduced cost of waste disposal and/or treatment can be gained through optimized water retrieval from microalgae systems, the use of algal cultures for methane and biodiesel production, and the identification of species and co-products for integrated marine systems. These areas warrant further study and technology development in the near future. See Table 5 for additional details.

System Engineering

Another very important gap to be addressed is the efficient and cost effective engineering of the recirculating systems. Seed production operations will require technologies to maintain high quality water even under closed or semi-closed conditions. However, seed production operations are relatively small compared to the volume and flow requirements that must be met during food-fish growout (which, to be economically feasible, must accommodate densities of over 100 kg/m^3). The technical and financial success of the land-based approach is impacted by multiple issues. Engineering will be required to overcome issues of scale for the culture tanks, the life support systems, and system hydrodynamics. In addition, due to the corrosive nature of saltwater, the type of materials and building designs are all barriers that will impact the success and the economy of the land-based approach. Mechanical and biological filtration systems have to be space and cost effective, and long-lived, while striving for full waste removal and zero discharge to the environment. One of the biggest impediments to the commercial development of land-based systems is their energy efficiency (or lack of). Systems must not only be engineered to use as little energy as possible, but must also possess improved denitrification and the value-added ability to collect their waste products to generate bio-energy to off-set a portion of the energy cost. Systems must be also engineered to provide full bio-security, including the prevention of farmed fish escaping to the wild, and the transmission of diseases between cultured and wild fish and vice versa.

Measurement technologies must be developed to analyze and assess the durability, efficiency, cost effectiveness and environmental compatibility of the systems. Automatic, on-line measurement methods and instrumentation must be engineered for water chemistry and quality, as well as for indicators of system and fish performance. Standard methods and language for describing and evaluating system performances and life phase-specific production systems, optimized for either broodstock, hatchery or growout, must be developed and implemented. To this end, defining and measuring ‘full recirculation’ for marine systems and the implementation of novel waste removal/utilization technologies will be important. See Table 7 for additional details.

Feeds and Nutrition

Feeds often represent over 50% of the variable costs of production and it is vital to minimize these costs to make production economically viable. Sustainability, nutrient retention/discharge and fecal integrity are also all critical considerations in the development of efficient land-based aquaculture systems. Fish meal has been the primary protein ingredient in aquaculture feeds for decades. Not only can the use of fish meal introduce contaminants, but the practice is no longer considered to be sustainable, and the supply is severely limited with no more expansion possible. Alternate protein sources need to be developed from plants, algae, seafood processing wastes or co-products from industrial uses such as bio-diesel or ethanol production. Any source that economically provides available nutrients with a minimum of anti-nutritional factors (ANFs) should be considered. Moreover, ANFs and anti-metabolites in current sources should be identified and removed. These materials, which act against the digestion process, are prominent in plant proteins and other feed component sources. Likewise, currently unidentified positive nutrients in fish meal that are not found in alternate ingredients should be identified, preferably species-specific. Recent research with salmonids has demonstrated that total replacement of fish meal is feasible, yet specific requirements of marine carnivores need to be addressed (e.g., taurine).

Aquaculture feeds are sometimes over-formulated, resulting in excessive nutrient discharge that requires over-sized biofilters. In order to reduce initial and operational costs, diets need to be formulated to have minimal nutrient discharge or maximal nutrient retention. Identifying feed attractants and improving palatability will undoubtedly aid in this effort, as will improved feed and pellet characteristics, better measurement protocols and ‘smart’ delivery systems. In addition, in order for recirculation systems to efficiently remove fecal wastes, the fecal pellet should ideally be dense and durable. Some formulations result in loose feces that degrade water quality and reduce the efficiency of particulate removal equipment.

Fish oil has been used as an energy source in aquaculture feeds, and like fish meal, supplies are limited and can be a direct source of environmental contaminants (i.e., polychlorinated biphenyls, heavy metals, phosphates). To this end, fish meal and oil production via aquaculture may become safer and more sustainable source. Fish oil does contribute significantly to the heart-healthy characteristics of farmed fish. As dietary fish oil is replaced, the final product quality must be maintained through the development of finishing diets essential to restore the heart-healthy characteristics of the fillets. Finishing diets are just part of a life stage, or phase-feeding approach, which is essential to efficient production. Diets for broodstock maturation, larval production (weaning from live feeds in some cases), juvenile and growout production will all be important. Each phase of production will have different goals with regard to formulations. Feed cost is the most important consideration for growout diets, whereas survival is more important for larval and weaning diets. Scientific and technological advancements will lead to the development of tailored, environmentally friendly and cost effective diets, as well as better life stage and species-specific diets. The identification of immunostimulants and the formulation of science-based ‘prophylactic diets’ that help prevent diseases will also enable higher productivity and enhanced cost-effectiveness. The identification and characterization of genes regulating metabolic processes will greatly aid our understanding of fish food conversion efficiency, as well as the ultimate fate of feed. Measurement technologies, to include biochemical, physiological and molecular assays (e.g., gene chips for evaluating product quality and diet performance), are needed to assess and monitor the diet efficiency, performance and compatibility with the recirculating system. See Table 8 for additional details.

Health Management and Disease Prevention

One of the major risks in fully contained, land-based operations is the introduction of pathogens leading to the rapid spread of disease. Technological gaps range from the need to establish rigorous protocols to avoid pathogen introduction and overcome outbreaks, to the development of antibiotic alternatives (drug-free production), better diagnostics, and prophylactic tools. Better-designed facilities and health management protocols (BMPs) are also key components to reducing aquaculture mortalities. Measurement gaps include the efficient detection and quantification of pathogens and the characterization/assessment of fish stress and disease parameters. Molecular technologies and gene chips should be developed and tested for rapid and sensitive early diagnostics and for measuring viral, bacterial or eukaryotic disease agents. Effective vaccines/multi-vaccines and more efficient delivery methods must be developed for major pathogens, based on live or attenuated microbes or on DNA/RNA approaches. New antibiotics that will specifically eliminate the pathogens but not affect the beneficial microbes responsible for waste removal need to be evaluated. Immunological, biochemical and molecular tools will be used to assess the efficiency of the vaccines and/or antibiotics, and the health status of the cultured fish. Additional and improved anesthetics would also be useful to the field. A more complete understanding of environmental impacts on the fish immune system is essential. Species-specific genes related to fish health must be identified and utilized for screening protocols (e.g., broodstock health screening) and health management regimes. The use of probiotic, immunostimulant and immunomodulant approaches in recirculating mariculture systems are all promising to some degree, but optimized and predictable responses and clear mechanisms of action must be established. Further investigations into technological and measurement approaches will certainly enhance health performance, real-time evaluation and assessment of fish welfare in marine production systems. See Table 9 for additional details.

Economics

In order for land-based growout systems to become a competitive and robust contributor to future US marine aquaculture, they must be economically feasible, produce fish at a cost that can compete in an increasingly global seafood market, and allow for reasonable profits. The increase in control of the production system and reduction of environmental impacts resulting from recirculating aquaculture come at a cost compared with alternative production systems. These increased costs are attendant in both the initial capital investment and recurring operating costs. To make recircultating aquaculture competitive with other production technologies, it is imperative that the systems be optimized from an economic perspective, to keep production costs at a minimum. To this end, modeling and business planning for large-scale recirculating marine aquaculture ventures must become more widely available. The lack of demonstration projects at a meaningful scale has hampered the collection of commercial-scale operations data, including economies of scale and cost functions, as well as the assessment of economic feasibility and the identification of bottlenecks (see Table 10). Appropriately-scaled RAS demonstration projects would also allow for meaningful comparisons to cage production, projections of market demand, and development of market plans (including market dynamics, consumer perception analyses, value-added brand effectiveness, pricing structure, specialty markets, new species R&D, etc). See also the Quality Control, Product Branding and Public Relations section and the Short Term Deliverables section of this text, as well as Tables 10 and 12, for additional details on RAS economics, marketing, demonstration projects and related topics.

The relative differential in costs between recirculating aquaculture and other production technologies may differ when comparing direct costs of production versus the "full" costs as measured by Life Cycle Assessment research. This is because commercial fishing and various aquaculture technologies can have very different external costs that should be included in the cost calculations. It is essential that the full costs of seafood production (i.e., the direct and indirect or external costs) be used in comparing these technologies. The quantification of the societal costs of seafood production can lead to improved government policies concerning aquaculture.

There are some areas in which recirculating aquaculture has a distinct comparative advantage over other production technologies. For example, they have the added value of potentially improved biosecurity for producing non-native or genetically modified fish. A comprehensive evaluation of species for use in recirculating aquaculture will enable the industry to capitalize on this advantage. Another advantage may relate to the health and safety of seafood raised in recirculating systems. A better understanding of the demand for seafood, particularly related to consumer perceptions, will contribute to the expansion of the industry. As noted above, the need to analyze market demand and perception, conduct product testing and measure value-added product benefits could potentially be addressed via multi-stakeholder demonstration projects. External costs of production and the real cost of reducing environmental impacts could also be better quantified. See Tables 10 and 12 and the Short Term Deliverables section of this text for additional details.

Quality Control, Product Branding and Public Relations

Seafood and aquaculture products are praised by health care professionals, and thought of by the consumer as products that support a healthy lifestyle. It is essential for farmed products to support that concept by being free of contaminants and high in the nutrients that provide the healthful benefits (and value-added differentiation for marketing; see also Table 10). The primary source of contaminants is from poor quality feed ingredients, which in the past has been fish oil and fish meal. Development of alternative feeds (see also Feed and Nutrition section of text, as well as Table 8) will decrease the possibility of bio-concentration and accumulation of these pollutants in the final product. However, it will be vital to develop a monitoring system to prevent the sale of product that may be considered "contaminated". While fish oil often carries the pollutants, it is also the source of the healthy omega-3 fatty acids that give seafood a good reputation for supporting heart health. Development of diets and feeding practices to minimize contaminants and optimize the fatty acid profile of the final product is essential.

The flavor and texture of the final product is affected by diet, feeding practices and water quality. Bacteria and algae have been known to affect flavor of aquaculture products. Even if the product has the correct fatty acid content and contains no pollutants, an unacceptable flavor and texture will render the product to have very little value. Systems need to be developed to optimize these characteristics and to monitor them during production. See Table 10 for additional details.

Regulatory Issues

Regulatory issues have increasingly become a major challenge and roadblock to developing aquaculture operations. A brief synopsis of issues (not ranked or prioritized) has been included in Table 11 and in the detailed list of technological and measurement gaps included at the end of this text (Appendix I).

Aquaculture practices that interact with the environment, such as flow-through ponds or floating cages require multiple permits, at both the federal and state government levels. There is a pressing need for policymakers to provide clear guidelines regarding the regulations that must be met by industry, as well as to facilitate the regulatory process and enable a "one-stop-shop" for aquaculture permits. In the case of land-based operations, it is important to carefully analyze and assess threats to the environment and evaluate regulatory solutions. Near-zero discharge land-based systems should be able to quickly meet regulatory requirements related to environmental pollution, although they may still require nominal sewage discharge permits. In recent years, land-based marine operations (such as marine fish hatcheries) have increasingly begun to operate with a higher percentage of water recirculation – i.e., becoming more contained. The reasons for this can be summarized as follows:

- Coastal seawater sources are often contaminated from other natural and human inputs. Operators using less makeup water can cost-effectively filter and sterilize it and thereby make it more suitable for culturing fish, especially early life stages of marine organisms, which are highly sensitive to pollutants and pathogens.

