Building Capacity of Land-based Atlantic Salmon (*Salmo salar*) Aquaculture in the United States

Prepared by

The Recirculating Aquaculture Salmon Network (RAS-N)
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RECIRCULATING AQUACULTURE SALMON NETWORK
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FORWARD

This Concept Paper is focused on Atlantic salmon (S*almo salar*) recirculating aquaculture systems (RAS), which are gaining favor in the US and global aquaculture industries. We are focused on salmon RAS, among other reasons, because (1) globally, most salmon are produced in coastal net-pens/cages, but suitable net-pen sites are very limited on the US coast, (2) the US imports approximately 95% of the $3.4 billion worth of Atlantic salmon consumed in this nation and is a prime target for domestic production, the latter of which is a mounting priority in national food security (3) RAS facilities are better able to control growth conditions and have improved biosecurity measures, and (4) RAS excels in addressing a number of environmental issues while reducing the overfishing of wild fish, offering a sustainable form of aquaculture and food production.

To help ensure the success of the fast-emerging US salmon RAS sector, the Recirculating Aquaculture Salmon Network (RAS-N) program is focused on developing a national public-private support network (R&D, business and economic support, workforce training, and outreach & education) for Atlantic salmon recirculating aquaculture.

It is not the intention of the RAS-N project to discourage other methods of salmon aquaculture or cast non-RAS production methods in a negative light. It is the RAS-N's consensus belief that meeting the projected future US demand for Atlantic salmon will require a variety of intensive production methods, including land-based RAS. As such, this text strives to ensure the success of the fast-growing US salmon RAS industry by identifying sector needs and priorities as well as providing recommendations for future resource allocation and external support.

Specifically, with solicited input from the industry and relevant stakeholders, this Concept Paper will (1) provide background on salmon production practices and describe the state of RAS technology in general and in particular to Atlantic salmon, (2) examine economic feasibility, (3) assess the status of available technologies, future needs, gaps in knowledge, (4) identify biology and technology bottlenecks and R&D needs, (5) pinpoint potential solutions and progress to address current topics of industry concern and (6) discuss strategies for improving workforce development, topical education, and extension.

Moreover, this comprehensive document will be dynamic and responsive to changing stakeholder needs and public perceptions and will be updated as new information is acquired in future workshops/meetings, national conferences, and other venues.

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The State of Global Atlantic Salmon Supply and Production Practices

<u>Global Atlantic Salmon Supply and Demand</u>

Globally, 2.6 million metric tons of Atlantic salmon are produced annually[1]. This represents an increase of approximately 6.5% from the prior year's production and the highest annual increase since 2014. The primary producing countries are Norway and Chile, with production also coming from Canada, the United Kingdom, and the Faroe Islands.

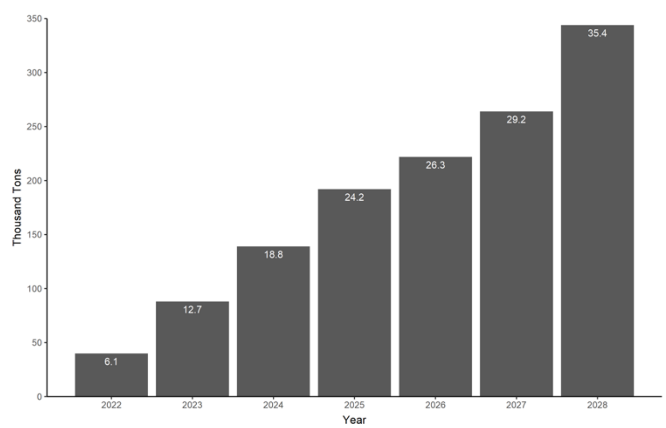
<u>Global Atlantic Salmon Production Practices</u>

The global production of Atlantic salmon is currently a net-pen/sea cage industry, supplying over 99% of Atlantic salmon for food fish production. This accounts for the majority of the 80 million tons of farmed fish globally harvested each year. This supply method, however, has limited ability to increase in scope (due to site limitations, regulatory restrictions, and environmental/pathogen challenges), while the annual demand for Atlantic salmon in the food fish market continues to grow. For these reasons, alternate production practices, primarily land-based salmon RAS operations, are being constructed, planned, and explored by some of the world's largest food fish producers and entrepreneurs interested in land-based aquaculture.

<u>Current Status of Recirculating Aquaculture System (RAS) Technology</u>

Water recirculation technology platforms and their application in aquaculture have seen extensive progress in the last decade, with new technologies and methodologies emerging and equipment supplies becoming more available and cost-efficient[2,3]. Less than 5% of salmon species, including Atlantic salmon, are produced in RAS systems, but this is predicted to rise to 40% by 2030 (Skretting Inc., personal communication, see **Fig 1**). RAS is used in various applications that include research facilities, State, Federal and Tribal conservation and production fish hatcheries, and food fish production facilities, where many benefits are gained from growing fish in a biosecure, controlled environment.

Figure 1. Projected Atlantic salmon RAS production in the US. *Indicates the corresponding percentage of projected US Atlantic salmon consumption. *Modified from Skretting data, 2020.*



<u>Current Status of Salmon RAS</u>

There are currently at least a dozen commercial ventures worldwide producing market-size salmonids in land-based RAS facilities [2] with many more in the planning phase. Remarkably, these farms did not exist 5 years ago and highlights trends that land-based RAS salmon production represents an emerging and fast-growing sector of the overall aquaculture industry, especially in the US (**Fig. 1** and below).

I. The Status of Available RAS Technologies, Bottlenecks & Resources

II.i. Review of Biological and Technological Needs

In the following pages, the primary biological and technological obstacles and needs will be discussed. The presented items have been identified by industry stakeholders from US companies invested in Atlantic salmon production and other experts from associated fields (feeds, health, and engineering as examples). In most cases discussed below, the efforts aimed at overcoming the challenges will rely on federal funding and/or other sources of investment to support additional research. A more extensive discussion of potential solutions, R&D activities and rationales will be discussed in a future 'Road Map' document, which will be completed in 2022.

Domestic Broodstock Development and Year-Round Production of High-Quality Eggs

Challenges to the Industry: At present, there are no domestic commercial breeding companies offering Atlantic salmon eyed eggs year-round for U.S. producers. A high-quality US-based broodstock and a large volume of biosecure eggs are needed to support the growing industry. Land-based farming of Atlantic salmon is projected to produce 100,000 tons of fish in 2023 and 320,000 tons in 2028. Assuming a typical 4 kg harvest size, 50 million eyed eggs available via import from overseas or domestic seed production will be needed on a year-round basis to produce 100,000 tons annually. At present, most large-scale salmon RAS operations in the US rely on eggs imported from international suppliers, primarily from one facility located in Iceland. Relying on just one source of eyed eggs is highly risky, particularly when the supply chain is subject to the vagaries of international importation regulations and logistics. Moreover, it is not clear whether the primary Icelandic source can accommodate global and US growing demand for eyed eggs as additional RAS operations come online. In addition, there are biosecurity, genetics, and performance concerns when relying on imports of salmon eggs.

Potential solutions: The identified challenges can be addressed by developing local domestic broodstock that can provide eggs year-round to the US industry with optimal performance in freshwater or saltwater RAS operations. Concurrently, selective breeding programs should be developed that include 1) a sustainable breeding program for Atlantic salmon incorporating quantitative genetic and genomic technologies, 2) a new reference genome assembly for Atlantic salmon of North American origin, and 3) a high-density, high-throughput genotyping platform customized for genomic analyses of North American freshwater and saltwater stocks. Strategies to improve the quality, quantity, and availability of domestic seed stock supplies are high priorities but must be coupled with efforts to address demand for eyed eggs by increasing hatch-to-harvest survival rates to be maximally effective. Collectively, it is expected that, by addressing these needs, we can enable domestic independence with improved performance, increased biosecurity, and readily available Atlantic salmon seed stock.

