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AN OVERVIEW OF **GENOMICS** IN **BRITISH COLUMBIA'S**

FISHERIES AND AQUACULTURE SECTOR

Genome BritishColumbia

Leading ▸ Investing ▸ Connecting

2018 Revision

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Executive summary

Fisheries and aquaculture are an integral to British Columbia's history, culture, and communities, and a primary economic engine for the province. BC is home to 2.5 per cent of the world's coastline, 20,000 lakes and 105 different river systems. Over 100 distinct species of fish, shellfish, and marine plants are currently commercially harvested from BC's waters. Seafood products contributed $1.3 billion (35 per cent)[1] to the province's combined agrifood and seafood exports in 2016.

Aquaculture and commercial fisheries provided 9,112 jobs[2] for British Columbians in 2015, particularly in rural and First Nations coastal communities. In 2013, BC's recreational fishery sector employed at least 5000 people and had a combined economic impact of over $950 million[3].

The goal for BC is to grow aquaculture and fisheries while preserving aquatic ecosystems and maintaining standing stocks. Without effective conservation of fish stocks and protection of both freshwater and marine ecosystems, the opportunity to harvest and produce fish will disappear and the fisheries and aquaculture sector would cease to exist. Climate change and associated fluctuations in aquatic and terrestrial ecosystems has compounded this challenge. Additional challenges include access to global markets; pressures to increase productivity in the face of rising input costs; complex, evolving regulatory systems, and increasing scrutiny of practices hampering the ability to gain social acceptance. However, in this sector, as in other natural resource sectors, the application of genomics has the potential to enable strong, competitive growth based on product quality and security, technological soundness, economic viability, environmental integrity, and social license.

The development and implementation of genomics technologies in this sector can support conservation efforts, monitor, and improve fish, shellfish, and ecosystem health, and provide a sustainable food source for BC and beyond from a socially-accepted sector.

This document lays out a strategy for expanding on previous Genome BC investments in genomics-based research to improve the sustainability and productivity of the fisheries and aquaculture sector. The overarching goal of Genome BC's fisheries and aquaculture sector strategy is to identify the challenges and opportunities facing the sector; the previous investments, results, and strengths; and the priorities of all stakeholders relevant to the sector into an actionable set of next steps.

1. Importance of BC's Fisheries and Aquaculture Sector

Commercial and recreational fisheries and aquacultural activities (growing aquatic animals or plants for food) in British Columbia contribute significantly to the provincial economy each year and are the foundation of many rural and First Nations coastal families and communities. The sector includes primary production from commercial fishing and aquaculture as well as recreational fishing.

In 2016, provincial production totalled 291,600 tonnes with a landed value of $1.17 billion[4]. The commercial capture fisheries harvest of 188,000 tonnes was worth $392.8 million to fisher-people, while aquaculture operations realized a farm-gate value of $776.8 million from 103,600 tonnes of production.[4]

Aquaculture and commercial fisheries provided 9,112 jobs[2] for British Columbians in 2015, particularly in coastal communities. In 2016, the farm-raised salmon industry alone contributed $557.8 million to the provincial GDP and 6,610 jobs[5]. In 2013, BC's recreational fishery sector employed at least 5000 people and had a combined economic impact of over $950 million[3].

The provincial government recently outlined plans to increase agrifood and seafood annual revenue to $15 billion per year by 2020 in the *B.C. Agrifood and Seafood Strategic Growth Plan*. The fisheries and aquaculture sector plays a key role with the province setting targets to increase aquaculture production, including fish, shellfish, and marine plants, by 13,000 tonnes (14 per cent) per year and to increase the wholesale value of the wild fishery by $102.5 million (13 per cent)[6].

Genomic sciences can, and should, support informed sustainable development and management of Canada's aquatic ecosystems and resources to the benefit of its people, its natural resources and the national economy. Genomics will provide new tools to understand biological processes of aquatic species and their habitat at the molecular level. Benefits to BC include:

- improved management program for the health of cultured and wild stocks,
- improved sector sustainability,
- increased consumer confidence and acceptance of products.

This strategy is intended to outline a path to support development and application of genomics to address sector challenges and opportunities. Genome BC promotes sector innovation by facilitating ongoing partnerships with researchers, industry and government, with Genome BC playing a leadership role in bringing stakeholders together to facilitate delivery of benefits.

This strategy provides an update for areas of focus consistent with the priorities identified in the Genomics Strategy developed in 2013-2014 and developed in consultation with sector stakeholders since that time. It is designed to complement and align with existing industry, government, and sector strategies.