- Discharge regulations are becoming more and more stringent – especially in regard to nutrient inputs. As a point source discharge, mariculture outfalls are easy "targets" compared to more generalized watershed runoff in coastal areas. Less water coming in means less water going out, which facilitates treatment of discharge.
- Coastal properties, as well as the associated aesthetics are very highly valued. Near-zero discharge land-based facilities could be operated in more remote, inexpensive areas.
- The farming of non-native or transgenic species will require that facilities are fully bio-secure, which will necessitate a high level of "control" over facility operation and the discharge characteristics to prevent escapement.

Short-Term Goals

Since recirculating and contained marine aquaculture operations are still largely experimental and not widely implemented in the industry, addressing technological and measurement gaps should lead to a few deliverables within the next five years. First, candidate species for land-based systems should be identified, including cold and warm water species. Candidate species should be prioritized based on their economic value, their market, the availability of seed production technologies and their amenability to tank systems (Table 12). For several representative species, demonstration land-based operations should be established, capable of producing up to 20 MT of fish annually. Several of these demonstration farms should be strategically located regionally and paired with offshore demonstration farms to provide a source of seedstock. The land-based demonstration should consist of all production components, to include broodstock, hatchery, nursery and growout systems. Based on those demonstration systems, a business plan can be improved and ground-truthed for larger-scale production of the relevant species. Demonstration projects will need to be conducted under the partnership of multiple stakeholders, including federal, state, academic, private, and environmental entities. Funding sources for large-scale demonstration projects will need to be identified and secured. The business plan should include conceptual engineering designs of the operation under consideration. See Table 12 for additional details.

Application of Measurement Science in Overcoming Technical Barriers

Land-based marine aquaculture must rely on re-using the seawater, either obtained from the natural environment (if the operation is located in proximity to the coast) or artificial saltwater. The degree of water re-use will determine the level of containment of the systems, and as such its environmental compatibility and bio-security. Recycling the seawater relies on microbial communities and processes that consume fish waste and in doing so remove it from the system and allow for the water to be re-used. As the percent of recycled water increases, the system accumulates more toxic compounds and must include an increased complexity of microbial species to efficiently eliminate them. Inoculating and maintaining the microbial consortia that will enable efficient waste removal through "biofiltration" of the culture water is a major technological challenge in marine land-based operations. A variety of biofiltration systems have been described in the literature and used in the industry. Measurement sciences and technologies are badly needed to open the biofiltration "black box" and to fully characterize, understand and improve the bacteria and processes involved in waste removal. Microbial communities/processes occurring in marine systems are unique and include aerobic, anaerobic, autotrophic and heterotrophic bacteria responsible for nitrogen, phosphorous, sulfate, sulfite, CO_2 and sludge removal.

Correlations between different biofiltration techniques (trickling filter, fluidized-bed, moving-bed and more) their microbial community structure, and their efficiency in aerobic/anaerobic microbial nitrogen removal processes, must be made and measured in real time. Such information will allow us to best fit the biofiltration technology to system requirements. Moreover, definitions of “good” or “bad” microbial communities in aquaculture biofilters have to be put into a coherent evaluation index that represents their competence to support adequate water quality. For example the ratio between autotrophic and heterotrophic bacteria in aerobic nitrifying biofilters can be correlated to ammonia oxidation rate and put into an “efficiency index” for each of the different biofiltration techniques. Anaerobic nitrogen removal processes such as anammox and denitrification need to be measured, evaluated and put into process numbers and values that can be used for systems engineering and initial design. Moreover, best biofiltration configurations for applying these processes must be determined and evaluated in pilot and up-scale recirculating Aquaculture Systems (RAS).

Assessing the microbial communities and activities of marine RAS will require multiple traditional and molecular methods. Community analysis, identification of the bacterial species and measuring abundance can be carried out by traditional culturing methods and by 16S rDNA gene analysis using a denaturing gradient gel electrophoresis (DGGE) method. Phylogenetic assignments of the microbial community can be also performed by a terminal restriction fragment length polymorphism (T-RFLP) method that is based on terminal restriction fragment lengths obtained from the digestion of communal microbial DNA with a series of restriction enzymes. Correlating the microbial community to activity will require the use of functional and meta-genomics tools, as well as proteomics and metabolomics methods that must be developed to measure microbial activities and relevant processes in real time. Gene chip and micro-array technology must be specifically designed to evaluate expression of functional genes that are relevant to waste removal processes (i.e., ammonia-oxidizing genes, nitrate and nitrite reduction genes, etc). Moreover, such gene chips can be loaded with genes that are relevant for the detection of pathogenic bacteria, thus improving possibilities for early detection and disease prevention. Understanding and measuring the microbial species and activities involved in marine waste removal, and their correlation to biotic and abiotic parameters (e.g., fish species, feed type, salinity, source of water, temperature) will enable us to engineer and tailor optimal biofltration systems and, thus, allow for efficient and cost effective water-reuse to enable land-based operations.

Establishing and understanding the mutual relations between water quality parameters, fish growth and the biofilter microbial community/activity will require on-line measurement of many water quality parameters. Some measurement techniques need to be developed and adapted to marine systems. For example, on-line monitoring system for nitrate, nitrite and ammonia, as well as water alkalinity and turbidity, are not readily available. These parameters have to be monitored in real time and correlated to the microbial community/activity of the different biofiltration configurations.

Finally, in order to increase the environmental sustainability and economic feasibility of land-based marine aquaculture systems, an efficient microbially-mediated technology must be developed to eliminate marine sludge, preferably producing fuel-grade bio-gas in the process. Again, using the microbiological and molecular techniques listed above, marine bacterial and archeal organisms that are known to convert sludge to methane must be studied, characterized, inoculated and augmented in the sludge removal component of the marine recirculating systems. This will lead to the engineering of an optimal bio-reactor that efficiently digests and eliminates the solid waste produced by the fish, while off-setting the cost associated with the system's energy needs.

Table 3. Ranked priorities for larval rearing and nursery technologies			
Priority	**Technology Area**	**Goals**	**Technology Gaps**
#1	Measurements of performance and quality	Standardized species-specific quality standards	• Understanding species-specific light requirements
#2	Tailored and inert feed formulations	Artificial microdiets to replace live feeds	• Understanding digestion physiology • Methods to prevent nutrient leaching while allowing time for consumption and digestion • Better floatation/buoyancy control of microdiets • Maximize chemoattractants • Weaning protocols
#3	Food chain production	High density, optimal quality production of algae, rotifer, *Artemia*, copepods, etc.	• Reliable stable automated systems for food chain organisms
#4	Automation of husbandry		• In-tank counting and grading methods • Larval tank cleaning • Stress-free harvesting of larvae
--	ID of optimal environments for larval culture	ID by species; Stress tests	• Too few • Larval tank cleaning • Understanding species- specific light requirements
--	Counting and grading methods	Automated counting and grading systems	• In-tank passive grading and counting systems
--	Probiotic support	Optimize microbial communities and ecology	
--	Understanding developmental physiology		
--	Transfer of maternal immunity		

Table 4. Ranked priorities for broodstock and spawning technologies

Priority	Technology Area	Goals	Technology Gaps
#1	Year-round, consistent and induced spawning	Develop protocols for and techniques for on-demand seed production	• Understanding broodstock nutrition • Understanding natural cues and pheromones • FDA approval of spawning agents • Seed bank (embryos) • Broodstock security
#2	Assessing and controlling gamete quality	Optimal quality and supply of gametes; Maternal delivery of therapeutants	• Standards and indicators and for assessing gamete quality • Lack of quality gametes
#3	Selective breeding	Improved broodstock program by species	
#4	Endocrine and molecular measurements of performance	Evaluation of water quality on breeding	
--	Gender identification, sex control	Produce optimally performing seeds; Maximize efficiency of broodstock operations	• Sex change control in hermaphrodites • Induced sterilization
--	Gamete cryopreservation		• Inability to cryopreserve fish eggs
--	Control of maturation		• ID cues • Better understanding and control of the onset of puberty

Table 5. Ranked priorities for microbial processes and water quality technologies

Priority	Technology Area	Goals	Technology Gaps
#1	Dissolved and solid waste (nutrients) treatment	Cost-effective large scale solids removal and dewatering; Full utilization of all waste assets	• Designing the specs and limits of biofilters and solids separation equipment • Understanding polyculture systems • Accurate simple water chemistry tests (e.g., ammonia, nitrate, etc)
#2	Bio-energy production	Convert sludge to fuel, offset cost	• Algae ponds for biodiesel, methane, etc • Water retrieval from microalgae systems
#3	Microbial consortia and processes	Establish and maintain stable microbial consortia and processes enabling optimal fish and bacterial performance	• ID and improvement of nitrogen removal and processing • ID and measure microbial species within biofilter consortia • Innoculum; innoculation and start-up procedures • Monitoring/probes • Economy of scale models
#3 (tie)	Probiotic activities	Use probiotic approaches to enhance fish health and growth; Probiotics and microbiota to feed the bacteria	• ID probiotic spp. and species-specific mechanisms of effects
--	Environmental, biotic and abiotic effects	Optimize microbes and biofilters for different environments (cold, warm, salinity)	• Measure and optimize the health of the microbial consortia
--	Integrated marine aquaculture model systems	Improved economics and reduced cost of wastes	• ID species and co-products

Table 6. Ranked priorities for growout production technologies			
Priority	**Technology Area**	**Goals**	**Technology Gaps**
#1	Measuring and optimizing performance	Achieving fastest time to market size at maximal density and survival; Feed efficiency; Stress tolerance; Streamlined costs; Maintain product quality (texture, oxidation rate, shelf life, flavor, fillet yield, etc); Reducing cannibalism; Preventing precocious puberty	• Understanding dynamics of off-flavor components and managing of off-flavors • Understanding the physiology of growth • Digestibility by species • Control of sex differentiation • Real-time measurement of food component • Tailored feeding schedules
#2	Enabling species diversification	Flexible and generic systems	• ID new species (single spp or integrated aquaculture) suitable for land-based systems • ID environmental conditions that promote optimal performance
#3	Genetic and molecular approaches	Improved quality and performance (faster growth, improved fatty acid ratios, etc)	• Understanding genetic mechanisms of performance • Constructs and gene insertions
#4	Automation of operations	Minimal handling from larval to growout stages; Efficient and cost-effective grading, counting, harvesting, biomass estimation, feeding systems, mortality removal	• Reliable and cost-effective systems • Loss/damage of product • Limited market
--	Water recirculation and reuse	Optimize water quality; Maximizing water reuse	• Unknown water quality inhibitors
--	Rearing post-nursery environment	Cost-effective rearing environment (reduced capital and energy costs)	• ID environmental conditions that promote optimal cost-effective performance