Risks Associated with the Importation of Atlantic Salmon Eggs

Challenges to the Industry: At present, there are no domestic commercial breeding companies offering Atlantic salmon eyed eggs year-round for U.S. producers. Existing and emerging land-based Atlantic salmon operations in the US are thus totally reliant on foreign suppliers for eggs. Aside from the inherent strategic risk presented by this scenario, the dependence on imported eggs presents a risk pathway that could undermine the health integrity for land-based facilities and potentially compromise market access if pathogens are introduced. Inadequate import controls at the federal or state level for egg importation threatens the health of all domestic susceptible species, cultured or wild. It is, therefore, vital that land-based Atlantic salmon producers choose their egg source(s) carefully by assessing the risks involved in purchasing eggs from each source, as the consequences of a pathogen introduction could result in economic loss through halted production, mortality, loss of markets, and potentially mandated livestock depopulation and/or facility closure orders.

Currently, to import eyed salmon eggs into the US, the eggs must meet the requirements and procedures for import established in Title 50 of the Lacey Act, as overseen by the US Fish & Wildlife Service (US-FWS). Within Title 50, the list of specified fish pathogens that must be screened is very limited. This pathogen list is less than comprehensive, leaving the importing company/entity or the receiving state to request additional testing. In addition to US-FWS import requirements, FDA may also have requirements for the health of the imported animals intended as seafood.

Potential solutions: Thought must be given to the reality that new pathogens are continually emerging, especially when novel environmental conditions present evolutionary pressure to transition from avirulent to virulent pathogen forms. Emerging pathogens will inevitably be a concern within land-based intensive salmon farming but could also occur in egg-producing facilities. Clinical diseases in US RAS facilities could occur if emerging pathogens go undetected during routine screening of imported eggs. Thus, amendments are needed to rectify procedural gaps and oversights on import controls. In addition, commercial facilities in the US would be best served by a fluid assessment program (e.g., UDSA-APHIS Commercial Aquaculture Health Program Standards, CAHPS) that focuses on real-time threats (versus a proforma checklist of pathogens) during production. Assessment and research are required to investigate and characterize potential threats through risk modeling and to develop sensitive monitoring programs for the early detection and remediation of novel fish pathogens.

Early Maturation of Atlantic Salmon Cultured in Fresh and Brackish Water RAS

Challenges to the Industry: Numerous biological and environmental factors influence the maturation process of Atlantic salmon. The breadth of possible influencing factors means that the age and size at which sexual maturation is initiated can be highly variable and this often results in early sexual maturation of farmed Atlantic salmon. Early sexual maturation is undesirable for several reasons, which include decreased growth performance and feed efficiency, reduced product quality (filet texture and color as examples), and increased susceptibility to disease. All result in reduced harvest yields and commercial value of the fish, both of which are a major source of economic loss. The traditional (net-pen) salmon industry has partially resolved the issue of early maturation through net-pen photoperiod manipulation, but it remains a significant problem for land-based Atlantic salmon producers. This is because of the novel and optimal rearing environment of RAS and the factors therein that can instigate salmon populations to mature. To date, very little research has been conducted that specifically examines early salmon maturation in RAS, and the effect on land-based farm economics has not been adequately assessed.

Potential solutions: Research is needed on other potential influencers of maturation that are specific to RAS, in addition to the photoperiod and water temperature variables mentioned above. Controlling these factors to slow the onset of maturation may compete with the aim of increasing body growth, therefore a balance must be discovered and determined through extensive research. This knowledge will enable the industry to develop effective standard operating procedures for optimized production.

Additional approaches to eliminate early sexual maturation (besides the traditional environmental manipulations) is using an all-female population or reproductively sterile fish. The use of a monosex all-female population is a promising approach for preventing early maturation in RAS-grown Atlantic salmon, as early maturation is associated with male Atlantic salmon. In reproductively sterile fish, the most practical approaches to sterility are production of triploid salmon (now practiced commercially, but methods must become 100% effective with fewer adverse side effects) or the use of non-genetic modification (non-GM) gene silencing to disrupt early development of the gonads. Non-GM gene silencing is a very promising alternative to generating infertile fish but is still in the research phase. More details on reproductive sterility are provided in the next section "Technology to Produce Reproductively Sterile Salmon".

<u>Technology to Produce Reproductively Sterile Salmon</u>

Challenges to the Industry: 'Normal' Atlantic salmon grown under optimal farm conditions enabled by RAS (e.g., constant optimal temperature and photoperiod, dissolved oxygen, efficient feeding regimens, etc.) tend to reach sexual maturation before attaining desired harvest size. The consequence is slowed growth, diminished fish health and lowered flesh quality.

Sterile animals do not divert energy resources from body growth to the resource intensive process of gonadal development. Therefore, sterile farmed salmon can be expected to grow faster and have better quality muscle [meat] growth as they do not undergo sexual maturation. Sterile salmon provide other advantages as they are better suited for intensive rearing and provide protection of proprietary genetics.

Potential Solutions: Triploidy and gene silencing are the two most attainable solutions for inducing sterility at early life stages. Sterility is traditionally achieved through induction of triploidy, by applying a physical shock to eggs after fertilization resulting in functionally sterile offspring with one paternal set of chromosomes and two maternal sets. Triploidy is an effective method, with sterilization rates nearing 90% or more per batch of eggs. However, relative to normal (diploid) fish, pressure-induced triploid Atlantic salmon are generally recognized as displaying inferior growth, performance, disease resistance, and hardiness, especially when reared in suboptimal or stressful conditions. Triploid Atlantic salmon have thus not been readily accepted by the aquaculture industry and more research is needed to optimize this approach and gain widespread use. Although pressure is the most common, triploidy can also be induced via rapid changes in water chemistry or temperature or by crossing diploid brood with tetraploid (4n) brood, by which they naturally receive a 1 set of chromosomes from the diploid parent and 2 sets from the tetraploid parent. Anecdotal information suggests that triploids produced by other means may be more robust than those produced via pressure treatment.

Other promising sterilization strategies involve the disruption of germ cell development or elimination of germ cells via genetic modification (GM) and non-GM approaches. In one non-GM method, development of special cells (primordial germ cells, PGCs) that ultimately form mature eggs and sperm in ovarian or testicular tissue, respectively, is temporarily disrupted, which prevents formation of gonads, leading to sterile fish. This effect is achieved when compounds, named morpholinos, are introduced to salmon eggs via microinjection or bath immersion. Genes are not altered or modified (during this process but gonadal development is nonetheless disrupted. This approach has been successfully used in research trials with several species, including Atlantic salmon. Optimization protocols are needed to achieve 100% sterilization rates and facilitate automation and commercial scaling this approach. GM methods of disrupting PGCs are also technically feasible, but these approaches would undoubtedly face considerable hurdles in regulation and public perception.

<u>RAS-Specific Salmon Diets and Alternative Sources of Proteins to Replace Fish Meal/Oil</u>

Challenges to the Industry: Atlantic salmon diets in the U.S. utilize a wide scope of locally available raw materials, including terrestrial, plant, marine, and novel proteins, and oils. Industrial fishmeal has, historically, been considered the gold standard dietary protein but is also considered environmentally and economically unsustainable. Thus, a partial shift toward using trimmings meals and oils from marine sources has developed. Pressure to find and utilize alternative proteins has dramatically reduced our reliance on fishmeal. Several new, domestic ingredients have been developed, recently, in the US, including a specialty soy concentrate, high-protein soybean meal, protein concentrate made from barley and insect meals. Product development has also focused on finding new omega-3 sources to replace/supplement fish oil which is a key ingredient that is in short supply. Aqua feed companies have replaced some fish oil with vegetable and poultry oils. To ensure that the high omega-3 levels are maintained in the salmon, a few commercial producers of algae products have emerged and are in commercial production. In this way, high levels of omega-3 fatty acids can be maintained in the feeds and the farmed salmon. The price of algae products is high but with increasing production of algal products, and increasing cost of fish oil, the price of algal oil is becoming competitive with fish oil. Through the hard work and collaboration by aqua farmers, ingredient producers, nutritionists and feed companies, the industry challenge to find more cost-competitive ingredients to the declining supply of fishmeal and fish oil is being met with success of several domestic solutions.