BC's Fisheries and Aquaculture Resources

With over 100 distinct species commercially harvested, BC is known globally for its excellent seafood[7]. Salmon is iconic and BC hosts Canada's only wild salmon fisheries. Five species of Pacific salmon (Chinook, Coho, chum, pink and sockeye) inhabit coastal waterways and have provided a foundation for the wild fisheries. Other salmonids, including several trout and char species, dominate the freshwater lakes and benefit from a provincial hatchery and stocking program.

Salmon are also the primary aquaculture stock in BC. Atlantic salmon are not native to BC's waters but dominate this economically-significant sector. Trout, tilapia, sablefish, sturgeon (reared for caviar production) and seaweed are also grown commercially in BC and account for a small portion of total revenues. Production of shellfish (oysters, mussels, clams, and scallops) has increased in recent years but constitutes a much smaller industry. Unlike the larger salmon aquaculture industry, the shellfish industry is built around several small companies and family holdings.

A diverse array of groundfish, including flounder, dogfish, hake, halibut, cod and others, predominate the capture fisheries, yet significant contributions are made from higher-value species such as tuna, halibut and prawns. Most of BC's fishery products are exported to global and highly-competitive markets in the United States, Japan, Europe, and elsewhere.

Collectively, these resources support economic activity in four primary areas.

1.1 Capture fisheries

BC's capture fisheries harvested 158,900 tonnes (landed value, $370.2 million; wholesale value $773.5 million)[7] in 2015. Average annual employment in the sector reached its lowest levels in 2011, down approximately one-third since 1996. Landed value for the sector has varied significantly in recent years due in large part to variability in wild salmon returns combined with conservative harvest policies. In 2015, groundfish (93,300 tonnes) represented most of the BC capture harvest, followed by pelagic and other finfish (primarily salmon, herring and tuna), with a small contribution from shellfish (18,300 tonnes)[7]. Higher value species such as salmon ($51.9 million), tuna ($13.8 million), halibut ($53.8 million), and prawns ($32.7 million) make a significant economic ***c***ontribution to this segment of the sector (all values, landed values, 2015)[7]. BC leads the country in production of these species and is the only province with a commercial salmon fishery.

1.2 Seafood processing

Fish and seafood processing playsan integral role in the fisheries and aquaculture sector, and contributes significantly to the wholesale value of capture fisheries landings. BC's seafood processing sector produces almost 500 products. In 2015, it created $1.43 billion for the province, the second highest wholesale value in more than 25 years[7]. In the same year, 171,500 tonnes of processed BC seafood were shipped to 79 markets with a total value of $1.13 billion[7].

1.3 Aquaculture

Aquaculture, also known as 'fish farming', now provides half of all seafood for human consumption[8] worldwide and represents about one third of Canada's total fisheries production[4]. The aquaculture portion of the BC fisheries and aquaculture sector has experienced significant growth over the last two decades. In 2015, BC produced 83,800 tonnes of farmed salmon with a landed value of $463.6 million[7]. Atlantic salmon is the primary cultured species with a harvest of 80,500 tonnes and is BC's largest agricultural export[7]. Shellfish, including oyster, mussel, geoduck, and other clams, are also produced in BC and contributed to BC's economy with a landed value of $24.6 million[7] in 2015. Trout, tilapia, sablefish, sturgeon, Artic char, and seaweed are also grown commercially in BC and contributed with a landed value of $9 million in 2015.

1.4 Recreational fishing

BC's recreational fisheries provide at least 5,000 direct jobs and more when secondary and tertiary industries, such as tourism and transportation, are included. In 2013, revenues from this segment were $957 million[3]. Rainbow trout is the primary focus of the freshwater fisheries, accounting for almost 60 per cent of caught fish. Cutthroat trout, Sockeye/Kokanee, other trout and Steelhead make up the remainder. Salmon, primarily Chinook and Coho constitute much of the catch in tidal fisheries.

2. Sector Challenges and Opportunities

To realize the many opportunities for growth and investment in the sector, it is necessary to examine the challenges facing BC's fisheries and aquaculture sector in the context of a fluid socio-economic and geo-political environment. The overarching challenge for BC is to increase aquaculture production and grow fisheries while preserving aquatic ecosystems and maintaining standing stocks. Effective conservation of fish stocks and the protection of both freshwater and marine ecosystems is the foundation for sustainable harvest and fish production and a thriving fisheries and aquaculture sector.