Table 7. Ranked priorities for system engineering technologies

Priority	Technology Area	Goals	Technology Gaps
#1	Biofilters and life support systems	Most efficiently maintaining optimal water quality; Long-lived filters; Energy efficiency	• Denitrification • Establish species specific baseline levels for denitrification • Non-corrosive materials • Energy efficiency
#2	Energy balance/efficiency	Reduce energy costs	• Cost-efficient heat and cooling systems for marine systems • Alternative energy sources
#3	Defining, measuring recirculation	100% seawater recycle (in some cases)	• Novel waste removal/utilization
#4	Buildings/greenhouses/tanks/ Materials	Cost-effective, energy efficient and manageable operations tailored to the fish of interest	• Cost-effective non-corrosive materials and coatings • Tank insulation choice
--	Life-phase specific production systems	Systems optimized for broodstock, hatchery, growout etc	• CFD modeling for mixing and tank design • Tank color
--	Bio-security	No interaction with the environment	
--	Material handling, processing and distribution	Cost-effective marking systems for fish Cost effective, efficient distribution and storage of fish, feed, etc Harvesting Chemical additions Extensive automation	
--	Automated, real time monitoring	Online water quality monitoring	
--	Ergonomics/Safety	Optimized production and safety	

Table 8. Ranked priorities for feeds and nutrition technologies			
Priority	**Technology Area**	**Goals**	**Technology Gaps**
#1	Fish meal and oil replacement	Maximize fish conversion efficiency ; Produce from aquaculture fish meal and oil for feed; ID and remove anti-nutrients	• ID by species unidentified positive nutrients in fish meal not found in alternate ingredients • ID genes useful in understanding metabolic processes
#2	High efficiency/ non-polluting diets	Optimized for recirculation systems; Identify attractants and improved palatability	
#3	Species and life phase specific nutritional requirements and diets	Diets that help prevent diseases; Develop diets for different species and production systems; 100% survival	• Develop diets for all life stages • ID immunostimulants • New gene chips for evaluating product quality and diet performance
#4	Non-contaminated feeds	Develop diets deprived of heavy metals, PCBs, etc	• Reduced phosphates
--	Feed and pellet characteristics	Standardized suite of measurement protocols	
--	Feed delivery systems	Smart delivery systems	
--	Ultimate fate of feed		
--	Feed economy		

Table 9. Ranked priorities for health management technologies			
Priority	**Technology Area**	**Goals**	**Technology Gaps**
#1	Measuring fish health and stress	Develop sensitive diagnostic tools	• ID and understanding stressors • ID species-specific genes related to fish health • Nondestructive broodstock health screening protocols
#2	Probiotics, immunostimulants and immunomodulants	Uniform optimized predictable response	• ID and understanding of the mechanisms
#3	Vaccine development and efficient delivery	Develop efficient multi-vaccines and simple delivery methods	• Stable and effective auto delivery systems (oral, immersion, mechanical)
#4	Health management protocols	Reduce transport-related deformities; Optimizing hygiene barriers	• Understanding the environmental impact on the immune system • Assessing efficacy
--	New, compatible antibiotics	Alternatives to antibiotics	• Limited available antibiotics • Understand mechanisms
--	Improved anesthetics		• Too few anesthetics
--	Design for health management	Drug-free production environment	• Good fish health management protocols (BMPs)
--	Measuring fish welfare		• Standardized definition and measurement tools

Table 10. Ranked priorities for economics and marketing			
Priority	**Focus Area**	**Goals**	**Implementation Constraints**
#1	Modeling and business planning (near-term)	Effective sensitivity and risk analyses to guide investment decisions, research and business operations; A comprehensive plan that includes marketing dynamics and other aspects (see below)	• Commercial data collection • Cost functions (how do inputs and outputs compare) • Lack of demonstration projects at meaningful scale (!)
#1 (tie)	Economic feasibility and bottlenecks (near-term)	Profit maximization and cost reduction; Relative cost comparisons (by species, region and market); Economy of scale	• Commercial data collection • Cost functions (how do inputs and outputs compare) • New species R&D • Lack of demonstration projects at meaningful scale • No measurement of pricing structure for different market segments
#1 (tie)	Compare to cage production (near-term)	Quantify the full costs of aquaculture production, including the external costs, environmental costs, etc (not just the costs to the grower)	• Estimates of external costs of production • Real costs of reducing environmental impacts • Lack of demonstration projects at meaningful scale
#2	Market demand and perception analysis; flesh quality	Establish that consumers care about the value added approach/brand	• Marketing plans (to capture market dynamics), surveys, consumer data • Product testing
#3	Measuring added-value (eg, organically grown, cleaner, non-native, etc)	Higher value by differentiation from other products	• Demand models • Quantify food/transport miles from egg to end user
#3 (tie)	Product branding and specialty markets	Industrial consumers of juvenile fish	
--	Industrial consumers of juvenile fish	Meeting cost expectations of industrial consumers	
--	What is the marketing chain? Is there a market?	Define the market dynamics	• Market dynamics are not currently known

Table 11. Breakout group report on regulatory issues*		
Focus Area	**Goals**	**Implementation Constraints**
Assess environmental risk	(Detailed goals were not provided by breakout group)	(Implementation constraints were not provided by the breakout group)
Assess regulatory roadblocks and solutions		
Facilitate regulatory clearance (State, Federal); One stop permitting		
Provide clear guidelines to prospective aquaculturists		

* Regulatory issues were not been prioritized or discussed in detail by the breakout group.

Table 12. Breakout group report on short term goals

Technology Area	Goals	Technology Gaps
Identify a list of top candidate species by category (eg warm water, cold water, etc) (Note: Developing a matrix-based system for grading each spp and the identification of bottlenecks was suggested)	Develop the criteria and weigh the criteria for candidate spp.; Use the overall categories (eg., Broodstock and Spawning, Larval Rearing, etc) as an initial selection and sorting criteria for candidate species identification and demonstration	
Understanding the flow charts of all necessary components for culture of species above	Lack of data (see listings under Economics and Marketing)	
Develop business plans for species identified above		
Provide conceptual engineering designs (xx tons)	By species, establish business plans for above species; Capitalize on existing infra-structure, methodologies, expertise, etc	• Lack of systems level data for various scales; • An inventory of available resources does not exist
Establish demonstration systems	Clearly define the goals of the pilot/demonstration systems; Establish criteria for demo projects; Established partnerships between multiple stakeholders (federal, private, environmental, etc)	• Lack of established criteria for demonstration projects • Lack of funds for long term demonstrations (may need a combination of private and public funds; established partnerships)

Appendix I: Detailed List of Technological and Measurement Gaps

Seed Production

Broodstock management and spawning

- establishment of full control over environmental parameters
- development of reliable gender identification protocols
- measurement of physiological, endocrine, molecular and genomics-based parameters associated with broodstock performance, fecundity and year-round spawning
- development of measurement technology to include biochemical and genomic-based assessments for gamete quality
- measurement of environmental stresses (biotic and abiotic) using physiological and gene-based technologies
- examination of genetic considerations, selective breeding
- management of broodstock for consistent and year-round performance
- assessment and measurement of the need for hormonal spawning induction
- development of gene and hormonal “chips” to evaluate acquisition of maturational competence (small and large species)
- establish methods for production of sterile fish
- control sex reversal in sequential hermaphrodites

Hatchery and Larval Rearing

- optimized environmental conditions
- phase-specific rearing protocols (density and feeding)
- larval phase
- post-larvae/early juvenile phase(s)
- microalgae, rotifer, copepod and Artemia rearing capabilities
- multiple measurement technologies at the different trophic levels and water quality to standardize and optimize production efficiency
- probiotic support during larval rearing
- develop a better understanding the nutritional needs during the ontogeny of larval fishes in order to reduce or eliminate the incidence of malformation and malpigmentation
- establishment of weaning processes and prepared microdiets that will replace some or all of the live food requirement
- development of inert feeds which can completely replace the need for live prey

Nursery Production

- growth of post-larvae to around 40 gr.
- measurements of growth, metabolism and performance parameters, to include physiological, molecular and genomic-based parameters and technologies
- assessment of biotechnological approaches to optimize performance and growth
- control sex differentiation and production of monosex populations

- optimized tank dynamics (e.g. current velocities and water depth) as a means of improving water quality and fish performance, and reducing cannibalism, etc
- automation of size-grading and enumeration (via camera systems, etc)
    - reduce labor – current methods are not supportable
    - minimize cannibalism

Growout Production

- improvement of current capabilities to achieve consistent high holding densities (up to 75 kg/m3)
- optimization of current state-of-the-art toward fully recirculating systems (zero water or sludge discharge)
- conversion of sludge to methane
- establishment of flexible conditions to allow for species diversification
- development of multiple measurement technologies to monitor fish growth, metabolism and overall performance, physiological, molecular and genomic-based parameters
- development of gene chip, proteomic and metabolomic approaches to measure overall performance (for this and other life cycle stages)
- assessment and optimization of growout conditions (temperature, salinity, etc); tailor environmental conditions for species of interest (for this and other life stages)
- evaluation of biotechnological approaches to promote growth and performance
- establishment of methods for stress reduction (grading, fish move, etc)
- improvement of harvest and inventory management - automatic systems (fish pumps, etc.) and passing grading devices
- measurement of water chemistry and quality parameters, including oxygen, pH, ammonia, nitrite, nitrate, phosphate, sulfide, COD, BOD, salinity, redox potential and methane production
- development of automation and real-time technology for all measurements

Microbial Processes and Communities

- full characterization of the microbial consortia responsible for waste removal (dissolved, solid) under different environmental conditions (temperature, salinity, water source)
- study of microbial processes taking place in the system (aerobic, anaerobic, nitrification, denitrification, sulfur reduction, annamox, methanogenesis, etc.), including bacteriophage activities
- development of automated, real-time and online measurements for water/system chemistry
- development of specific molecular tools to monitor biofilters (gene chip, proteomics, metabolomics), especially in regard to anaerobic microbes
- development of detailed molecular, microbial, physiological and analytical measurement technologies related to microbial processes and water chemistry
- study of intestinal micro-biota as affected by both feed and the environment
- assessment of microbial communities in the culture water, to include potential pathogens and probiotics
- spectrum of water sources may require different water treatments (artificial; coastal; groundwater)

System Engineering

- assessment and development of all engineering aspects of the system, to include tanks, life support systems, mechanical and biological filtration units, gas transfer devices, and chemical balance (such as CO_2 and pH control)
- assessment of the performance of marine biofilters
  - different types of filters including MB, FSB, RBC, etc
  - cold water versus warm water biofilters in marine conditions
  - seaweed incorporation
- overcome scale-up issues in culture tank design
  - rapid removal of solids
  - create optimum swimming speeds
- overcome scale-up issues in foam fractionation
  - influence of salinity, ozone, and surfactants
  - side-stream requirements to meet water quality objectives
- assessment of continuous water disinfection (e.g., ozone & UV) technology
  - characterize dose requirements for different obligate marine pathogens
  - develop practices to avoid production of toxic bromine or bromate
- determine safe water quality limits for new marine species, e.g., carbon dioxide, oxygen, total gas pressure, ammonia, nitrite, nitrate, calcium, magnesium, swimming speed, etc.
- evaluate the consequences of reducing the amount of make-up water used in the system (i.e., closing the system)
  - product quality, especially off-flavor and potential toxicity
  - water quality
  - fish performance, especially health and growth rate
- evaluate building designs and costs for marine recirculation systems: corrosion resistance; insulation factors; energy efficiencies; HVAC designs; vapor barriers
- suitability of different building types according to region and species
- materials choice for marine recirculation systems (i.e., engineering and architectural choices): corrosion resistance; cost; durability; toxicity to fish
- establish standard methods and language for describing and evaluating recirculation systems, for example:
  - water reuse fraction based on system volume or flow replacement, cumulative feed burden per makeup flow (kg/m3)
  - what, how and where (in the system) to measure water quality parameters
  - standardize techniques for marine CO2 measurements that are appropriate and practical for aquaculture use
- establish standard practices for emergency and backup procedures and equipment
  - develop sensors and monitoring and control equipment that is technically and economically appropriate for aquaculture applications