Historically, the typical commercial diet designed for Atlantic salmon has focused on sea-cage farming applications. Feeds are made using extrusion technology, where a process of high temperatures and high pressures produces a stable storable palatable pellet devoid of pathogens. The composition of current commercial salmon diets is focused on providing diets that are nutritionally optimal for the fish and cost-effective. However, these standards were based on traditional salmon farming, when less was known about what constituted an optimal salmon RAS diet. In sea pens, overfeeding a nutrient such as protein or phosphorus was more of a cost concern as these nutrients are excreted into the open ocean, but in addition to the cost, in RAS these un-used nutrients strain the filtrations systems. For example, uneaten/excreted materials are not diluted or flushed in RAS as they are in net-pens, and therefore have a magnified effect on the culture system. Diet composition can significantly affect water quality, solid waste removal processes, and biological conversion cycles [bacterial/microbial digestion of waste] in RAS, all of which can impact salmon health, growing densities, and final yield.

Potential solutions: RAS facilities provide an opportunity to carefully monitor and develop feeds, optimize feeding behavior, and improve feed conversion ratios, while monitoring effects on water quality. New knowledge about raw materials and how they behave in the cold-water salmon RAS environment continues to be gained. Specifically, research addressing the effect that specific feed ingredients have on the consistency of fecal waste, use of alternative digestible and nutrient-rich proteins (insect meal, bacterial meals/oils, and plant concentrates as examples) to replace fish meal/oil, taste and color effects of novel ingredients, and identification of immuno-modulators (e.g., yeast), and maintenance of gut microbial health are of high importance. Diets for RAS are formulated to contain just enough of each essential nutrient for optimal performance, with no excess nutrients that will have to be processed by the filtration system. These diets should be specific to strain of salmon, life stage, water salinity and the rearing facility itself.

<u>Fish Health Management in RAS</u>

Challenges to the Industry: Aquaculture, like other agricultural processes, is constrained by disease and requires appropriate management practices. Managing health and disease in aquaculture operations can be especially challenging and new challenges may arise with the adoption of novel technologies. Older husbandry guidelines for raising salmon in traditional production systems are not applicable for next-generation aquaculture systems like RAS. Research focused on a wide range of environmental parameters (alone and in combination) that ensure optimal growth performance, health, and welfare is needed for RAS salmon culture. Fish health management is generally an exercise in identifying and mitigating infectious and environmental risks to health and welfare. Infectious threats in RAS must be managed in both the fish themselves and in the closed environment (i.e., recirculating water and tank system infrastructure). Just as RAS provides novel environments for Atlantic salmon, these systems also provide novel conditions from which unknown or opportunistic pathogens can emerge. Similarly, intensive salmon production in RAS provides unique physiological and metabolic challenges, which have the potential to induce pathologies not normally observed in traditionally raised salmon. Therapeutants for disease must be effective and RAS-friendly, meaning vital bacterial processes in the life support systems are not impaired through therapeutant administration. RAS holds the possibility of a zero/reduced risk due to pathogens, but risks associated with egg and juvenile importations, or certain water sources still exist.

Potential solutions: The high level of RAS environmental control and the ability to screen new water, eggs, fish, food, etc. provide unparalleled biosecurity and control against environmental risks or anomalies. Infectious threats in RAS are managed through biosecurity practices for pathogen management and culture environment optimization (e.g., ozonation or UV) that promote healthy, resilient fish populations. Procedures and products (vaccines, novel feed ingredients, medicated feeds, water-based sanitizing agents, etc.) are extant or in development to prevent or respond to disease, but not all are approved or commercially available for use in RAS. Research demonstrating the safety and effectiveness of these products is needed to secure the appropriate regulatory authorizations (i.e., FDA or USDA) for their use in land-based salmon culture. Areas that also need additional support include increased biosecurity of egg imports, innovative pathogen identification procedures, defining environmental conditions (alone and in combination) for various life stages of Atlantic salmon from egg to broodstock or market size (5-6 kg), and the application of probiotics aimed at improving water quality and as an additional preventative measure for bacterial infections.

Imported eggs are disinfected upon arrival to prevent transmission of pathogens found on the surface of the egg, however these methods do not address transmission of pathogens within the egg. Confirmation on whether pathogens are transmitted from within the egg needs to be addressed to create a more robust strategy in pathogen screening for imported eggs. New diagnostics including rapid, molecular-based diagnostic tools that can be used by personnel with minimal training and limited laboratory infrastructure (farmer-friendly tools) are also needed. Older husbandry guidelines for raising Atlantic salmon in traditional production systems are not 100% applicable for land-based RAS production, and therefore research focused on a wide range of environmental parameters is needed to ensure optimized growth performance, health, and welfare. Lastly, the use of probiotics is a promising tool for a range of production related issues that include pathogenic control and life-cycle bottlenecks.

Technologies to Maximize Growth from Hatch to Harvest

Challenges to the Industry: Achieving optimal Atlantic salmon growth, health, and welfare in RAS is largely a function of selecting and maintaining water treatment processes that optimize the fish culture environment. To this end, it is imperative that RAS operators have a detailed understanding of technological influences on salmon growth and water quality limits and thresholds. Proven technologies that maintain suitable conditions for Atlantic salmon production in land-based systems have already been partially adopted, and there is need for refinement, optimization, and development of new solutions. In addition, Atlantic salmon are currently reared in RAS using fresh, brackish, and full-strength sea water, depending on fish life stage and facility location. Therefore, fish production and system design requirements must be specific to life cycle and farm-specific water quality conditions. For example, salmon health and as well as microbial communities of the life support systems are impacted by water chemistry, water temperature, and tank hydraulics (i.e., “swimming conditions”).

Gas conditioning technologies that minimize carbon dioxide (CO_2) accumulation and maintain dissolved oxygen levels near 100% saturation are critical, as are biofilters that efficiently convert toxic ammonia (solid waste and urine are high in ammonia) to nitrite and ultimately to the less toxic nitrate compound. Although nitrate is the least toxic of the nitrogenous compounds, it is not actually known what levels are safe and/or unsafe for Atlantic salmon and as water re-use increases nitrate must be also treated and removed. Additionally, solid waste removal processes that limit accumulation of fine particles are also important for maximizing salmon growth. Moreover, better Atlantic salmon growth, and in some cases lower incidence of early maturation by increasing age-specific swimming speeds has been reported, but optimal speeds are not really known. Finally, a standard method for accurate fish size assessment in RAS (and other land-based systems) is physical capture of a subset of the population for individual or total population weight assessment. This approach enables accurate tank density calculations and feeding regimes, but temporarily disrupts culture conditions, inhibits feeding and growth, or causes physical (handling) damage to the skin and fins of sampled fish. In addition, current automated feeding technologies are not able to provide precise stage-specific feeding rates that minimize feed waste.