Global markets and competition

Canada is one of the world's largest seafood exporters, and most of BC's fisheries products are exported to global and highly-competitive markets in the US, Japan, Europe and elsewhere. BC exported $1.3 billion in seafood products to 80 global markets in 2016, a 17 per cent rise over the previous year[4]. However, concerns regarding the risk of disease and pathogen transfer from farmed to wild salmon and associated moratoria imposed by both the provincial and federal governments in recent years have imposed limitations on growth of the aquaculture sector in BC. At the same time, as consumer's awareness of food sources increases, the demand for sustainably reared or caught products will increase, as will markets for certain attributes like fat percentage and colour. This represents opportunity for the sector.

Climate change and environmental impacts

Climate change will have a significant impact on fisheries and aquaculture worldwide. Changes in water temperature and chemistry affect ocean ecosystems, food chains and the ability of fish and shellfish to thrive. Extreme weather events, such as floods, fires, and drought, will occur with greater frequency and intensity and require mitigations to ensure sustainability of wild populations and productivity of aquatic ecosystems. In addition to climate change challenges, a range of anthropogenic impacts - biological, physical, or chemical - may bring immediate or long-term changes to aquatic habitats and associated biodiversity.

Animal health and product safety

The health of aquatic organisms is paramount for wild and farmed stocks alike. Little is known about the endemic pathogens or the external incursions or introductions in BC waters and ecosystems. The impact of these pathogens on aquatic species, as well as manifestation and transmission of disease, require further investigation. Limited availability of therapeutics and vaccines and shortage of cheap, sensitive, and rapid diagnostics challenges animal health. Pathogens like norovirus, a potential threat to public health, and emerging diseases like whirling disease, highlight the need for improved diagnostics, monitoring, and traceability for fish and shellfish.

Wild stock monitoring and management

Conservation of wild stocks is the foundation of sustainable capture and recreational fisheries. The assessment of wild stocks and activities of wild fish (e.g migration, spawning, feeding, ecosystem impacts etc.) within the vast and dynamic environments of BC's extensive lakes and coastal waters is difficult and expensive. Data capture of size, structure and distribution of populations is rarely complete or comprehensive, but is crucial for generating models to inform stock and conservation management. Similarly, ecosystem models that show fishing down the food chain and the valuation of fisheries used for subsistence need improvements. On a global level, biodiversity and conservation has been impacted by directed and incidental harvests by all user groups (commercial, recreational, and First Nations). There is a need, globally and in BC alike, to conserve the genetic diversity of wild species and populations which are often better adapted to local conditions.

Social license, risk, and uncertainty

In the face of uncertainty, especially regarding wild stocks, management and regulators tend to be conservative, weighing uncertainty and potential risk more heavily than potential benefit, hampering and limiting the growth of the sector. In BC, uncertainty and associated concerns continue regarding the possible impacts of cultured fish on wild populations. Today, these concerns are focussed on salmon farming in open net pens. Genomics-based research helps better understand of the potential risk and impacts of this form of aquaculture and provides solutions to address challenges in the sector. This helps managers and policy makers in their decision-making at the company and sector level and ultimately will increase the social acceptance and growth of the sector. Overall, a stable, modern regulatory framework for the sector should be built and maintained on the best available information to enable security of access and stock sustainability.

Research and development capacity

For the sector to remain globally competitive in the long term, it is imperative to diversify genomics-based research leading to the development and adoption of innovative technologies. Current capacity of wet labs and quarantine facilities is limited which poses one of the challenges to the growth of the sector. Expanded research capacity and infrastructure, as well as improved collaboration between private and public research partners will be key to overcoming current bottlenecks and positioning end-users to increase global market share and to compete internationally.

3. Genomics in the Fisheries and Aquaculture Sector

Genomics is the science that deciphers and understands the genome – the code or blueprint, of a living organism (humans, animals, plants, microbes) – to better understand biological systems at a molecular level. In the last decade or so, the field has advanced rapidly and is increasingly becoming cost effective. The scientific knowledge and innovations emerging from genomics-driven research are unearthing solutions to a broad range of complex biological challenges, including applications in health, forestry, fisheries, aquaculture, agrifood, energy, mining, and environment. At the same time, these state-of-the-art approaches are also giving rise to the need for dialogue regarding societal, economic, and ethical implications of genomic information.