Energy Considerations

- develop ‘low head’ systems that are more energy efficient per unit production
- analyze and measure energy usage (input and output) and carbon footprint
- investigate use of alternative energy technologies for powering land-based systems – explore possible synergies between energy production & aquaculture, for example:

- building designs
- heat pumps – heating & chilling
- methane production from system's sludge
- solar – heating/chilling
- wind – direct pumping versus turbine

Bio-security

- assessment of the full containment capabilities of the system for use with non-native species and potentially transgenic species
- assessment of the need to develop biological controls for escapes (polyploids, steriles, etc)
- assessment of techniques for the prevention of disease transmission between cultured and wild fish and vice versa (e.g., influent and effluent sterilization to eliminate the access or potential discharge of living pathogens)
- develop methods to evaluate the health status of the cultured animals and adjust cultural practices to prevent potential problems

Feeds and Nutrition

- development and assessment of alternate protein ingredients to fish meal
- development and assessment of specific diets for the different life phases: broodstock, larvae, weaning, juveniles, growout
- development and assessment of high efficiency, less polluting diets, tailored for recirculating systems and relevant to the microbial consortia
- development of finishing diets for specific products (i.e., high omega-3)
- development of molecular assays for assessing physiological nutritional quality of diet

Health management and disease prevention

- measurement of fish and system health using genomic-based technology and gene chips; automation of data-collecting systems
- development of standards for disease-free systems
- establishment of health-management protocols to avoid and overcome pathogens and diseases
- development of precise and rapid molecular pathogen diagnostics
- vaccine development: live, attenuated, genetic
- evaluation of new antibiotics and probiotic approaches
- establishment of advanced molecular techniques (gene chips, etc) as industry standards

System Economy

- analysis of the economic measures and feasibility of the system for several marine finfish systems
- comparison of the economics of land-based versus net-pen (inshore and offshore)
- analysis of seafood markets and demand including product perception
- review of economic bottlenecks and optimization of systems from an economic standpoint

- assessment of the economic feasibility and competitiveness of land-based operations
- promotion of added value: bio-security and non-native species
- critical examination of funding and financing

Quality Control and Product Branding

- measurement of potential chemical pollutants in the system and the fish
- Evaluation of the retention of undesired heavy metals, chemical pollutants, pathogens, etc, in closed systems
- determination of fish “wholesomeness ” and effect of feed formulation
- measurement of fish flavor and texture and effect of feed formulation
- development of standards to brand fish products as “environmentally sustainable” or “healthy” products
- promotion of the environmental sustainability of recirculating mariculture

Regulatory issues

- provide guidelines for fish health and genetic monitoring plans
- provide risk analysis for environmental impacts based on species, geography, and production systems

Federal and state regulations

- clear current regulatory roadblocks for marine aquaculture
- evaluate individual threats and regulatory solutions
    - non-natives; GMOs
    - interactions with environment (minimal and maximal)
    - issues with federal & state EPA – NPDES permits
    - National Aquatic Animal Health Plan – USF&W, FDA, USDA, EPA
- provide clear guidelines of regulations that must be met by prospective aquaculturists
- consider the creation of "aquaculture parks" or areas covered by general permits to facilitate the growth of the industry while ensuring protection of the environment

Short-term goals

- identify candidate species
    - candidate cold water species
    - candidate warm water species
    - native and non-native

- establishment of a number of demonstration systems (<20 MT production) to include all components (broodstock, hatchery, nursery, growout) for several key species: cobia; halibut; cod; salmon; redfish
- development of conceptual engineering design for a commercial on-land operation (1000 ton production?)
- development of relevant business plan(s)

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A Roadmap for Commercialization of Biofloc-Based Production Systems Technologies for Marine Shrimp *Litopenaeus vannamei*

Technical Challenges and Measurement Barriers

Technology at Issue

Land-based closed system super-intensive shrimp culture utilizing microbial bioflocs to enhance growth, sustain production, cycle wastes and reduce production costs.

Technological Innovation at Stake

Production of marine shrimp in super-intensive systems close to large population centers in the continental U.S. offers unique opportunities for developing new markets for consistent high quality fresh local shrimp products. Consistent production of shrimp on a continuous basis in proximity to large markets can offer opportunities for product differentiation and brand development. At present there are no reliable domestic sources for fresh, never frozen shrimp, available on a consistent basis. However, achieving consistent year-round production, while maintaining control over production costs, remains a significant technological challenge. High costs of land, labor and energy require increasingly complex engineering systems to achieve high production intensities. Similarly, maintaining high growth rates and consistent survivability requires improved seed stocks and cost-effective specially designed feeds. Finally, environmental sustainability requires innovative approaches to water reuse and waste management. Key components of the present super-intensive production system include: 1) availability of improved SPF shrimp stocks, facility biosecurity and maintenance of the health of the target crop; 2) high quality feeds and efficient feeding practices; 3) advanced systems engineering for heating, oxygenation, particle filtration, water quality monitoring, alarm systems, automated backup systems and waste management; and 4) development and management of biofloc communities to support system water quality and boost shrimp performance.

<u>Shrimp Stocks</u>

Increased availability of high quality, genetically improved, disease resistant post larvae (PL) have resulted in greater consistency in shrimp growth, size at harvest and survival of stocked animals. Economic and biosecurity concerns have forced shrimp producers to consider protection of cultured animals through more stringent production methods – both to avoid diseases and to prevent spread of diseases. Since the early 1990s research by the U.S. Marine Shrimp Farming Program has demonstrated the advantages of stocking SPF shrimp as the basis for intensive culture systems. Over the past decade, production has shifted to SPF stocks of *Litopenaeus vannamei* worldwide. As shrimp prices have declined, producers have been forced to improve efficiency and reliance on high quality sources of brood stocks as an important strategy for some of the most successful producers. Genetic selection has played an important role in improving the growth and survivability of these SPF lines. Increasingly sophisticated breeding programs have contributed to continuing improvements in growth and resistance to Taura Syndrome Virus.

At the same time, aquaculture producers have increasingly applied principles of biosecurity, which form the cornerstone of modern agricultural production systems. The present super-intensive production systems technologies rely upon the best fast growing SPF stocks available on the market produced in enclosed systems managed under stringent biosecurity protocols.

Production efficiencies of the system have been improved by including a nursery phase. This provides several advantages including assurance of stock quality and animal health prior to stocking, better control over shrimp stocking numbers, survivability and system biomass estimates during the growout cycle, more efficient use of production area by stocking shrimp at higher densities during the nursery phase and shortening the growout cycle by stocking animals well into the linear growth portion of the shrimp life cycle.

Feeds and Feeding

It is well recognized that feed inputs are the major driver of the dynamics of intensive zero exchange shrimp culture systems. Control of feeding rates is one of the most important factors in assuring optimal shrimp growth while minimizing waste production and controlling variable production costs. Feed formulation is also a critical consideration in terms of feed costs, and shrimp growth rates. In general, financial analyses show that small increases in direct costs such as feed can be more than offset by incremental increases in growth. However, inefficient feeding practices or increases in costs without consistent increases in growth have a strong negative effect on financial viability. Recent studies have indicated that controlled application of nutrient-dense high protein feeds can improve growth performance when compared to lower protein diets offered on an iso-nitrogenous basis. As discussed below, the formulation of feeds can have an important indirect effect on the system microbial community. Inputs of carbon and nitrogen must be considered as part of overall management of the biofloc communities upon which system stability depends. Thus, some researchers suggest a lower protein feed formulation strategy to encourage heterotrophic biofloc production. Others rely more on nitrifiers in the biofloc recommending feeding strategies which rely upon careful control of application rates and use of nutrient-dense high protein feeds with highly digestible ingredients.

Systems Engineering

The present production system technologies are based on well mixed raceways to assure resuspension of particulate matter. Flow and mixing are accomplished by aeration and/or injection of recirculated water in growout raceways and by use of aeration in nursery raceways. The high carrying capacities projected for the systems require external particle filtration fractionation or settling to reduce total suspended solid loads. High feeding rates in these systems require significant supplemental aeration in nursery tanks and addition of supplemental oxygen to meet demand of the target crop and of the water column microbial community. High rates of oxygen demand necessitate monitoring, alarm and backup systems to assure oxygen supply in the event of power failure. One of the most important engineering components is the design of the enclosures and supplemental heating which will be critical for maintenance of optimal growing temperatures year round in the U.S. Sustainability and operation of the systems away from the coast necessitates waste collection, treatment and return of treated water. Treatment systems should be designed to dewater and digest volatile solids; to promote denitrification reducing nitrate levels and restoring alkalinity; and to recover salts. By returning treated wastewater and supplementing for lost salts and trace minerals, system water quality can be maintained while minimizing the need for fresh seawater inputs and solid waste disposal.

Biofloc Microbial Communities

When shrimp are reared at high densities without water exchange, a biofloc develops in the ponds that has several advantages for shrimp culture. These include increased recycling of waste and mineralization of nutrients within the system and improved water quality stability. The diverse microbial community in the biofloc-dominated systems is thought to increase competition with potentially pathogenic microbes including vibrios, reducing problems with non-excludable pathogens. In addition, the natural productivity associated with these bioflocs has been shown to provide growth enhancing factors which improve shrimp production.

Additional research has been conducted on the dynamics of the microbial communities in these systems, methods for measuring microbial activity and some techniques for manipulation of the makeup of these communities. Research has demonstrated that typically, ponds undergo an algal bloom and crash. Typically bioflocs include an active heterotrophic community and varying levels of photoautotrophic activity. The relative mix of bacteria and algae with very high feed inputs into the system is dependant upon intensity of cropping of biofloc particles, resulting light levels, and nutrient balances within the system. Chemoautotrophic nitrifiers make up a third important component of the community in biofloc systems. Nitrification is a significant component of overall microbial activity serving to control ammonia and nitrite levels in the system once the community becomes established. High levels of nitrification necessitate supplementation or regeneration of system alkalinity. The relative balance between these community components may vary depending upon management inputs and philosophies.