Potential solutions: As noted above, proven technologies to maintain safe conditions for Atlantic salmon RAS production in land-based systems are available and in use; however new solutions/technologies that enhance production, cost-effectiveness, environmental friendliness, sustainability and, importantly, animal safety and welfare could bolster the emerging US salmon RAS industry. Specifically, technical solutions that address the concerns/challenges outlined above are needed. For example, capital and energy efficient gas conditioning systems that achieve CO_2 levels supportive of rapid Atlantic salmon growth are necessary and may require further development, particularly for saline RAS. Land-based Atlantic salmon RAS can be sited (indoors) in very warm (e.g., Florida) or very cold (e.g., Wisconsin) climates which, along with the heat generated by pumps and other machinery, can significantly influence the ambient temperature and, correspondingly, water temperature. Integrated water chilling and/or heat exchange technologies capable of efficiently adjusting water temperatures, even under the limited water exchange rates characteristic of RAS, will help maximize growth and, in some cases, limit early maturation. However, only limited research has been carried out in RAS to pinpoint ideal thermal conditions for salmon growth at various life stages and salinities. Thus, research to define optimal stage-specific culture temperatures is needed to complement the technical advancements in RAS cooling/heating. Other water treatment techniques/technologies, such as ozonation for freshwater culture and protein skimmers/foam fractionators, as well as fine core membranes (for better removal of fine solids from feeds, etc.), have shown promise for enhancing salmonid growth in RAS via improved water quality. However, research evaluating the direct effects of these technologies on water quality and Atlantic salmon growth in commercial RAS is limited and deserves greater attention. In addition, culture tank designs for RAS that create hydraulics (i.e., water velocities) that effectively exercise the fish should be studied (especially for post-smolt to market-size salmon) and implemented in existing and future salmon RAS facilities. Swimming speeds that strike a balance between feasible engineering and optimization of Atlantic salmon growth, health, and welfare should be established via funded research for use by the industry. Likewise, the infrastructure to accommodate video, imaging and behavior monitoring systems used for fish size and health assessment and feeding efficiency should be considered in RAS facility design.

<u>Microbiomes in RAS: Identifying and Optimizing Microbial Communities Involved in Biofiltration</u>

Challenges to the Industry: The operational success of RAS depends directly on system microbial community activities, since water continuously flowing through the system must be processed relatively quickly by microbes in the biofiltration units before returning to the rearing tank. This is unlike net-pen aquaculture, in which waste is primarily diluted or naturally degraded. Without adequate remediation processes, recirculating water suffers with decreased water quality, primarily through the accumulation of fish waste and uneaten food[4]. Feces, urine, and other wastes contain ammonia (toxic to fish), which, through the process of nitrification, is converted to nitrite (toxic as well) and eventually to nitrate (the safest of the 'nitrogenous' compounds at low levels). This means that the time needed to reduce ammonia and nitrite levels to the safer nitrate compound is a major limiting factor to achieving higher RAS tank production. As water re-use is increased, nitrate levels reach unsafe levels, so efficient microbial-based nitrate reduction methodologies (i.e., denitrification) are also needed. High levels of toxic sulfides (e.g., hydrogen sulfide) can also occur as a by-product of microbial activity in RAS, especially in brackish and saltwater RAS, and its occurrence must also be prevented. RAS technology manages water quality by integrating filters and other components to capture and remove nitrogenous and organic (solid) waste products before returning water to the production tank.

While this enables safe high-density culture of salmon, solid waste accumulation still presents a series of challenges in Atlantic salmon RAS. A serious bottleneck is the need to store and dispose high volumes of accumulated solid wastes. For example, 1 ton of feed will produce 1 ton of salmon while generating 1.5-6.5 tons of organic/sludge waste, depending on percentage of dry matter in the sludge. As most US salmon RAS farms plan to produce upwards of 10,000 tons fish annually, a solution to treat the tens of thousands of tons of solid waste (typically salty waste) generated by each operation must be found. Thus, treating solid wastes from RAS systems is a major physical bottleneck (and expense) in the rapidly expanding U.S. and global RAS Atlantic salmon industry.

Potential solutions: In an optimally engineered RAS system, the biological output (waste) is remediated by optimized microbial communities with specifically tailored microbial consortia (i.e., optimized for the salinity, temperature, feed type, etc.). Highly engineered RAS are constructed to optimize water use, often achieving a 95% to 99% reduction in water consumption compared to more conventional methods[4]. The faster and more efficiently the 'consortium' of microbes in the RAS filters clean water, the more fish that can be safely cultured in a tank and the less water that must be discharged. Identification of microbial communities in RAS enables targeting, growing, and inoculating the most beneficial microbial species or consortia in tank systems. In this way, the microbes that best perform key biochemical processes (called nitrification, denitrification, and anaerobic ammonia oxidation [or anammox]) can be harnessed and utilized in RAS water clean-up and removal of sulfides and nitrogenous compounds. Modern tools of genomics, functional genomics and metabolomics are now available for identifying and understanding the functions of the microbial communities in RAS, and for developing tools that monitor the stability and health of these communities[5–7].

Future salmon RAS design would benefit from understanding the roles of these core taxa and from capitalizing on their structure, dynamics, and activities that are responsible for system efficiency, as well as selectively enhancing the function of the most beneficial of the microbial communities in RAS. R&D is underway to integrate these microbial consortia/processes into commercial salmon RAS, but additional studies on the microbial aspects of RAS waste remediation, as well as technology transfer to industry, are still needed.

Likewise, environmentally sustainable treatment of marine organic/solid waste from salmon farms, via the use of 'methanogenic' microbes for the on-site conversion of solid waste to fuel-grade biogas composed primarily of methane, is being optimized. Unlike typical municipal or non-fish animal crop solid waste, salmon waste is rich in nitrogen, salty and cold, which complicates the process. The approach used for salmon RAS reduces sludge volume, converting it to combustible biogas that can be used directly in the farm as a cooling/heating source or in a methane-driven generators. The system requires minimal energy input (obtained from the methane produced) and negates costs associated with transportation of the final product because it can be used on-site. However, it does require the development of very specific (methanogenic) microbial consortia, which work in anaerobic conditions (i.e., without oxygen), that are able to convert sludge from a cold saltwater salmon farm. Initial R&D work and large-scale trials in commercial salmon farms have already proven the feasibility of this approach, but it must be further optimized and more widely implemented in salmon aquaculture, where sludge volumes are extensive. Not only is costly and often environmentally harmful solid waste storage/disposal avoided by bioconversion, but the process generates value-added biogas for offsetting the energy consumption of the farm via heating/cooling water and/or electrical generation. Additionally, inclusion of decoupled hydroponic greenhouses or aquaponics can further maximize nutrient capture, reduce overall waste discharge, and improve economic feasibility, but more R&D is needed to effectively utilize sludge, especially saline sludge, towards crop cultivation.

<u>Optimized Engineering and Operation of RAS Platforms</u>

Challenges to the Industry: Commercial farms that produce market-size Atlantic salmon in RAS use large capacity water treatment processes to maintain good water quality for the fish, often flushing culture tanks of 500-5000 m^3 (132,000-1,320,000 gallons) at least once every 30-60 minutes when producing market-size Atlantic salmon. Fortunately, the optimum water quality requirements for Atlantic salmon production are generally understood, at least for major metabolites (e.g., oxygen, carbon dioxide, nitrogenous compounds, organic/suspended solids, and hydrogen sulfide). Based on this knowledge, RAS farms should be designed and engineered to maintain the best water quality for fish growth/performance and welfare when operated at high tank densities.

Few existing RAS facilities have achieved this to date, but the design of RAS for salmonids continues to evolve, particularly as larger systems are built. Upscaling technologies in RAS has not always worked. Several new RAS facilities have experienced catastrophic fish losses, and it is unknown if they have consistently met their stated production goals. For example, some farms that originally claimed their RAS would produce 1000 MT/yr. or 600 MT/yr. have reported production of only 700 MT/yr. or 400 MT/yr., respectively. Hence, it is obvious that challenges remain and there are lessons to be learned, especially in key areas such as (i) accurately predicting fish growth and maintaining optimal water quality at high tank densities and (ii) avoiding design and operation mistakes that compromise biosecurity, fish husbandry, flesh/filet quality (e.g., off-flavors), marketing, and/or business management.