In Canada, the Department of Fisheries and Ocean has long incorporated genomics into its management of wild stocks—as part of its stock survey work and in their network of wild salmon hatcheries – to monitor and facilitate hatchery management activities. While in the past protein electrophoresis and

identification of microsatellites were used to analyze populations, today genomics tools including genome wide association studies (GWAS) to identify single-nucleotide polymorphism (SNP) markers are integrated into fisheries management, conservation, and restoration programs.

As recently shown for one of the Pacific salmon species, the Coho salmon, parentage-based tagging (PBT) may replace the physical coded-wire tags (CWT) as it accurately estimates the proportion of hatchery fish in the wild and it assigns individuals not only to their stock but also to their parentage. Genomics were also applied to distinguish between ecotypes of North Atlantic cod providing valuable information for fisheries management.

Beside importance for sustainable commercial and recreational fisheries genomics are also contributing to advances in the field of biosecurity. Traceability is crucial to avoid food fraud, illegal fisheries and to protect people's health by tracking seafood to areas affected by health threats such as toxic algae blooms.

In this sector, like other agrifood sectors, industry has driven the application of genomics. To improve stocks of commercially relevant species such as salmon, cod, carp, and oysters, GWAS have been used to identify biomarkers for certain traits, including growth rate, disease resistance and age at maturation. Researchers in Norway and Scotland have led the way in this regard by identifying the genetic signatures and subsequent selection of salmon strains resistant to several pathogens, such as infectious pancreatic necrosis virus (IPNV). By using IPNV-resistant salmon, mortality was dramatically reduced resulting in lower costs for vaccines and therapeutics and greater output of marketable salmon.

Other infectious diseases are prevented by efficient vaccines or treated with specific drugs. Oligonucleotide microarrays were developed to study responses to drugs, vaccines, pathogens, or exposure to various environmental conditions on a transcriptional level, e.g. for salmon, cod, mussel, and sea lice. Mainly used for research purposes, these studies help to assess drugs, vaccines and to understand impact of external factors on individuals.

Genomic tools are constantly adopted to develop diagnostic assays for various pathogens which are routinely used in surveillance programs of farmed, wild and hatchery fish. A new, highly sensitive, emerging tool is the sequencing of environmental DNA (eDNA) with the potential to detect nucleic acids of pathogens in water samples, such as sea lice and algae harmful to farmed and wild fish.

Canada was the first country to develop a genetically engineered salmon which grows almost twice as fast as traditional salmon. The fish has been commercialized by Aqua Bounty in the US and is approved for sale in Canada. More recently, Norwegian researchers have applied gene editing to create sterile salmon through loss of germ cells. Used for research purposes only, gene editing as well as other approaches at the molecular level (e.g. gene silencing) to generate sterile fish may potentially become an alternative to triploid fish.

While the value of genomics for fisheries, aquaculture, conservation, and biosecurity is widely accepted, its application has stagnated. Efficient communication between researchers, managers and policy makers is a significant challenge, and one that must be overcome for effective translation of research outputs into practical solutions. In this regard, Genome BC plays a significant role by bringing academics, industry and government together to find solutions for future challenges such as climate change, increasing demand for seafood, and conservation of marine and freshwater ecosystems.

Impact of BC investment in genomics

Genome BC has been strategically investing to advance the application of genomics in BC's fisheries and aquaculture sector. Since 2000, Genome BC has invested more than $65 million in 17 projects spanning the sector and covering the research to innovation continuum. Early investments have focussed on large scale genomic research on salmon-generating tools and knowledge that can be used by researchers and end-users across the sector. Research at this time was necessarily collaborative and international given the scale, scope, and complexity of the salmon genome. Projects like GRASP, cGRASP and more recently ICSASG[1] established significant research capacity and infrastructure in BC that remains world-class today. This initial investment generated mapping and microarray tools that are used in private and public labs around the world today.

Over the years, Genome BC's investment portfolio diversified and expanded to include applied or translational research on salmonids, including freshwater species like kokanee and trout, alternative species like sablefish, and microbes and pathogens of salmonids and shellfish. As this work progressed, it attracted new partners across the sector who were committed to understanding and tackling challenges and opportunities for productivity and sustainability. Partners included Department of Fisheries and Oceans, BC Government Ministries, Pacific Salmon Foundation, Freshwater Fisheries Society of BC, and numerous aquaculture companies. Genomics is increasingly being integrated into the work of these partners to improve their operations and deliver benefits to BC.

In BC, the potential of this work is now being realized and the application of genomics is showing great promise. Early work is underway to identify a link to hypoxia tolerance in salmon, and the associated genetic variants have potential to help BC-based companies develop stocks that can withstand increases in ocean temperature and concomitant decreases in dissolved oxygen, reducing mortality and productivity losses. Results of this work will be applicable not only in BC, but the technology could be exported to other jurisdictions facing similar challenges and applied to domestic hatchery programs aimed at providing resilient wild stocks.