This roadmap focuses on a detailed review of super-intensive biofloc based shrimp production technologies to document key technology gaps and the most significant areas where innovation can lead to improved competitiveness. Although current configurations could compete in limited specialty markets, successful competition with commodity products will require significant reductions in production costs coupled with improvements in growth and production rates for an overall doubling in production efficiencies. Maintaining this level of improvement and translating it into industry growth in the short term will require integrated approaches which partner academic, government, and industry groups with appropriate resources. Translating these investments into economic gains will require not only the identification of areas where improvements would be most beneficial but also the directing of scientific resources towards outcomes which can be measured to document and assure progress.

Economic Significance of the Innovation

In 2006, penaeid shrimps represented the 6th largest aquaculture commodity produced in the world by volume, ranking second overall in terms of value (FAO The State of World Fisheries and Aquaculture 2006). According to the FAO Aquaculture Production Database, in 2005 penaeid shrimp aquaculture was valued at over 10.6 billion dollars (FAO Fishstat Plus). Shrimp imports into the U.S. in 2006 were valued at 4.1 billion dollars accounting for 31 percent of total edible imports into the country (NOAA Fisheries of the United States 2007). Per capita consumption of shrimp in the U.S. has increased over 27% from 3.2 lbs in 2000 to a record 4.4 lbs per person per year in 2006. The growing demand for shrimp in this country has been fueled by increasing world aquaculture production and declining shrimp prices.

Although the U.S. has been a global leader in the development of technologies for shrimp production, U.S. shrimp aquaculture production has been declining. Historically, domestic aquaculture shrimp production has made a very limited contribution to total shrimp supply in the U.S. As a result, domestic aquaculture producers have taken whatever is the prevailing commodity shrimp market price. As prices have dropped, U.S. producers applying traditional production technologies have been unable to compete on commodity markets. The cost of producing shrimp in the U.S. is high due to land, labor, energy and effluent compliance costs. Growing seasons are limited constraining consistency in product availability. Regulatory burdens have also contributed to reduced competitiveness of the U.S. shrimp aquaculture industry.

The present technologies overcome many of these constraints. Production levels of almost 50,000 lbs per acre per crop are almost 5 times higher than typical intensive pond production rates and are 2.5 times higher than the most successful current intensive pond production levels. This increase in production density reduces the overall cost per unit area or volume and allows for intensification of management inputs. It also allows for enclosure of production systems which is crucial for biosecure year round production. It is this continuous production which can further multiply annual production levels by a factor of four to almost 200,000 lbs per acre per year. Most importantly, consistent year round production allows for staggering of crops and consistency in supply of fresh product that can be differentiated from commodity imports. In the long tern, research efforts should be directed at significantly reducing production costs to approach those of foreign producers. As innovations lead to improved productivity, production costs can be reduced allowing for industry expansion as system outputs become competitive with low cost foreign producers.

The immense size of the U.S. shrimp market and growing consumer demand suggest a large initial market for fresh local products even with a significant mark-up over imported commodity shrimp. Each percentage point of market penetration in 2006 would have translated into 13.1 million pounds of production. However, long term success and growth of the sector will require significant continued innovation to further reduce cost of production and improve competitiveness with commodity products.

Crosscutting Non-Technical Barriers to Innovation

Integration of Research and Commercialization Efforts

Some of the most important factors in reducing production costs are economies of scale. On the other hand, scale up of current technologies will involve significant opportunities for modifications in current experimental or pilot scale applications. The development of large-scale commercially viable demonstration projects supported by experts in current state of the art research scale systems has often been a missing link in public and private investments in technology development. This has, at times, resulted in lack of focus in experimental efforts aimed at promoting commercial scale technology development and in "reinventing the wheel" in some commercial scale operations. A new paradigm is needed targeting scientific research coupled with commercial scale applications applying a robust and diverse funding base. This could lead to solving short term problems associated with scale up while improving systems applications for improved competitiveness in the medium and long term.

A blending of economic costs and biological decisions needs to be made. Modeling efforts which integrate economics and biological responses should be supported. Researchers need to identify critical areas to reduce costs and concurrently determine key factors limiting biological responses while improving understanding of interactions between the two.

Regulatory Issues

Regulatory issues may also impede commercialization of these technologies in some jurisdictions. The species most amenable to production of food shrimp in biofloc systems is *L. vannamei*. These shrimp are amenable to high stocking rates, are able to take advantage of microbial productivity in biofloc systems, and most importantly, stocks are available which are free of a long list of excludable pathogens and have been selected for growth performance over many generations. As the species is not indigenous to the U.S., current regulations in some jurisdictions may limit or prohibit commercial aquaculture production. Similarly, issues related to siting of large scale projects relative to land costs, cost of seawater or sea salts, sociological factors, protection of ground waters, disposal of waste, biosecurity, etc. all require some regulatory input. It is the bewildering array of local, state, and federal regulatory agencies that can constrain industry development. A coherent best management practices-based one-stop regulatory authority could improve the outlook for commercialization of sustainable U.S. aquaculture industries.

Economics

Economic modeling and planning is a key component of developing strategies to improve competitiveness. Accurate prediction of fixed and variable costs combined with effective sensitivity analyses will allow prioritization of efforts aimed at reducing production costs. Models can help define potential economies of scale and can provide a basis for examining cost effectiveness of efforts to improve energy efficiencies.

Marketing and Processing

As described above, the price of commodity shrimp has been on a downward trend for several years. This can be attributed to increasing supplies of white shrimp and decreasing production costs as Asian pond production efficiencies improve and as production areas expand. While these trends have led to growing global markets and per capita consumption rates, dropping commodity prices decrease competitiveness of high cost technology intensive production systems. Thus, in the near term, some premium must be achieved over imported commodity shrimp to assure financial viability. Emphasis must be placed on the processing and marketing of better quality live/fresh/frozen shrimp products. Efforts to determine the magnitude of specialty fresh product and or branding premiums along with estimates of the depth of these markets would help in determining initial feasibility and potential scope of financially viable commercialization efforts which rely upon specialty marketing. This will require attention to post harvest processing techniques to market product forms most advantageous for differentiation from imported commodity shrimp. These efforts can be facilitated by measurement and certification of quality in terms of sustainability of production systems, flesh quality, food safety, and human health benefits. Credible eco-labeling efforts, organic certification and effective product branding offer additional opportunities for marketing premiums which can improve competitiveness.

Technical Barriers to Innovation

Health Management

The maintenance of the health of the shrimp under culture is a critical prerequisite to profitability. Health assurance begins with use of SPF stocks and control of facility biosecurity. Tools for the evaluation of health status on an ongoing basis to see subacute indications of declines in fitness are needed. Existing tools for rapid diagnosis and longer term confirmation of acute pathologies should be refined. Emerging non-listed pathogens and disease caused by non-excludable pathogens will continue to be a problem. Pathogens need to be studied to develop diagnostics and improve basic knowledge. Methods to avert disease, immunostimulation and approved chemotheraputants for prophylaxsis or to treat disease outbreaks from non-excludable pathogens (including vibriosis) will be needed. This will necessitate better understating and control of microbial communities as addressed below. Improved appropriate applications for probiotics and better understanding of how to encourage growth of non-pathogenic microbes in the systems is necessary. Fundamental to these efforts are tools to measure immune status, fitness and health of the target crop on an ongoing basis.

Seed Supply

Genetics and Breeding: A stable year round supply of healthy genetically improved fast growing robust postlarvae is a critical prerequisite to industry competitiveness. Basing production of food shrimp on *L. vannamei* provides an important advantage in that much effort has gone into the closing of its life cycle and genetic selection for this species. Today there are commercial companies in the U.S. devoted to development of SPF, disease-resistant breeding stocks of *L. vannamei* selected for fast growth. These efforts are currently devoted to producing stocks for shrimp production in open pond systems. A focused breeding effort targeting performance in these biosecure closed systems would speed improvement. This would also avoid potential selection for traits which may be of significance in open pond systems in Asia but which could be negatively correlated with growth and other critical performance characteristics in the more biosecure systems. Efforts related to selection for new traits relative to survivability or production related characteristics such as dress out percentage could also improve competitiveness if new strains are protected and used only in domestic production systems. In the long term, improvement of genomic enablement for the species will allow for discovery science that could lead to important breakthroughs enhancing production and fitness related traits. Measurement technologies in the area of genetics and breeding will include objective assessments of heritability, genetic gains, pedigree tracking, and inbreeding coefficients. Development of molecular tools should include markers for traits of interest and for stock identification, genome maps, and functional genomic tools such as microarrays.

Seed Production: Maturation and hatchery technologies are well developed for *L. vannamei* although further attention to scalability issues and development of closed system hatcheries have implications for vertical integration especially during early phases of industry development. Improvement of maturation systems technologies to enhance efficiency of systems engineering, to eliminate reliance on fresh feeds and to otherwise maximize reproductive performance would be beneficial if nauplii quality and systems efficiencies are increased. Larval culture systems improvements in areas of systems engineering should focus on physical characteristics such as mixing, microbiology, and water reuse technologies. Systems still rely on live feeds and continuing incremental improvements in developing artificial diets should improve production efficiency and consistency. Developments in additives like pre- and probiotics, disinfectants and nutrients to enhance microbial activity should be beneficial. Husbandry improvements in assessing larvae and postlarvae, harvest and counting methods and transport techniques could be envisioned. Measurement technologies in the area of maturation and larval rearing should focus on determination of water quality conditions and organic loading, fitness of the broodstock, nauplii, larvae and postlarvae, fecundity in terms of oocyte and sperm development, mating, spawning, egg production, fertilization, hatch and metamorphosis rates. Determination of mixing and settling rates, microbial community composition and activity, feed nutritional quality and water quality effects, effectiveness of probiotics and disinfectants, as well as accuracy and efficiency of PL quantification should improve competitiveness of hatchery operations.

Production Systems

Systems engineering: Systems engineering for commercial scale applications of super-intensive closed system shrimp production technologies is one of the most important technical gaps to commercial competitiveness. It involves a highly complex set of issues which all interrelate, many of which are highly sensitive to changes in scale. First, the size, and type of enclosure for the systems is of paramount importance in terms of capital costs, energy efficiencies, and secondary effects on systems operations. Use of barn type structures, greenhouses or combinations of the two is a fundamental issue which relates back to importance of light, energy efficiencies and initial investment costs. Interrelationships between economic factors which vary by geographic location and biological factors which vary with operational methodologies complicate optimization. Second, optimal tank designs, dimensions, and materials may also vary according to specifics of the production system, relative cost and availability of materials in different parts of the U.S., and management philosophies. Alternative operational systems (automated where appropriate) for aeration and circulation, water heating, systems monitoring and control, filtration, waste treatment, water conditioning and reconditioning, and waste disposal offer many different potential options and solutions all of which have important implications for production efficiencies. Areas for which measurements could be applied to drive innovation aimed at simplifying operations and reducing costs include: efficiencies of water use; mixing and oxygen transfer efficiencies; heat transfers and energy efficiencies; accuracy of monitoring and control systems; effectiveness and cost of filtration alternatives; and waste treatment efficiencies.