Several RAS platforms are now commercially available (e.g., circular versus raceway tanks; multiple approaches to solid waste removal, etc.). Some elements are standard in all RAS designs (i.e., oxygenation systems, CO2 removal strategies, multi-faceted waste removal) and allow for high stocking of fish per tank, but developments in oxygenation and CO_2 control continue. Improvements in dissolved gas control are important because dissolved O_2 and CO_2 are both critical factors impacting fish performance and energy use in RAS. In addition, although most biofilters remove wastes as expected, some continue to be installed that cannot consistently control ammonia and nitrite at safe levels when large amounts of food are added to the system at levels projected in the design plans. The reasons for this vary, from design to operational errors. Saltwater salmon culture (versus fresh or brackish water) also has important effects on RAS process efficiencies and design and must be considered in the engineering scheme. In general, substantial differences appear to remain in the performance, footprint, fixed and variable costs, and reliability of the various RAS designs for salmonids that are now in operation.

In addition to the primary RAS water treatment processes, large commercial Atlantic salmon RAS farms must optimize the engineering of systems for large-scale fish transfer and grading, purging and humane slaughter, feed delivery, water flow and hydraulics, denitrification, foam fractionation in brackish or seawater, low-dose ozonation for water quality control, alkalinity addition, heating/cooling of water and air, capturing and dewatering biosolids, water supply, and wastewater treatment before discharge or groundwater injection.

Potential solutions: Operational salmon RAS farms have advanced greatly in terms of design, engineering, production capabilities, waste remediation, cost-effectiveness, and sustainability (as has land-based RAS in general). But improvements are still needed, and the following developments and R&D efforts are of critical importance to maximize sustainable cost-effective production: (1) Innovative engineering systems are being tested to recover biosolids (solid waste) from RAS, biologically treat it and reduce their volume and salinity (and odor) for more efficient storage and/or discharge, (2) Combining RAS and hydroponics can increase resource utilization by transferring waste from the land-based system to a greenhouse for plant cultivation, but this has its own challenges, including the desalination and remineralization of solid waste as well as a better understanding of nutrient bioavailability and demand once scaled(3) Hydraulics and waterflow should be optimally engineered to prevent the accumulation of organic waste that has already shown to generate toxic levels of hydrogen sulfide and result in sudden, major mortalities, (4) Improved fish transfer systems are being engineered to move fish through 10-40 cm (4-16 inch) diameter pipes from tank-to-tank, sometimes through graders and counters, and to purge and slaughter areas. Careful fish handling is imperative at all stages (i.e., from juvenile to harvest sizes), particularly with between $100,000 and $1 million in livestock in a single culture tank, and (5) RAS are being designed to use and discharge less water per unit production than in the past, but discharging less wastewater often requires more clean-up (and more time) since accumulated wastes are concentrated into less volume and strict regulations place limits on effluent discharge. Several currently operating salmon RAS farms have already designed innovative treatment designs to address their discharge levels, so they adhere to restrictions.

The salmon RAS industry is growing faster than ever before while building larger units. Building larger RAS provides economies of scale to reduce both fixed and variable costs. When the same turn-key supply company or farming company is involved with each successive RAS build, it is hoped that this continuity in the design and operation practices will allow improvements in each iteration of the technology, standardized equipment, and construction methods, and in due course reduce risk, optimize performance, and/or reduce capital and overall operating expenses.

Techniques to Minimize Off-Flavor (Geosmin and MIB) in Harvested Salmon

Challenges to the Industry: A common challenge encountered when producing Atlantic salmon and other species in RAS is the tendency for fish to bioaccumulate earthy and musty off-flavors that are unacceptable to consumers. Two compounds, geosmin (GSM) and 2-methylisoborneol (MIB), produced by bacteria that commonly live in the tank systems, are typically associated with off-flavors that are of greatest concern in RAS-produced salmon (and other species). These unpalatable flavors must be remediated before RAS-produced salmon are harvested and sold into the marketplace. Failure to do so will likely result in a less desirable product, lost revenue, and negative consumer perception. At present, the only proven method to eliminate off-flavor from RAS-produced salmon is relocation of fish from the production tanks to separate "purge" systems, which flush clean water through the tanks for days to weeks while also withholding food (a process known as depuration). This practice is labor intensive, stressful to the fish and results in economic loss due to loss of fish weight during the process.

Research has offered insight on how to achieve lowest residual off-flavor levels in Atlantic salmon flesh and how to clean tank systems prior to stocking to eliminate/reduce off-flavor bacteria. These suggested procedures, however, are typically not in line with cost-effective commercial practices because they disregard time and expense commitments and the large water volumes needed may not be readily available. Additionally, most of the depuration water must be discharged to the environment, creating challenges. Adoption of standard operating procedures (SOPs) that limit the duration of the depuration period is desired because extended off-feed periods result in weight loss and reduced lipid content of fillets, which equates to reduced revenue for the farmer. As such, additional research is needed to refine standard operating procedures that are more cost- effective for Atlantic salmon depuration. Research identifying the bacterial source(s) of GSM and MIB and the variables that increase production of these compounds in RAS and their accumulation in Atlantic salmon fillets would prove valuable in addressing this bottleneck to Atlantic salmon production. Using microbiome identification/manipulation approaches will be beneficial to understanding the diversity of the GSM/MIB producing microbes, their dynamics and lead to developing new approaches to the mitigation of the source microorganisms.

Potential solutions: SOPs are available to industry for purging off-flavors from pre-harvest RAS salmon and treating/disinfecting tanks post-harvest to eliminate bacteria sources from production systems. However, there is room for improving the efficiency and cost of current SOPs. Experiments are underway to evaluate variables that may increase the metabolism and release of off-flavor compounds from market-bound Atlantic salmon[8], as well as those that may reduce (e.g., decreasing off-flavor bacterial levels in the water supply) or hasten reduction (e.g., swimming velocities, dissolved oxygen concentrations, water temperature) of GSM and MIB. Several technologies and approaches have shown promise for off-flavor remediation in the primary RAS production system. For example, anaerobic zones of RAS, such as denitrifying reactors that contain waste sludge, have been found to absorb off-flavor compounds. Batch dosing of peracetic acid has also been found to reduce off-flavor at certain concentrations and other approaches, such as ultrasonically induced cavitation and aeration/degassing techniques, have shown promise in experimental settings. Further, approaches utilized in the potable water industry may be applicable in RAS but have not been extensively evaluated. These include advanced oxidation process (AOP) technologies, such as high-dose ozone followed by ultraviolet irradiation, electrochemical AOP, bacterial-based bioremediation and activated carbon filtration. Some trials investigating AOP and bacteria to reduce salmon off-flavors are in progress now[9]. Solutions to off-flavor remediation in RAS production systems may also involve manipulation of the microbiome to eliminate off-flavor producing bacteria. Identification and development of bacteria consortiums that contain microbial species that can act as antagonists to specific off-flavor-producing bacteria have been discussed. Further, although published research is not available in this area, diets containing ingredients that influence the RAS microbiome or provide nutritional attributes that can limit off-flavor uptake are being considered.

II.ii. Review of Non-Technical Barriers and Areas of Concern

Economic Analysis and Feasibility of Atlantic Salmon RAS Production

Challenges to the Industry: Land-based RAS salmonid production represents an emerging sector of the overall aquaculture industry. While the economics of nearshore and offshore salmon aquaculture have been extensively studied[10,11], there is limited published literature on land-based salmon production in RAS systems. RAS technology poses unique economic challenges relative to traditional net-pen salmon aquaculture, such as high capital investment costs, particularly for small-scale projects, few financially successful models at the commercial scale, off-flavor issues, and higher risks of catastrophic inventory loss. In addition, technological advances related to production (e.g., domestic US brood stocks, induced sterility technologies, RAS specific fishmeal/oil-free alternative diets, improved diagnostics, RAS platform improvements, etc.) which may result in more cost-effective production are still in the R&D stage and have not been fully implemented.