Currently in Phase Two, the Strategic Salmon Health Initiative (SSHI) project is undertaking a survey of wild and farmed fish to look at the distribution of microbes across species and over time. It is a first step to understanding the flow of these microbes in and between wild and farmed fish, and their association with disease in these fish.

Ensuring a productive and sustainable salmon aquaculture industry will economically and socially benefit the coastal communities who rely on it. Improving our understanding of the reasons behind poor returns of wild salmon and informing actions to manage these stocks is priceless. Overall, the investment in foundational research and applied technologies within the fisheries and aquaculture sector is critical to maintaining a sustainable and productive industry built on wild and farmed fish stocks that are resilient in the face of current and future challenges posed by a dynamic and changing environment.

[1]GRASP, Genomics Research Atlantic Salmon Project; cGRASP, Comparative Genomics Research Atlantic Salmon Project; ICSASG, International Cooperation to Sequence the Atlantic Salmon Genome

4. Opportunities for BC

Creating Opportunities for Genomics in BC's Fisheries and Aquaculture Sector

Thanks to previous investments by Genome BC and others, BC has a significant and world-class research capacity for development and delivery of genomic applications. Paired with success stories emerging from these investments and an educated and increasingly 'genomics savvy' receptor community within industry and government, it becomes clear that genomics can address many of the productivity and sustainability issues of the sector. From improved management of cultured and wild stocks, to growing sector sustainability, and increased consumer and societal confidence, the sector is well-positioned to take advantage of opportunities in several areas, including:

Conservation and population preservation

Salmon hatchery programs have long relied on family-based tagging to inform and manage their efforts. This work is now expanding to include whole genome analysis allowing greater resolution and facilitating longer term management of wild fish. Tools like eDNA are being developed for use in surveillance and monitoring of seasonal, transient, and species-at-risk. Other molecular markers, such as expression markers or other predictive biomarkers, may be developed as early warning indicators of changes in environmental conditions allowing early, more effective response. Genomics may be used to look at diversity within and among populations, facilitating actions such as selective breeding to increase diversity, development of tools to monitor diversity, or even enforce poaching and traceability of wild species.

Improving aquatic animal health

Genomics has shown exciting potential to contribute to the health of wild and farmed species. Moving beyond conventional molecular diagnostics, genomics is facilitating the large-scale analysis (multiplexing) of microbes of interest, decreasing diagnosis and response time and potentially reducing the costs of biomonitoring. Genomics is also being used to identify biomarkers for disease resistance and environmental stressors including infection. Genome-wide functional analysis also holds potential for design and development of more effective vaccines and therapeutics.

Environmental integrity

The health and long-term sustainability of any aquatic species, whether farmed or wild, in marine or freshwater, depends on the integrity of the surrounding environment. There is a role for genomics in monitoring both the environment and interactions within the environment, and in contributing new tools to reduce negative environmental impacts. Simple molecular tools, as well as high throughput and genome-wide methods like microarray or metagenomics analysis, may be used to monitor for specific environmental harms or to study the response of an organism or ecosystem. Genomics has long been used to improve the sustainability of aquaculture by providing an alternative source of protein and reducing the pressure on wild capture fisheries. Genomics may also be used to reduce negative impacts through applications such as bioremediation or production of sterile aquaculture stocks that cannot interbreed with wild stocks.

Producing high quality sustainable food

The application of genomics in aquaculture offers further significant opportunities to increase

production of high-quality, sustainable food. Genomics is routinely used in selective breeding programs for many species in BC and around the world However, new genomic tools are improving this work by making it faster, more informative, or cheaper. Genomics can be used to identify markers for traits of interest and to understand the function of associated genes. Microbiome analysis can provide insights and tools for understanding and improving feed conversion and associated traits like growth, or developing new feed alternatives, decreasing production times or costs, and increasing sustainability. Genomics can assist in domestication of local species for aquaculture thus helping to diversify the sector and to secure a new sustainable supply of alternative seafood to consumers.

Enhancing social license

One of the most important applications of genomics and related sciences in the sector relates to enhancing the sector's social license. Deployed judiciously, and in context, genomics can provide a science-based justification for management actions, regulation, and policy development. By contributing new data to existing stock assessment models or on fish behaviour or function, genomics can reduce uncertainty and risk associated with decision-making.