Feed Program

Feed is one of the most important components of variable costs. The feed is the driver of the system both in terms of nutrient inputs and shrimp performance. Feed effects on shrimp growth and production, both direct and indirect, are a major component of system financial returns. Feed nutrient quality, nutrient density and physical properties should be optimized to promote cost effectiveness, growth and condition. Management of feed inputs is critical to maximize growth while eliminating water quality deterioration from overfeeding, and optimize nitrogen conversion efficiencies from feed to shrimp. This would include the amount of feed offered, frequency, timing, opportunities for automation, etc. Feed additives including immunostimulants, gut microflora stimulants (prebiotics), probiotics, etc. can offer opportunities to improve shrimp growth, condition and feed conversion efficiency. Feeds and feeding must also be considered in the framework of overall system sustainability. The ratio of live weight unit of forage (reduction) fisheries used to produce one live weight unit of product is an important measure of long term sustainability of global fishery resources. Development of fishmeal and fish oil replacements are important in this regard and may become a prerequisite to organic certification. Finally, consideration of the flavor, appearance and human health characteristics of the final product depend upon feed inputs and may offer opportunities for development of specialty finishing diets. Application of measurement science to optimization of a feeds program in terms of costs, financial returns, and sustainability of the technology involves both traditional and new approaches. Methods for determination of digestibility, leaching, attractability, nutrient densities, nutrient toxicities, feed conversion efficiencies, shrimp performance and feed conversion efficiencies are well documented. Further efforts are necessary to better measure feed performance in these systems to better formulate feeds for this application. Some things can be measured in small scale systems allowing for quantification of contributions from system productivity and thereby optimizing formulations to supplement and not duplicate. More problematic is measurement of long term impacts of feeds in systems reusing water between crops. Buildups of excess nutrients and potentially toxic trace metals and anti-nutritional factors must be measured. New measures of conversion efficiency of marine proteins can enhance sustainability. Finally, measures of product palatability, appearance and quality in terms of human heath effects offer opportunities for optimizing diets and development of finishing diets with an eye towards improving competitiveness through product differentiation.

Husbandry

In the general area of husbandry are some of the most significant challenges to stability and efficiency of production in biofloc-based systems. Maintenance of optimal water quality is a challenge in that system designs and cost prohibitions for inland systems preclude any significant use of seawater exchange to maintain growing conditions. At inland locations, protection of aquifers and waste disposal can be significant issues. Management of water quality must be accomplished through the exchange of water within the system and through the proactive maintenance of optimal biofloc communities in the systems over individual growing cycles and between multiple cycles over time. It is this management of biofloc communities which present one of the greatest opportunities for improvement in competitiveness and one of the greatest risks to consistency over time. Optimizing microbial communities will require improved understanding of relative advantages and disadvantages of the heterotrophic bacterial growth, the blooms and crashes of different species of algae, the relative activity of chemoautotrophs responsible for processes of nitrification and denitrification, as well as the effects of ciliate grazers and other zooplankton. Once strategies targeting specific community compositions and levels of microbial activity are designed, development of management protocols to achieve these ratios will be necessary. Techniques must be optimized for direct application of probiotics and algal inoculations, and indirect management through control of nutrients, filtration, light, etc. Management of long term water quality profiles must take into consideration build up of waste materials and nutrients from feed inputs and supplementation of micronutrients which may be depleted over time. Clearly, optimization of husbandry and system management will depend upon accurate measurement and analysis of traditional water quality parameters in real time. Development of targeted monitoring systems will be crucial to enable managers to react to changes in water quality. Innovation to optimize biofloc and water management for system productivity, profitability and sustainability will require new strategies for measuring community composition and activity. Better metrics for description or quantification of floc densities and improved understanding of the significance of measures like total suspended solids (TSS), volatile suspended solids (VSS), turbidity, light absorbance, etc. are needed. Community composition can be measured through direct microscopic observation and application of more indirect methods such as quantification of algal pigments, or analysis of bacterial strains using DGGE techniques. Measurement of activity will require accurate determination of oxygen fluxes due to respiration and photosynthesis or indirect measurements of changes in nitrogen species. Once accurate estimates are made, models can be developed to better understand carbon and nitrogen fluxes within the system. Similarly, correlations can be made with shrimp growth and fitness to optimize productivity if techniques can be developed to accurately determine shrimp survival, condition and growth in real time.

Stocking and Harvesting of Nursery Systems

Nursery systems can contribute to increased profitability in a number of ways. They can provide for a buffer to accept PL from hatcheries as they become available. Better facility utilization, short-cutting growout cycles allows for higher production rates per unit area per year. A nursery can allow for quarantine and elimination of poorly performing batches of postlarvae in a timely manner particularly if a pre-stocking acclimation station is included in facility designs. This is particularly important when postlarvae are procured from outside sources. Survivability of juveniles can be more predictable than that of direct stocked postlarvae improving management during the production cycle. Benefits of nursery systems are maximized by efficient and rapid transfer of juveniles from nursery to growout. Optimizing design and operation of nursery systems depends upon appropriate sizing of production units coupled with efficient scheduling of stocking and harvest to allow for efficient cycling of on-growing systems. Development of more accurate methods to estimate survivability and performance of juveniles during this phase would improve management efficiency. Improved techniques for rapid accurate measurement of harvest biomass and condition of juveniles integrated with more automated and efficient transfer technologies could improve control during subsequent growout.

Harvesting of Growout Systems

Improving overall competitiveness requires appropriate design and husbandry of growout systems as described above along with successful harvest strategies. Harvesting systems should be automated and should facilitate water recovery while assuring product quality. Effective post-harvest handling techniques for live or fresh shrimp could improve quality delivered to the customer. Growers will need to design harvest timing strategies based on market demands and to develop alternative partial harvest techniques. These efforts will require good models of system economics, of risks associated with delayed harvest and of key market segments. Better control of molt synchrony would improve the percentage of high quality product. Measurement of compensatory growth and density effects on system productivity help optimize harvest strategies in general and partial harvest strategies in particular. Accurate assessment of product quality is a prerequisite to improvement of harvest and post harvest product handling.

Clearly, there is an urgent need to build and operate pilot shrimp production systems in different locations to demonstrate to the aquaculture industry that the current technologies work and to compare comparative advantages of the production systems in various locations.

Prioritized Technology Gaps

During the workshop, participants discussed and prioritized technical gaps to technology innovation for industry competitiveness. A tabular summary of technological areas, goals and technology constraints was complied during the first breakout session. Summaries were made for systems engineering, husbandry, feeds programs, health, seed supply, as well as economics and marketing as summarized in Tables 13-18 respectively. In each table, results of prioritization exercises are shown by numbers in parentheses. Participants prioritized all of the technology areas in the first exercise and then prioritized all of the technology gaps in a second round.

After the workshop a final summary was complied and distributed to participants for comment. The priorities were ranked based on the following:

- **Feasibility**. An evaluation of the scientific and technical potential for overcoming technological barriers. What is technically feasible? What can be accomplished through research? How difficult is it to overcome the barrier?
- **Importance/Relevance/Urgency**. How pressing is the need? How critical to overall success is overcoming this particular gap?
- **Socio-economic Impact**. Projections of expected benefits and consequences. Are results broadly applicable or narrowly focused? What is the relative return on investment made to overcome a gap?

The following are final prioritized summaries of areas needing research and development effort for biofloc-based production systems technologies for the marine shrimp *Litopenaeus vannamei* with special emphasis on those areas with measurement needs.

1. ***System Engineering and Life-Support Systems***. Improve the cost-effectiveness of life-support technology. Improve system energy efficiency, particularly for maintaining water temperature. Establish standards and specifications for system engineering design, with the goal of improving production efficiency as measured by shrimp growth and production potential. Establish standard management techniques to establish, manage, and maintain the structure, abundance, and activity of stable biofloc communities that maximize contributions to shrimp growth and water quality management. Improve methods to collect, dewater, digest, and dispose of waste solids. Improve methods for denitrifying, desalting, and treating water to reclaim minerals for reuse.

2. ***Genetic improvement***. Continue to invest in robust selective breeding programs for penaeid shrimp. Develop new and use existing molecular tools to understand the genetic basis of shrimp production performance and disease resistance and apply discoveries to improve selection. Develop methods for monosex female production.

3. ***Feeds and feeding***. Develop feeds that maximize the efficiency of fishmeal use, minimize the ecological footprint of all ingredients, improve water quality, and maximize the contribution from biofloc to shrimp growth. Improve techniques for monitoring shrimp density and survival throughout growout in order to optimize feeding rates.

4. ***Health and biosecurity***. Improve understanding of the factors affecting shrimp health and fitness. Develop diagnostic tools that permit rapid assessment of stress and disease. Develop standard biosecurity protocols, including pathogen monitoring and disease control systems. Establish protocols for management response to early warnings of stress or disease.

5. ***Value-added products***. Develop products that can provide added value or some other premium quality over competitive products and can be distinguished in the market through branding or labeling. Examples include fatty acid enrichment, organic certification, and marketing live or fresh-never-frozen shrimp.

6. ***Bio-economic models***. Develop accurate, flexible, and user-friendly financial models that include sensitivity and risk analysis. Apply marketing studies to determine market depth for value added products.

7. ***Larval culture***. Develop replacements for live foods in larval culture. Establish standards for postlarval quality and fitness. Develop non-invasive methods to accurately count post-larvae and juveniles.

Application of Measurement Science to Overcoming Technical Barriers

For biofloc-based super-intensive shrimp systems, an example of a key technology gap and illustration related measurement science constraints is as follows. A key technical gap constraining competitiveness may be the management of the complex structure and activity of system microbial assemblages to promote shrimp performance, water quality and system assimilation efficiencies. The highly complex microbial communities in these systems include algal assemblages, complex bacterial communities, as well as grazers and larger zooplankton components. The activity of these microbes includes primary production, heterotrophic metabolism, as well as important chemoautotrophic processes of nitrification and denitrification. Development and application of management interventions depend upon effective measurement of impacts produced by the microbial community structure and function on shrimp performance.

Examples of measurement technologies to document community structure include direct epifluorescent microscopic examination to facilitate enumeration of algae (450-750 nm chlorophyll cube), bacteria (DAPI (4',6-diamidino-2-phenylindole) staining with 320-520 nm DAPI cube), or cyanobacteria (525-725 nm rhodamine cube). Recent work with fatty acid profiling of the biofloc communities shows promising results for monitoring bacteria dynamics. Techniques such as DGGE, high-performance liquid chromatography (HPLC) analysis of algal pigments, pyrosequencing of DNA, biolog systems and others also can be used to better characterize these complex communities. In-situ continuous recording Chl *a*, phycocyanin, and phycoerythrin electrodes (YSI 6600 series Sondes) are being used to monitor changes in the algal community and to warn of cyanobacteria blooms. Continuous measurement of photosynthetically active radiation (PAR) available throughout the biofloc water column is being applied to better understand the drivers of microbial community structure. Other measures of physical structure such as suspended and volatile solids or biofloc particle size may be associated with or promoting of important taxa. Microbial biofloc communities exhibiting varying structures are being studied for potential supplemental nutritional value to shrimp through analyses for proximate analyses and detailed lipid analyses of fatty acid contributions. Promoting desired assemblages from both water quality and supplemental nutritional perspectives depends upon development of effective and efficient techniques for enumerating and/or qualitatively describing and characterizing relative and absolute abundance of the major functional microbial taxa.