Potential Solutions: U.S. production of salmonids in RAS has the potential to create jobs resulting in positive economic impacts to local communities, reduce the overall U.S. seafood trade deficit, and minimize environmental impacts when appropriately sited[12]. While land-based production of salmon was not included in the analysis due to the lack of available information, Lipton et al [12] estimated the total economic impact of salmon produced in net pens in the US was over $1.1 billion in 2015. To explore the economic feasibility of Atlantic salmon production in RAS, RAS-N economists, in collaboration with extension, research, and industry partners, have developed a financial model to simulate RAS operations. The financial model projects Net Present Value (NPV) for a hypothetical 5,000 MT firm over a 14-year time frame. Expected minimum and maximum costs for nine capital investment cost categories and twelve operating cost categories were provided by RAS-N survey respondents, academic partners, and others familiar with the industry and were deemed to be plausible. These minimum and maximum expected costs were used to construct a range of input values for each cost category. Key market and biological parameters for the financial model include market price ($10.14/KG per Nasdaq index of head-on gutted [HOG] Atlantic salmon on March 2, 2022), the mortality rate (16% per Freshwater Institute), and discount rate (8.76% per literature review of finfish aquaculture[14]). The financial model uses Monte Carlo methods along with capital and operating cost uncertainty to calculate the average NPV from 5,000 simulations. For the hypothetical 5,000 MT firm financial model using the price and survival listed above, the average NPV is -$45.2 million.

There has been an ambitious industry push to achieve greater scale, with planned projections exceeding 100,000 MT for multiple firms. For firms with smaller production scales, there has been a focus on value-added products. Our financial model results, in conjunction with the emphasis on production scale and value-added products, do raise concerns about the financial viability of small-scale firms without price premiums or value-added products.
To determine how plausible changes in the market and production might affect NPV and the viability of a RAS industry entrant at the 5,000 MT level, an analysis was conducted for a 5,000 MT facility with a 50% price premium (increasing from $10.14/KG to $15.21/KG), and with the same price premium combined with a reduction in mortality from 16% to 3%. NPV is positive in both cases, with an average NPV of $28.8 million with a price premium and an average NPV of $63.1 million with both a price premium and a mortality reduction. There was no analysis done for value-added products due to the variety of value-added products in the marketplace and the uncertainty associated with their production costs and distribution to retail markets.

In summary, the baseline financial model's negative NPV is unsurprising given the current industry emphasis on increasing production scale and/or producing value-added products. However, there may be reason for optimism at the 5,000 MT scale, with positive NPV associated with potential price premiums and mortality reductions. The findings in this report provide support for further research on the impacts of the potential of price premiums for RAS-produced Atlantic salmon. Research into price premiums is a major focus of upcoming economics and marketing work in the $10 million USDA grant "Sustainable Aquaculture Systems Supporting Atlantic Salmon" (SAS^2).

<u>Education, Career, and Workforce Development for Atlantic Salmon RAS</u>

Challenges to the Industry: Career opportunities in RAS are diverse, ranging from facility technicians or managers to positions in supporting fields including processing, sales and marketing, aquaculture technologies, engineering, animal health and welfare, research and development, and extension services. Most positions are multidisciplinary, requiring comprehension of biological and technical skills common to aquaculture production. The RAS industry is especially challenging because it involves highly technical specialized and niche skills unique to land-based systems. During the 2020 RAS-N Workshop participants noted skills in the following areas were of value in a commercial facility: water quality, fish production/animal husbandry, engineering, feed management, operational maintenance, and biosecurity protocols. Likewise, supporting industries, such as health diagnostic and feed technology companies, express a need to recruit individuals that meet highly specific job criteria unique to those industries.

Finding people with the necessary skills is a major constraint to production across aquaculture sectors, where securing a well-trained workforce is prone to several bottlenecks including low recruitment with little retainment[15–18]. Aquaculture, generally, has poor visibility among youth and adults as a potential sector for jobs and careers and there are few opportunities to gain relevant experience. Of the available university courses and programs with practical and operational training, training capacity is often limited by the species relevant to a particular state or region, and would thereby also define the production system(s) individuals are trained in.

Basic aquaculture skills and knowledge can easily transfer from other aquaculture practices (ponds, raceways, cages) to land-based RAS production, but it would not ensure industry-relevant skills. Presently, industry provides a high degree of in-house training for new employees, often stating they can teach fish [biology] to somebody who knows the mechanics and vice versa. Methods for hiring and training employees shared by stakeholders include seeking new hires from other labor pools (maritime merchant services and milling industries, as examples) to train in-house or recruiting new hires from a training program (although there are few, as mentioned). With the promise of 100^{+} new jobs by larger commercial companies, this approach may be insufficient to meet the rapidly growing labor demands in the US and at some specific facilities. Additionally, in-house training requires investment of time and money in upskilling or reskilling new employees who are traditionally difficult to retain.

The expansion of domestic aquaculture production in the United States, more than ever, necessitates a skilled workforce than what currently exists[19,20]. Unfortunately, the funds and resources to support, expand, and maintain training programs have been difficult to maintain or attain. This has left the aquaculture industry vulnerable, as workforce development has not been strongly pursued on a national or regional level. Only recently, have we seen stronger initiatives to address gaps in training and education through funded projects by the National Science Foundation (Award 1764383), National Sea Grant Office (NOAA-OAR-SG-2019-2005963), and the North Central Regional Aquaculture Center (2014-28500-25753).

Potential Solutions: The long-term solution is to enable and provide career readiness for current and future workers with skills the RAS industry needs now and later (as RAS technologies are rapidly evolving and expanding as next generation systems). Important partners for effective workforce development programming include industry, university extension and education specialists, and federal, state, and local agencies. Workforce needs can be initially addressed in several ways. First, work with partners to identify skill competencies, complementary skills and labor pools needed for commercial RAS jobs using a workforce labor assessment. Second, support programs across multiple education levels to develop RAS skills and promote careers in aquaculture. Success requires defining job roles and improving educational pathways (degrees, training, certificates, etc.) through experiential, hands-on learning, training opportunities and diverse age-appropriate curricula that align well with the skills and needs of industry. Third, increase training capacity, scope, organization, and reach of workforce development programs and aquaculture courses. Effective partnerships and synergistic programming would guarantee that the competency base of participants was equal in skills and knowledge, producing a stronger, more consistent workforce. Fourth, it is important to recognize some of the highly skilled workforce needs of research-oriented industries that support RAS facilities, which include diagnostic testing, RAS engineering and system design, feed supply and nutrition. Career positions in these industries often require advanced degrees and experience in several fields of study.

Therefore, education and extension programs must be broad in approach to the learners they reach including both primary through higher education students and programs aimed at older age groups. Training should focus on education and workforce readiness by providing skill development and hands-on experience through internships and apprenticeships, which prepares and places learners in related jobs following their training. Expanding existing and creating new programs will help increase that visibility consistently from age 5 through adulthood. Finally, attention must be paid to industry's proprietary concerns regarding their facilities. Successful training for careers in RAS systems will require building trust leading to open dialogue among industry and training providers (labor departments, universities, certificate/apprenticeship programs, etc.)

Extension

Challenges to Industry: The role of extension is wide, inclusive of information sharing, capacity building, technology transfer, and movement towards sustainable options. Where there are barriers to technology, there are also barriers to information for industry, consumers, educators, legislators, and more. In the case of land-based Atlantic salmon production, industry is well-informed of current technologies and actively participates in demonstration research projects designed to address technical bottlenecks. Technology transfer is already an integral part of their success, as demonstrated by projects concerning waste management and off-flavor removal. The challenge in extension is that consumers, public, and decisionmakers lack an understanding of aquaculture and its growing sector of land-based production. The aim is to provide information so that the choices made in a food aisle, in a public hearing, or in any other public discourse can be made with greater confidence.