A Roadmap for Genomics in BC's Fisheries and Aquaculture sector

Genome BC is continuing its efforts to support the uptake of genomics within the sector to realize benefits across the entire fisheries and aquaculture value chain. Genome BC will continue to support foundational, large-scale research and development—like the Functional Annotation of All Salmonid Genomes (FAASG) Initiative – as a platform for innovation across the sector. Like the human and mouse initiatives that have gone before it, this international initiative will provide a forum for collaborative annotation of the functional elements of the salmon genome providing the latest information to inform applications in the fisheries and aquaculture sectors. In addition, Genome BC will work with industry and other end-users to pilot or take to scale genomics applications with the goal of implementing and operationalizing innovations in the sector that can deliver tangible benefits to companies, communities, and individuals citizens in BC and across Canada.

4.1 Pilot projects

Within the current strategy the following types of pilot projects may be considered to provide a range of impacts that benefit stakeholders across BC's aquaculture and fisheries sector value chain:

Pilot Project	***Impact***	
	Short term	***Long term***
• *Development of diagnostic tools for emerging pathogens*	*Reduction in pathogens, improved fish health*	*Lowering risk of severe outbreaks due to preventive actions*
• *Selective breeding and biomarker identification to adapt to a changing environment*	*Species able to cope with changing environmental conditions and other stressor such as pathogens*	*Food security; sustainable aquaculture; increased competitiveness*
• *Apply genomics within recirculating aquaculture*	*Improving operation of land-based aquaculture*	*Sustainable land-based aquaculture; social acceptance*

system (RAS), e.g. water treatment, biofilm analysis		
• *Applying genomics for parentage analysis*	*Cheaper more powerful stock assessment capability*	*Protection of wild stocks and aquatic ecosystems*
• *Microbiome analysis, e.g. to develop and validate new feed*	*Reduced reliance on fish and fish meal inputs, improving fish health and feed conversion rate*	*Fostering sustainable aquaculture and ensuring fish welfare*
• *Genomic tools to generate sterile fish*	*No interbreeding between farmed and wild fish*	*Maintenance of genetic variability of wild fish, thus protection of wild fish stocks and aquatic ecosystems*
• *Diversification of aquaculture species adapted to BC's climate conditions*	*Strengthen aquaculture industry in BC, increasing production*	*Growth of aquaculture industry; economic benefits to BC; protection of wild stocks; creating jobs*
• *Genomics for traceability of seafood*	*Ensuring food quality and safety*	*Protection of public health; access to global market*
• *Genomic tools for freshwater inventory and monitoring*	*Sustainable hatchery and stocking management practices without interfering with native species*	*Continued excellent and sustainable recreational fisheries*
• *Valorization of fish processing waste to produce high value bio-products*	*Fostering innovation across sectors; reduction in waste*	*Market diversification; new revenue sources; enhancing sustainability; increased competitiveness and jobs*
• *Social license: role and impact of genomics on aquaculture and fisheries*	*Develop tools for assessment of societal benefits; engagement with First Nations and other communities*	*Realizing socioeconomic benefits of genomics research in aquaculture and fisheries; guiding policy decisions for sustainable and efficient management in aquaculture and fisheries in the future*

4.2 Community engagement

While the opportunities and applications of innovative genomics research and technology are well known among BC researchers engaged in fisheries and aquaculture genomics, there is a persistent gap between this community and some managers and executives in both the public and private sectors whose responsibilities relate to broader issues of public policy, management, or competitiveness. To increase the adoption of genomics-based tools and achieve higher impacts in industry sooner, a coordinated approach to broad community engagement is required.

5. Advancing the Implementation of Genomics

This document lays out several significant opportunities for practical applications of genomics in BC's fisheries and aquaculture sector including: selective breeding, diagnostics, development of feed, stock assessment and traceability (see chapter 4).

To realize these opportunities, Genome BC has been consulting with stakeholders not only in BC's aquaculture and fisheries sector but across the rest of Canada, as well as with international experts, to understand how genomics might continue to be applied to maximize economic and social benefits arising from various sector activities. The overarching goal of developing this genomics strategy for BC's aquaculture and fisheries sector is to identify the challenges and opportunities facing the sector; the previous investments, results, and strengths; and the priorities of all stakeholders relevant to the sector into an actionable set of next steps.