In addition to accurately describing biofloc community structure, reliably characterizing and measuring community metabolic activity is crucial for optimizing system processes and for achieving predictability in understanding system demands for oxygen, alkalinity, nutrients, minerals and other key inputs. Techniques applied to date have measured total system (including shrimp) primary production and respiration by short term removal of aeration and continuous recording of dissolved oxygen changes using YSI 6600 Sondes. Such measurements can be coupled with enhanced light-dark bottle measures of the microbial biofloc community using a rotating ambient water incubator to keep the biofloc in suspension and an automated titrator to ensure precise oxygen measurements. These approaches enable accurate prediction of oxygen demand in the system for both the microbial community and growing shrimp. Incorporation of specific metabolic inhibitors permit further description of the relative metabolic activity of prokaryotes, photoautotrophs, and chemoautotrophic nitrifiers. Additional direct short term measurements of changes in several chemical species in spiked samples permit quantification of nitrification and denitrification rates. Dynamic system models constructed from the measurements of biofloc community structure and function are being developed to better understand the drivers and control mechanisms of these systems with the goal of enhanced predictability and improved management strategies.

Both the structural and functional community characterizations must be correlated with target crop performance and overall efficiencies. While most of the technologies described are research tools for improved understanding of these systems, it is essential that the most relevant measurement technologies for optimizing target crop productivity be identified, prioritized, and incorporated into routine management protocols. For example, research suggests that shrimp growth may be enhanced by a diatom-dominated algal community and inhibited by cyanobacteria attached to biofloc particles. The aquaculturist might then manage for a community that falls within certain limits of PAR light penetration by cropping solids while retaining sufficient particulate levels to maintain a functioning nitrification community sufficient to handle the loading rates of the system. Incorporation of a few other easily measured community-critical parameters such as silicate levels as well as the standard shrimp-critical parameters like dissolved oxygen will permit optimization of management protocols. Measuring the effect of the microbial community on shrimp performance is a complex undertaking which requires development of replicated systems which can be managed to reliably reproduce an optimal community structure and function. This type of holistic approach and systems outlook is constrained by the large numbers of variables which can have significant primary and secondary effects on performance. Much effort to accurately and dependably measure biofloc communities will be required to identify the key system drivers necessary for an efficient, economically competitive, technologically-based shrimp aquaculture industry in the United States.

Measurement Science Gaps

During the workshop, participants selected priority technology gaps identified during the first breakout session for further discussion during breakout session 2. The second session addressed measurement parts of the technological gaps identifying measurement standards and needs which can foster this innovation and lead to new technical breakthroughs. The results of this second breakout session are shown in Table 19. Although preliminary, these lists suggest important areas where targeted science focused on standards and measurement techniques can lead to innovation and to development of means to track progress over time.

Roadmapping Exercise

On the final morning of the workshop participants worked on building a first draft of a technology roadmap for biofloc-based production systems technologies for the marine shrimp *Litopenaeus vannamei.* In the exercise, participants explored an extended look at the future of the technology and, where possible, to apply metrics to drive innovation and improvement in key areas. The result is a preliminary list of technology needs organized according to short, medium and long term goals. The results provide an initial diagram that lays out a vision for future development, give examples of specific measurable objectives, and suggest a plan for moving the technology forward over time. The exercise was limited in time and scope and the preliminary draft results are presented in Figure 1. However, this type of planning exercise can drive the development of a mix of focused research activities with measurable goals aimed at driving technology innovation forward.

Table 13. Breakout group report on shrimp biofloc production systems engineering. Numbers in parentheses indicate number of votes assigned to each item during the prioritization exercise for technology areas and technology gaps

Technology Area	Goals	Technology Gaps
Buildings/greenhouses (8)	Enclose systems cost effectively for energy efficiency and for conditions which support biofloc and shrimp performance.	• Designs that can be thermally adaptive and efficient (4) • Systems that provide natural light; compare systems that use sunlight (natural) and sunlit systems (quality of light) (2) • Structural integrity, corrosion (1) • Ventilation requirements and moisture control (0) • Span – cost/benefit (0)
Production units (15)	Design cost effective production units for simplicity, and maximum performance and operability.	• Dimensions/size/design (including size of property and greenhouse; shape) (7) • Depth (2) • Artificial substrates (3) • Materials (0)
Aeration, circulation and oxygenation (8)	Assure adequate dissolved oxygen levels and efficient mixing.	• Tank hydraulics (methodology) (0) • Water movement technologies (1) • Air or oxygen delivery systems (2) • Gas balance; CO_2 (0)
Water heating (6)	Maintain temperatures at set levels within acceptable limits (+/- 1)	• Heat delivery (0) • Efficiency/Insulation of system (1) • Exchange (0) • Heating-cooling (0) • Solar/alternate heat sources (0) • Biofloc = biofuel (0) • Heat recovery (1)
Monitoring and control systems (8)	Apply cost effective monitoring and control to facilitate management and protect crops	• Photosynthesis (1) • Dissolved oxygen monitoring (2) • Microbial structure and activity (1) • Population size/total biomass (animal) (10) • Equipment monitoring and feedback (remote) (0)
Filtration systems (8)	Provide cost effective options for cropping of biofloc to manage microbial community structure abundance and activity	• Floc cropping methods (7) • Hybrid systems – external/internal biofiltration (3)
Waste management and treatment (26)	Develop effective methods for collecting, dewatering, digesting, denitrifying, and desalting waste and for treating water and minerals for reuse.	• Separate biofloc management (9) • Ozone use (1) • Phosphates (0) • Digestion of solids. Minimize feed waste. Methane production (2)

Table 14. Breakout group report on shrimp husbandry in biofloc systems. Numbers in parentheses indicate number of votes assigned to each item during the prioritization exercise for technology areas and technology gaps

Technology Area	Goals	Technology Gaps
Water quality (15)	Assure optimal water quality at all times while minimizing water use within and between crops	• Define optimal parameters (3) • Frequency of measurement (0) • Initial treatment of incoming water (0) • Salt/salinity (ion concentration) (5) • Micronutrients (0) • Nutrient model, pathways (0) • Alkalinity (3) • Trace mineral depletion over time (0) • Denitrification (6)
Biofloc development and management (25)	Manage systems to establish and maintain biofloc communities which maximize contributions to shrimp growth and water quality management	• Microbial community structure and activity, is light needed, bacteria versus algae (7) • Control, stability, C:N ratios (5) • Inoculation/Start up (1) • Preparation /optimum density (4) • Pre-/pro-biotics (1)
Nursery systems harvest and transfer (2)	Establish harvest and transfer protocols which minimize stress and promote management of growout phase	• Stocking number estimations (5) • Optimal size and density (0) • Multiple staging/direct stocking (0) • Handling and transfer stress (0) • Transfer protocols (0) • Juvenile fitness (0)
Growout (Final) harvest logistics (3)	Apply harvest techniques which are efficient and contribute to product quality	• Stress management (0) • Multiple staging (0) • Live harvest techniques/equipment (2) • Partial harvesting (5) • Chill-chain (0) • Grading (0) • Hazard Analysis Critical Control Point (HACCP) procedures (0)
Water quality (15)	Assure optimal water quality at all times while minimizing water use within and between crops	• Define optimal parameters (3) • Frequency of measurement (0) • Initial treatment of incoming water (0) • Salt/salinity (ion concentration) (5) • Micronutrients (0) • Nutrient modeling, pathways (0) • Alkalinity (3) • Trace mineral depletion over time (0) • Denitrification (6)
Biofloc development and management (25)	Manage systems to establish and maintain biofloc communities which maximize contributions to shrimp growth and water quality management	• Microbial community structure and activity, is light needed, bacteria versus algae (7) • Control, stability, C:N ratios (5) • Inoculation/Start up (1) • Preparation /optimum density (4) • Pre-/pro-biotics (1)

Table 14 (continued). Breakout group report on shrimp husbandry in biofloc systems. Numbers in parentheses indicate number of votes assigned to each item during the prioritization exercise for technology areas and technology gaps		
Technology Area	**Goals**	**Technology Gaps**
Nursery systems harvest and transfer (2)	Establish harvest and transfer protocols which minimize stress and promote management of growout phase	• Stocking number estimations (5) • Optimal size and density (0) • Multiple staging/direct stocking (0) • Handling and transfer stress (0) • Transfer protocols (0) • Juvenile fitness (0)

Table 15. Breakout group report on shrimp feed programs for biofloc systems. Numbers in parentheses indicate number of votes assigned to each item during the prioritization exercise for technology areas and technology gaps (NR not ranked, added after the exercise)		
Technology Area	**Goals**	**Technology Gaps**
Physical characteristics (3)	Enable feeds which attract shrimp and maintain optimal physical characteristics until consumed	• Water stability/leaching, Extrusion/pellet (1) • Density (1) • Particle size (0) • Buoyancy (0) • Hardness/fines/durability (1)
Nutrient quality, density, toxicity (4)	Optimize feed formulations to meet nutritional demands to maximize growth and production while maintaining water quality	• Digestibility/nutrient availability (2) • Attractants (0) • Palatability (0) • Nutritional requirements (NR) • Storage time (shelf life) (0) • Effect on human health/nutrition (0) • Ingredient costs efficiency (2) • Toxic factors (0)
Relationship with contributions from bioflocs (9)	Maximize contributions of natural productivity by designing complementary feeds	• Requirements (1) • Specially-designed diets (NR) • Relationship between feed and biofloc management (NR) • Feed – biofloc (NR) • Biofloc- shrimp (growth factor)(NR)
Pre- and pro-biotics (0)	Maximize contributions of gut microflora to shrimp performance	• Efficacy (0) • Strains(0)
Feeding timing, frequency, amounts (9)	Optimize feeding protocols for maximum economic return	• Automation/feed delivery/frequency (2) • Relationship with oxygen demand (0) • Demand/feed trays(2)
Sustainability - fishmeal fish oil replacement (12)	Maximize shrimp edible flesh production per pound of edible fish input	• Approach zero inclusion (2) • Alternative proteins (10) • Alternative oils/human health (2)
Sustainability of other ingredients (0)	Minimize the ecological footprint of all feed ingredients	• Toxicity factors (0) • Algal supplements (0)

Table 16. Breakout group report on shrimp health in biofloc systems. Numbers in parentheses indicate number of votes assigned to each item during the prioritization exercise for technology areas and technology gaps (NR not ranked, added after the exercise)

Technology Area	Goals	Technology Gaps
Fitness (6)	Maintain optimal shrimp health and fitness	• Shrimp condition (growth/survival) (11) • Activity – morbidity (0) • Shell quality (0) • Immune system response (0) • Stress test (0) • Baseline (0)
Disease (9)	Accurately diagnose disease and have a working understanding of significant pathogens and pathologies.	• Disease ID/diagnostics (1) • Real time Pathogen monitoring (NR) • Emerging pathogen (2) • Pathogen control (6) • Beneficial versus bad bacteria (0)
Biosecurity (6)	Exclude pathogens through effective biosecurity protocols, escapement, toxicity, and predation	• Pathogen control (disinfection) (2) • Detection/toxicity monitoring (0) • Vector/predator monitoring/management (2) • Escapement monitoring (0) • Exclusion (0) • Inputs (feed/water) (0)
Chemotheraputants (0)	Control infectious disease with safe and effective treatments.	• Approved drugs by life stage (1)