Potential Solutions: There are several tools in the extension toolbox that can be used to better inform non-industry stakeholders about land-based production and RAS technologies. The industry is very new and there are few operations in production or construction, therefore, extension activities are currently more limited. The suggested approach is to initially engage using more traditional approaches to provide a baseline in programming. The following are recommendations:

Increase public awareness and literacy of land-based salmon farming using video content that provides a better understanding of the salmon RAS industry and its innovative technologies. Providing transparency while showcasing its contribution towards a sustainable domestic supply chain is the first step extension can make in helping people make decisions. Public desire for this content is well demonstrated through Maryland Sea Grant, whose YouTube analytics indicate that viewer engagement is greatest with videos covering aquaculture, seafood technology, and fish farming. Similar measurements of video engagement will need to be tracked by extension so that they can be evaluated for their effectiveness. As we learn what is most engaging to audiences, material can be tailored and augmented to meet specific needs and settings. Video can also be used to provide online options for group and field day viewings of research labs and demonstration facilities. Additionally, a legislative outreach plan should be developed to communicate, market, and education to various public policy officials and their staff on the potential for RAS.

Engage communities experiencing RAS development as there are often questions and concerns regarding the impact that RAS development will have on their economy and local environment as well as valuable lessons learned. Some communities already have salmon operations in the construction phase of development, while others are only in the siting and permitting phase. At the earliest stages of development, public interest in the project is voiced through news coverage, public hearings, and op-ed pieces. This is a critical time in which extension can lead an effort to identify stakeholder perceptions, knowledge gaps, and community priorities. Conducting community-listening sessions, interviews, and attending public hearings can inform the kind of programming that extension should be providing. In addition to developing community-specific materials, it is recommended that cross-regional lessons-learned are combined, so that a better understanding of the gradient of community perspectives of salmon RAS is achieved.

Technology transfer and delivering science-based knowledge to end-users is a core principle of extension and a baseline approach is to produce traditional publications and web-based content. Deliverables should focus on 1) progress and findings of new research results, 2) topics of concern among stakeholder groups, and 3) application of developing technologies in salmon RAS. To help distribute extension products, agents can provide workshops, offer field days/tours, table public events, and other relevant and related activities. A benefit of the RAS-N network is that we have established demonstration facilities that should be used to attract public stakeholders as active learners, providing technology demonstrations and in-depth Q&A sessions. Participation can be enhanced by 1) aligning events with relevant local activities/fairs; and 2) hosting invited events for interested community members. Over time, programming of in-person events can be informed by attendees, thereby increasing the value of the program.

Technology transfer with industry is well-established and to ensure that this continues, extension and research need to facilitate industry-focused workshops, organize workshops at national conferences that industry is known to attend, provide tours for industry and the investment community), and provide technical advising (e.g., during patent licensing, contracted service agreements, informal settings, etc.). In addition, opportunities for targeted industry extension and promotion of technologies/practices that enhance salmon RAS sustainability, environmental responsibility and cost-effectiveness should be pursued.

Youth extension programming and community outreach is a step extension can take in introducing the world of aquaculture and sustainable practices to the next generation. Youth also introduce new knowledge in households, where adults responsible for making informed decisions can be reached. There are number of programs dedicated to teaching aquaculture at the K-12 level (e.g., Aquaculture in Action and UMaine's 4-H Aquaculture Club) that can be used as a framework for Vo-Ag/FFA classrooms and informal 4-H extension. Extension efforts can focus on developing educational strategies around workforce development and entrepreneurial skills. These efforts would be best served by trained 4-H educators and volunteers familiar with the basics of RAS technology. Developing and piloting these programs would be crucial to developing a national model for 4-H and Vo-Ag organizations.

Seafood safety and consumer education is important to acknowledge and address because land-based production of Atlantic salmon is unfamiliar among seafood consumers. For most people, salmon aquaculture is synonymous with net pens, so a concerted effort to familiarize consumers would help improve their knowledge and decision-making. Initial extension efforts can focus on providing science-based information about RAS salmon seafood safety and nutrition. A consumer survey would also be useful in identifying consumer knowledge gaps that could then be used in planning future programming. Additionally, extension could serve a role in providing input on seafood best practices to the salmon RAS industry, as well as inform a HACCP model and related RAS training materials.

Community Engagement

Challenges to the Industry: A gradient of salmon RAS industry development is occurring among different states in the US: in production (WI, FL, IN); in construction (ME); and in permitting (MD, CA). To advance a U.S. land-based salmon RAS industry requires identifying areas where RAS facilities can be built in an economically and environmentally successful way. As noted in discussions above, a facility will need access to land, water, transportation, markets, and labor. Also needed will be a local workforce with a diversity of skills necessary for supporting a viable RAS commercial enterprise. Though technology and training, outlined above, are key to RAS advancement, without buy-in from local jurisdictions amenable to growing the RAS industry in their communities, there will be no industry. Community engagement and acceptance will be critical if the US and RAS industry are to reach their RAS Atlantic salmon production goals.

Community involvement early in facility site selection is critical to building support and gaining valuable input from residents. Support of RAS aquaculture does not translate if a proposed or leased Atlantic salmon RAS facility lacks social license, defined as the acceptability or perceived legitimacy of an operation. Coined 'Not In My Backyard', community resistance of potential environmental costs associated with development, changes in land-use, and broader aesthetic impacts can weigh on citizens' acceptance of RAS facilities in their communities.

Potential solutions: Throughout industry development there is a constant need for on the ground community interaction. Overcoming barriers requires a multi-tiered approach through education, empowerment, and community engagement. Success requires bringing industry, regulators, community members and non-profit organizations together for balanced dialogue and decision-making. Education and Extension experts provide opportunity to engage with communities as unbiased and neutral individuals who engage in statewide and/or county-based programming and are often familiar with the communities they serve. They utilize important tools such as community-based participatory research and collaborative learning, to facilitate constructive conversations among multiple-interest groups and individuals to together produce equitable solutions. These approaches are important because they treat communities as partners from the beginning of a project's development, empowering the community to participate rather than passively receive information.

Involving communities at the beginning of a project's development to understand their concerns and answer any questions they may have can be an effective approach to building consensus and RAS facility development. Often, a collaborative learning approach can improve RAS advancement by allowing other voices to be heard and creating an equitable space where people can feel comfortable talking about contentious issues and finding solutions together. Listening to and learning from a community about their priorities and gaining insight from their rich understanding of the land, water, and people around them can help improve site design and provide insight into local workforce capacity. Collaborative learning techniques can include conducting qualitative needs assessments to identify stakeholder perceptions, knowledge gaps, and community priorities. It can also include surveys, community-listening sessions, interviews, and attendance at public hearings. Such approaches can help industry and government understand the gradient of community perspectives on salmon RAS and help educators and extension specialists identify and address community-specific priorities and concerns. Inclusion of relevant stakeholders and consideration of local contexts are critical components for building socially acceptable, sustainable, and economically viable RAS facilities in the US.

Regulation and Policy

Challenges to the Industry: In a US-Japan Natural Resources Technical Report, DeVoe[21] stated global seafood demand would increase 70% by the year 2025, based on the Joint Subcommittee on Aquaculture (JSA)'s projections[22]. Given the stagnant (or declining) wild fisheries, the JSA further projected that aquaculture would have to increase production by 700% to a total of 77 million metric tons (MMT) annually by 2025[22]. Global aquaculture production reached that milestone in 2010 (77.9 MMT) and has risen steadily ever since to a total annual production level of 114.5 MMT as of 2018 [23]. Earlier than DeVoe, Harvey[24] projected that aquaculture (both international and domestic) would supply 25% of seafood consumed in the US by 2000. By 2017, that consumption figure reached an estimated 62.5% of the US per capita, with salmon accounting for roughly 15% of aquaculture products consumed by US households (at 2.4 lbs./capita, second only to shrimp). Only a small portion (~5%) of that salmon is produced in the US and domestic aquaculture production has not grown at a rate necessary to offset the US consumer demand for seafood. To this end, our policies should promote biosecure US domestic production.