Genome BC has developed this Roadmap to encourage the uptake of genomics in all sectors, and makes the following commitments to support the Roadmap:

- Education
    - All stakeholders: Inspiring students through education programs and empowering teachers with new education tools
    - Genome BC: Geneskool, public talks through the GeneTalks program
- Stakeholder engagement
    - All stakeholders: Bringing together and supporting the life sciences community to reach a common vision and achieve a common goal
    - Genome BC: Sector work/task forces
- Partnership development
    - All stakeholders: Engage with partners and catalyze user-academic interactions to bridge the academic-industry gap
    - Genome BC: Sector work/task forces
- Development of pilot projects
    - All stakeholders: Pilot projects demonstrating the practical and cost-saving value of genomics
    - Genome BC: Funding for partnered, applied research
    - Genome BC: Through the development of Sector Innovation Centres, Genome BC's goal is to help build ecosystems beyond projects – as a partner with key players in the sector.
- Communicating successes
    - Genome BC: Position Genome BC and the corporate brand as an "honest broker" contributing to government policies, strategies, and regulations
    - Genome BC: Share success stories in targeted publications, including Genome BC news releases and sector-relevant trade journals

Appendix 1. Members of the Genome BC Fisheries and Aquaculture Sector Advisory Council, as at March 1, 2018

- Christina Burridge, BC Seafood Alliance
- Bruce Swift, TRI-GEN Fish Improvement Ltd.
- Adrian Clarke, Freshwater Fisheries Society of British Columbia
- William Davidson, SFU
- Jim Powell, BC Center for Aquatic Health Sciences
- Myron Roth, BC Ministry of Agriculture
- Jeremy Dunn, BC Salmon Farmers Association
- Darlene Winterburn, BC Shellfish Grower's Association
- Yvonne Sheehan, Marine Harvest Canada
- Nathan Taylor, DFO
- Brian Riddell, Pacific Salmon Foundation
- Ben Koop, UVIC
- Chris Sporer, Pacific Halibut Management Association
- Edward Safarik, Ocean Fisheries Ltd.
- Robert Devlin, DFO
- Greg Taylor, Fish First Consulting

Appendix 2. List of Key Projects

UPP003 – Genomic solutions for informing sockeye repatriation and kokanee fisheries management (2014-2016)

Total Budget: $285,000

Program: User Partnership Program (UPP)

Project Leaders: Prof. Michael Russello and Richard Bussanich (University of British Columbia)

Kokanee, a freshwater form of sockeye salmon, supports popular recreational fisheries in lakes across BC's Okanagan region and the Pacific Northwest and is also a traditional food source for First Nations. Cumulative impacts of population growth and land use practices may be leading to the "invisible collapse" of Canada's freshwater fisheries. This project explores how freshwater fisheries can be better informed and subsequently managed using genomic technologies. Researchers identified genomic markers to segregate shore and stream spawning salmon and develop genomic markers to discern resident and anadromous phenotypes. Reference genomes were created for several salmon populations across BC which can be used to inform broodstock selection.

C50SAS – International Cooperation Project to Sequence the Atlantic Salmon Genome (ICSASG) (2009-2017)

Total Budget: $10,000,000

Program: Applied Genomics Consortium Program (AGCP)

Project Leaders: Profs. Willie Davidson (Simon Fraser University), Ben Koop (University of Victoria), Steve Jones (University of British Columbia & Simon Fraser University), Rodrigo Vidal (University of Santiago), Patricia Iturra (University of Chile), Alejandro Maass (University of Chile), Stig Omholt (Norwegian University of Life Sciences), Sigbjorn Lien (Norwegian University of Life Sciences), Inge Jonassen (University of Bergen)

The international collaboration has sequenced the Atlantic salmon genome using Sanger and next-generation technologies, and integrated sequences with comparative genomics to produce a high-quality reference genome for use by researchers and industry. This effort has generated a high-quality resource to benefit the commercial salmon fishery in BC and worldwide.

The salmon genome can provide valuable information about the impact of cultured fish escapees on wild populations, preservation of populations that are at risk, strategies for fighting pathogens, and environmental sustainability issues, and provide a reference genome for work with other salmonids, such as rainbow trout.