Table 17. Breakout group report on shrimp seed supply for biofloc systems. Numbers in parentheses indicate number of votes assigned to each item during the prioritization exercise for technology areas and technology gaps (NR not ranked, added after the exercise)

Technology Area	**Goals**	**Technology Gaps**
Genetic selection and breeding and Molecular biology (25)	Assure access to genetically improved stocks; Enable molecular tools for improving the understanding of the genetic basis for shrimp health and production performance	• Genotyping, molecular identification (1) • Diversity preservation (4) • Multi-species breeding program (NR) • Selection programs (14) • Heritability (0) • Marker assisted selection (0) • Genome mapping (0) • Genetic protection, Monosex (4)
Maturation systems (1)	Consistently produce desired quantities of high quality healthy nauplii cost effectively	• Broodstock feeds / pelleted (3) • Recirc systems (0) • Intensive broodstock production (0) • Spawning water reconditioning (1)
Larval culture systems (0)	Consistently produce desired quantities of high quality PL cost effectively.	• Recirc systems (2) • Pre- and pro-biotics (0) • Year round supply availability (0) • Live feed replacements (0)

Table 18. Breakout group report on shrimp economics and marketing for biofloc systems. Numbers in parentheses indicate number of votes assigned to each item during the prioritization exercise for technology areas and technology gaps (NR not ranked, added after the exercise)

Technology Area	Goals	Technology Gaps
Modeling and business planning (14)	Develop and refine accurate financial models which are flexible and user friendly	• Accessibility to all, User friendly (0) • Bioeconomic models (tied to biological performance) (7) • Inclusion of environmental sustainability (5) • Regulatory compliance costs (0) • Sensitivity analyses, risk assessment and uncertainty (2) • Geographic sensitivity (1)
Flesh Quality (5)	Demonstrate shrimp flesh quality which outperforms competition	• Contaminants (NR) • Taste, flavor (biofloc effects (3) • Organoleptic analysis (NR) • Firmness (2) • Shelf life, Melanization, hepatopancreas condition (1)
Processing (14)	Assure post harvest methods which differentiate and bring out qualities to provide a competitive advantage in the marketplace	• Irradiation (1) • Byproduct use (chitin) (5) • Automation (7) • On farm HACCP procedures – food safety (0) • Melanization control (0)

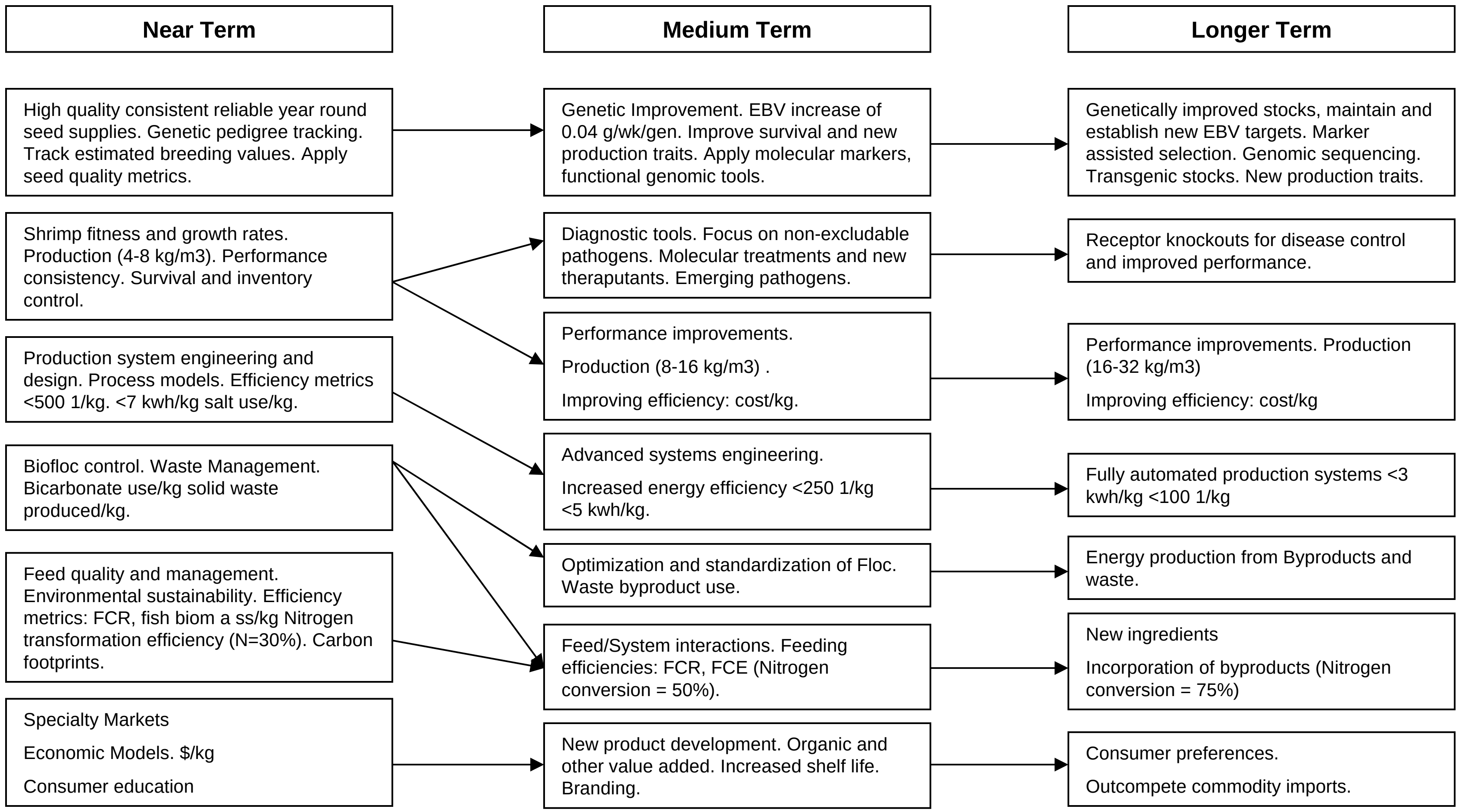
Table 19. Breakout group report on measurement standards and needs for biofloc-based shrimp production systems

Technology Gap	**What are the measurement or standards needs?**
Shrimp fitness	• Activity • Feed consumption • Systematic health screening checks • Lesions • Gut fullness/content analysis • Biochemical indices • Physiological indices (hematocrit) • Color • Stress response • Mouth and gill exams • Muscle opacity • Condition factor (weight and carapace length) • Uniformity of size • Diseases • Deficiencies
Crop biomass inventory	• Video • Activity • Sonar • Waste collection • Mortalities • Feed consumption • Stocking • Stocking mortality • Sampling (sub selections and tag and release etc.) • Oxygen consumption

Table 19 (continued). Breakout group report on measurement standards and needs for biofloc based shrimp production systems	
Technology Gap	**What are the measurement or standards needs?**
Waste management and treatment. Technologies to manage nitrogen within the system, to maximize N and P conversion efficiencies, to reclaim salt and to digest sludge.	• Filtration efficiencies • Settling efficiencies • Percent recovery of solids (solids/kg shrimp) • Percent recovery of salt (salt use/kg shrimp) • Chloride content of waste • Nitrogen utilization efficiency • Carbon, nitrogen and phosphorous modeling and budgeting • Water use efficiency • Measurement of phosphorous and other micronutrient discharge • Relationship of feeds formulation, digestibility, nutrient requirements • Micronutrient and macronutrient depletion and accumulation • Alkalinity consumed (bicarbonate used/kg shrimp) • Measuring the reduction of organic material
Genetic improvement	• Breeding value and heritability • Genetic markers • Persistence of a trait • Genetic component of growth and survival • Disease resistance • Real life commercial trials • Comparison with baseline wild stock • Genomics • PL quality (physiological)
Production unit design	• Standardize production metrics • Measurement of hydrodynamics • Heating efficiencies • Oxygenation efficiencies • Variable cost efficiencies (energy) • Lighting • Density • Unit cost (per cubic meter of capacity or kg shrimp) • Space utilization efficiencies (2 and 3-dimension) • Ergonomic designs • Personnel usage efficiency • Safety

Table 19 (continued). Breakout group report on measurement standards and needs for biofloc-based shrimp production systems	
Technology Gap	**What are the measurement or standards needs?**
Biofloc management	• Density, Turbidity, TSS, VSS, etc. • Autotroph vs. heterotroph (structure and activity) • Composition • Light and epifluorescent microscopy, image analysis • Fluorometrics • Molecular techniques (DGGE, PCR etc.) • Isotope studies (nutritional uptake, conversion) • DAPI • fluorescence in situ hybridization *(*FISH) • Stability, consistency • Reproducibility • Beneficial: pathogenic ratio • Harmful algal species (presence, abundance) • Cyanobacterial abundance and control • Nutrient composition analysis • Floc consumption rates, vitamin and amino acid availability • Automated measurements • Harvest on pre-set level • Hydraulic residence time (HRT)/Floc age • Photosynthetically active radiation availability • Fatty acid composition • Oxygen production and consumption • Floc particle size • Floc growth inhibitor (pathogens, toxins) • Floc effect on shrimp • Number of protozoans • Trophic composition • Algal inoculation success • Carbon:nitrogen ratio of floc • Standardize measurements to understand or effect management input

FIGURE 1. Initial roadmap diagram for future development of biofloc-based production systems for marine shrimp *Litopenaeus vannamei*. Examples are given of specific measurable objectives suggesting a plan for moving the technology forward over time.



Shrimp Culture Sub-Group Members

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Sub Group Members

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LIST OF ACRONYMS

C	Celsius
C	carbon
Chl *a*	chlorophyll *a*
CO_2	carbon dioxide
CZMA	Coastal Zone Management Act
DAPI	4',6-diamidino-2-phenylindole
DGGE	denaturing gradient gel electrophoresis
DNA	deoxyribonucleic acid
EPA	Environmental Protection Agency
FAO	Food and Agriculture Organization (of the United Nations)
FDA	Food and Drug Administration
GIS	geographic information system
HAB	harmful algal bloom
HACCP	Hazard Analysis Critical Control Point
HCP	heat-cool pasteurization
HHP	high hydrostatic pressure
HRT	hydraulic residence time
IQF	individually quick frozen
kg	kilogram
L.	*Litopenaeus*
lbs	pounds
m	meter
MT	metric ton
N	nitrogen
NIST	National Institute of Standards and Technology
nm	nanometer
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollution Discharge Elimination System
P	phosphorus
PAR	photosynthetically active radiation
PCR	polymerase chain reaction
pH	the measurement of the concentration of hydrogen ions in a solution
PHP	post harvesting processing
PL	post larvae
PSI	Pacific Shellfish Institute
RAS	recirculating aquaculture system
SPF	specific pathogen free
TSS	total suspended solids
U.S.	United States
USDA	U.S. Department of Agriculture
UV	ultraviolet
VSS	volatile suspended solids