The lack of domestic production has been linked to several issues, including concerns about domestic food security, US seafood trade policy, federal oversight, and coordination of import/export regulations and, more broadly, domestic aquaculture development and the US industry's competitiveness with the rest of the world. Thus, from a policy standpoint, the development of the U.S. aquaculture industry remains vital to the future of the nation because it promises to produce: (1) high quality seafood to meet consumer demands and to provide greater traceability and compliance with US standards; (2) products for domestic consumption and export to reduce some of the country's foreign trade deficit; (3) economic development opportunities for US producers, including rural and suburban communities; and (4) new employment opportunities for skilled workers in both the RAS commercial industry and their related businesses (construction, materials, aquafeeds, diagnostics/health management, seafood processing, packaging, distribution, etc.).

Potential solutions: Recent changes in regulation (or proposed changes, such as the USDA CAHPS initiative and others) should reflect both US policy initiatives and the need to address unresolved or newly emerging issues in the changing landscape of 21st century aquaculture. Addressing every conceivable aspect of US regulation and policy related to salmon aquaculture (or even just the areas of concern) is a herculean task that is beyond the scope of this Concept Paper. Aquaculture operates at multiple levels of regulation and policy: federal, state, and local. Synchronization of federal and state policy/regulation is undoubtedly an unachievable aspiration, nor would it address the most salient state and local issues and concerns. Thus, this section focuses not on the details of what is needed in regulation and policy, but rather the essence of what is needed to achieve safe and productive land-based Atlantic salmon farming in the US. Success for the emerging US salmon RAS sector in the area of regulation and policy should be measured by a combined metric of how well the sector does in three main areas: (1) the amount of US production of RAS salmon (i.e., increasing tonnage), (2) the number of producers adopting land-based RAS methodologies for salmon and, very importantly, (3) the sector's ability to generate these increases while maintaining the highest level of food security and safety and environmental responsibility. For this reason, reflecting on the goals and spirit of our national aquaculture policy and the overarching objective of federal regulations is worth examination, with an eye toward realigning policy and our regulatory framework to meet current needs and challenges. The emerging US salmon RAS industry, a new industry utilizing new and ever evolving technologies to domestically produce a well-known product, could certainly benefit from policies and regulation that do not conflate it with traditional production methods and imported products.

Technical advancements in the last two decades have transformed the capabilities of RAS facilities. With the emergence of several US producers (e.g., Superior Fresh, Riverence, Atlantic Sapphire, AquaBounty) and the planned or ongoing construction of multiple salmon RAS operations in several states (ME, CA, MD, FL, and others), the situation is dramatically changing. Domestic production of Atlantic salmon via RAS operations has the potential to resolve several of the issues of concern identified above. Moreover, advances in technology may provide solutions to prior threats and obstacles to US food security as well as regulatory challenges. However, national policy and US regulations must encompass and reflect the increased US aquaculture output, changing modes of production, and advances in our ability to produce, and monitor domestic seafood (salmon).

An examination of several areas of industry and public concern, including (i) biosecurity of seed import, (iii) comprehensive national diagnostic and health management plans, (iii) environmental security, and (iv) competitive fairness for domestic producers, will provide an example of how national policy and the current regulatory terrain can actually work against the domestic salmon RAS industry, and how changes (some of which are in progress) may provide a boost to our domestic sustainable seafood goals. Although this is not an exhaustive list of examples, the underlying aims of enhanced food security and safety, increased domestic production and improved sustainability of processes may be assimilated to other policy and regulatory issues in the future. A more comprehensive discussion of regulation and policy issues affecting domestic salmon production and the nascent US salmon RAS industry will be undertaken in an upcoming 'Road Map' of strategic initiatives that will be disseminated by the Recirculating Aquaculture Salmon Network in 2022.

II. Summary

There is a pressing need for the US to support the land-based salmon RAS industry that is rapidly emerging throughout this nation. A substantial US seafood trade deficit exist, to which Atlantic salmon contributes significantly. In addition, the biosecurity and sustainability of our seafood supply must be improved, in part by the reduction of imports, to achieve the goals of our national aquaculture policy. Domestic land-based RAS production of the most consumed finfish in the United States, Atlantic salmon, would resolve many of these overarching issues. Moreover, for many years the US has been an aquaculture technology hub. Resolutions to the technological and non-technological barriers identified above are well within the capabilities of our national resources (both intellectual and physical resources). A thriving US industry could not only directly create jobs and support local communities in a variety of regional and national settings (rural, urban, underserved, waterfront, etc.), but it would also benefit other sectors such as processing, transportation, marketing, and retail. Thus, the partnership of federal, state, academic and private sector entities and the targeted dedication of resources toward this domestic salmon RAS production is key to realizing the enormous potential of this emerging US industry.

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Domestic Broodstock Development and Year-Round Production of High-Quality Eggs, *Sean Nepper (Riverence)***,** *Brian Peterson (USDA National Cold Water Marine Aquaculture Center)***,** *Yonathan Zohar (Institute of Marine and Environmental Technology)*

Risks Associated with the Importation of Atlantic Salmon Eggs, *William Keleher (Kennebec River Biosciences), Christopher Good (Conservation Fund Freshwater Institute)***,** *Kathleen Hartman (USDA Animal and Plant Health Inspection Service), Deborah Bouchard (University of Maine Aquaculture Research Institute)*

Early Maturation of Atlantic Salmon Cultured in Fresh and Brackish Water RAS, *Christopher Good (Conservation Fund Freshwater Institute) and Yonathan Zohar (Institute of Marine and Environmental Technology)*

Technology to Produce Reproductively Sterile Salmon, *Ten-Tsao Wong (Institute of Marine and Environmental Technology), Yonathan Zohar (Institute of Marine and Environmental Technology), Jesse Trushenski (Riverence)*

Fish Health Management in RAS, *Christopher Good (Conservation Fund Freshwater Institute), William Keleher (Kennebec River Biosciences), Gregory Fischer (UW- Stevens Point Northern Aquaculture Demonstration Facility), Jesse Trushenski (Riverence), Deborah Bouchard (University of Maine Aquaculture Research Institute)*

Technologies to Maximize Growth from Hatch to Harvest, *John Davidson (Conservation Fund Freshwater Institute) and Gregory Fischer (formerly, UW- Stevens Point Northern Aquaculture Demonstration Facility)*

RAS-Specific Salmon Diets and Alternative Sources of Proteins To Replace Fish Meal/Oil *Jason Mann (Riverence), Steve Summerfelt (Superior Fresh), Brian Peterson (USDA National Cold Water Marine Aquaculture Center)*

Microbiomes in RAS: Identifying and Optimizing Microbial Communities Involved in Biofiltration, *Keiko Saito (Institute of Marine and Environmental Technology)***,** *Kevin Sowers (Institute of Marine and Environmental Technology)*

Optimized Engineering and Operation of RAS Platforms *Brian Vinci (Conservation Fund Freshwater Institute*) and *Steve Summerfelt (Superior Fresh)*

Techniques to Minimize Off-Flavor (Geosmin and MIB) in Harvested Salmon, *John Davidson (Conservation Fund Freshwater Institute)***,** *Greg Fischer (UW-Stevens Point Northern Aquaculture Demonstration Facility), Brian Peterson (USDA National Cold Water Marine Aquaculture Center)*

Economic Analysis and Feasibility of Atlantic Salmon RAS Production, *Scott Knoche (Morgan State University) and Kaitlynn Ritchie (Morgan State University)*

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David Noyes (Nordic Aquafarms)

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