B16SHB – Inventory and Assessment of Health Risk of Microbes in BC (Phase 2b) (2016-2019)

Total Budget: $6,312,812

Program: Strategic Salmon Health Initiative (SSHI)

Project Leaders: Drs. Brian Riddell (Pacific Salmon Foundation) and Kristi Miller-Saunders (Department of Fisheries and Oceans)

Over 90% of juvenile salmon migrating from freshwater into the ocean will die before returning to freshwater to spawn, and disease may be a significant factor contributing to this mortality, however not enough is known about what the disease agents are. This is the most comprehensive study yet of the temporal and spatial distribution patterns and diversity of microbes in BC salmon, and their potential to negatively impact productivity of wild and cultured populations. By collecting wild, hatchery and aquaculture salmonids from southern BC, the team provided a tissue inventory for assessment of microbes carried both by wild and cultured salmon in BC. Then the team demonstrated the application of a sensitive, broad scale and high throughput genomic platform for the identification and quantification of important pathogens that may influence the health and survival of native populations of BC salmon and described the distribution of these microbes in wild and cultured salmon populations, The team are currently designing and implementing of a surveillance study to describe the presence, prevalence and loads of microbes in Southern BC Chinook, Coho and sockeye salmon smolts.

UPP018 – Genomic Basis of Variation in Hypoxia Tolerance in Atlantic Salmon (2015-2017)

Total Budget: $266,436

Program: User Partnership Program (UPP)

Project Leaders: Dr. Diane Morrison (Marine Harvest Canada), Prof. Patricia Schulte (University of British Columbia) and Yvonne Sheehan (Marine Harvest Canada)

Integrating genomics into breeding programs allows aquaculture organizations to be more competitive and address certain conditions that may affect broodstock. This project recently initiated a family-based breeding program to improve broodstock by using genomics to explore the ability of farm-raised Atlantic salmon to tolerate low oxygen conditions (hypoxia) in the ocean, a climate change related issue that results in poor fish performance. Agenomics-based approach to addressing this problem by increasing their capacity to incorporate hypoxia-tolerance as a trait in their broodstock selection program is being developed.

229COH – Enhancing Production in Coho: Culture, Community, Catch (EPIC4) (2015-2019)

Total Budget: $9,867,636

Program: 2014 LSARP Competition Genomics and Feeding the Future (GFF 2014 LSARP)

Project Leaders: Profs. Louis Bernatchez (Université Laval), Ben Koop (University of Victoria), Willie Davidson (Simon Fraser University)

This project is aiming to use recently available genomics tools to address challenges in improved management and the re-evaluation of hatchery / wild interactions of Coho salmon. The team will sequence the Coho salmon genome, document the genetic diversity of thousands of individuals, and determine how Coho salmon from different geographic regions vary genetically. They will apply newly

found knowledge to help sustain the wild Coho salmon fisheries, improve hatchery production of the species, and help develop BC's Coho salmon land-based aquaculture industry to make it more productive. The outcomes of the project should also be transferable to other species of Pacific salmon and salmonids from other regions of Canada.

242RTE – Sustaining freshwater recreational fisheries in a changing environment (2016-2020)

Total Budget: $4,386,173

Program: 2015 LSARP Competition Natural Resources and the Environment: Sector Challenges - Genomic Solutions (NRE 2015 LSARP)

Project Leaders: Profs. Patricia Schulte (University of British Columbia), Ben Koop (University of Victoria), Anthony Farrell (University of British Columbia)

Rainbow trout are a cornerstone of recreational fishing, but wild populations are in danger due to climate change and human impacts. The team will sequence the genomes of rainbow trout from different populations to assess their genetic diversity and identify appropriate strains of fish for stocking that will be resilient to the effects of climate change. They will also develop low-cost tools for fisheries managers to monitor the genetic health of rainbow trout populations and develop policy recommendations for managers and stakeholders to help them manage and preserve rainbow trout.

Appendix 3. Resources and references

1 https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/agriculture-and-seafood/statistics/market-analysis-and-tradestatistics/2016_bc_agrifood_and_seafood_export_highlights.pdf

2 http://www.dfo-mpo.gc.ca/stats/cfs-spc/tab/cfs-spc-tab2-eng.htm

3 https://www.gofishbc.com/PDFs/Footer/2013_bc_freshwater_sport_fishing_economic_impact_r.aspx

4 https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/agriculture-and-seafood/statistics/industry-and-sector-profiles/sector-napshots/bc_seafood_sector_snapshot_2016.pdf

5 http://bcsalmonfarmers.ca/wp-content/uploads/2015/01/BCSFA_Econ_ImpactStudy-SEP2017.pdf

6 https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/agriculture-and-seafood/strategic-growth-plan.pdf

7 https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/agriculture-and-seafood/statistics/industry-and-sector-profiles/year-in-review/bcseafood_yearinreview_2015.pdf

8 http://www.dfo-mpo.gc.ca/aquaculture/sector-secteur/frm-tml-eng.htm