Canadian

FISHERIES & AQUACULTURE

How genomics can address sector challenges

A Sector Strategy led by Genome Atlantic and Genome British Columbia, with support from regional Genome Centres across Canada and funded by Genome Canada.

August 2013

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Genomics* is the science that aims to decipher and understand the entire genetic information of an organism (i.e. microorganisms, plants, animals and humans) encoded in DNA and corresponding complements such as RNA, proteins and metabolites.

The knowledge and innovations emerging from this field are finding solutions to complex biological challenges, while at the same time raising questions of societal and economic importance.

Genomics has already brought huge economic and societal gains to Canadians through better healthcare, improving food quality, safety and production and protecting our environment and natural resources.

Looking ahead, genomics will be the foundation of Canada's growing bio-economy (all economic activity derived from life science-based research), which is estimated to be responsible for some 2.25 per cent of GDP, or about $38 billion, by 2017.

Increasingly, genomics is equipping a range of Canadian industries—agriculture, energy, mining, forestry, fisheries and aquaculture and health, among others—with cutting-edge science and technologies. This is driving growth, productivity, commercialization and global competitiveness, while finding solutions to environmental sustainability problems.

Genome Canada and the six regional Genome Centres across the country are working to harness the transformative power of genomics to deliver social and economic benefits to Canadians.

This paper is one in a series of four sector strategies funded by Genome Canada and co-led by the Genome Centres. They include: Agri-Food, Energy and Mining, Fisheries and Aquaculture, and Forestry. Each strategy, developed in consultation with sector stakeholders, maps out how the sector can further leverage the transformative power of genomics, and related disciplines, to its advantage.

Given Canada's footprint in these key natural resource sectors, the time is ripe for our industries to take full advantage of the power and promise of genomics.

**Broadly speaking, our definition of genomics includes related disciplines such as bioinformatics, epigenomics, metabolomics, metagenomics, nutrigenomics, pharmacogenomics, proteomics and transcriptomics.*

For more information, visit
www.genomecanada.ca/en/sectorstrategies

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Published by Genome Canada, 2013

Cette publication est aussi disponible en français.

Genome Canada would like to thank the Government of Canada for its continued support.

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1. EXECUTIVE SUMMARY

In 2012–2013 key stakeholders across Canada were consulted as to the challenges and genomics opportunities for the fisheries and aquaculture sector. Individuals representing industry, government, and academia were contacted, and invited to participate in a national workshop, entitled **Canadian Fisheries and Aquaculture: A Strategy to Increase Competitiveness and Sustainability through the Application of Genomics**, held on April 11–12, 2013 in Toronto. The event was hosted by Genome Atlantic and Genome BC with support from Genome Canada and other Genome Centres. Prior to the workshop, participants were provided with a copy of a *Draft Genomics Sector Strategy Paper,* which was based on the extensive consultation and research process that took place during 2012–2013.

"Genomics–a vital link in the future success of Canadian fisheries and aquaculture"

The application of genomics[1] has the potential to provide Canada's commercial[2] and non-commercial fisheries with the tools to support strong, competitive growth based on product quality and security, technological soundness, economic viability, environmental integrity and social licence. The cross-cutting theme of this **Fisheries and Aquaculture Genomics Sector Strategy 2013 Paper** is that the genome sciences can, and should, support and inform the sustainable development and management of Canada's aquatic ecosystems and resources to the benefit of its people, its natural resources and the national economy.

Fisheries and aquaculture is a global sector of strategic importance to Canada. Capture fisheries and aquaculture supplied the world with about 148 million tonnes (Mt) of fish and fish protein in 2010 valued at $217.5 billion. Of this, global capture fisheries contributed about 90Mt and farmed fish production around 60Mt. Capture fisheries has, in all likelihood, reached its maximum global limit, and over 70 percent of the world's marine stocks or species groups are either fully-exploited, over-exploited or are depleted/recovering stocks.[3, 4] It is generally agreed that the global marine system is overstressed, experiencing a reduction in biodiversity and is anthropogenically challenged. Its major challenge and focus are conservation and sustainable marine biodiversity. Global farmed fish production is growing at 6.3 percent per year and priorities are increasingly being directed to achieving efficient, safe (most farmed fish is for human consumption), high-quality, and economic food protein production that has minimal impact on the ecosystems with which it interfaces.

Canada has 25 percent (243,000 km) of the world's coastline, on the Atlantic, Northern and Pacific coasts, an exclusive economic zone encompassing some 3.1 million km^2, and 16 percent of the world's fresh water. In total, commercial and non-commercial fisheries contribute $14.7 billion annually to the Canadian economy and support over 130,000 jobs. Yet Canada produces less than one percent of the world's fisheries (capture and farmed) product.

1 Genomics is defined as a branch of biotechnology concerned with applying the techniques of genetics and molecular biology to the genetic mapping and DNA sequencing of sets of genes or the complete genomes of selected organisms, with organizing the results in databases, and with applications of the data. The genome sciences include disciplines such as, genomics, transcriptomics, proteomics, metabolomics, metagenomics, systems biology and bioinformatics.

2 Commercial is defined as aquaculture production and capture (wild) fisheries landings; non-commercial is defined as recreational, cultural and subsistence fishing.

3 The State of World Fisheries and Aquaculture, 2012, FAO

4 Review of the Status, Trends and Issues in Global Fisheries and Aquaculture, with Recommendations for USAID Investments, USAID SPARE Fisheries & Aquaculture Panel

A modest increase in market share would result in substantial economic and social gains for Canada's industry, and its coastal, rural and Aboriginal communities.

Supported by funding from Genome Canada, large-scale projects such as the Atlantic Cod Genomics and Broodstock Project (CGP), Pleurogene (Halibut genomics), the Genomic Research on Atlantic Salmon Project (GRASP) and its successor, the Consortium for Genomic Research on all Salmonids Project (cGRASP), have resulted in Canada's recognition as a global leader in fish genomics. Researchers are supported by a first-class research infrastructure encompassing universities, research institutes, and federal research labs, as well as innovative companies. Success in the sustainable development and management of aquatic ecosystems will depend on reducing uncertainty and having a better knowledge of the impacts of highly complex issues such as climate change, anthropogenic forces, disease, population genetics, biodiversity, and wild and farmed fish interfaces. The application of Canada's fisheries and aquaculture genomics capacity to these challenges will support industry, communities and government to make strategic decisions based on sound scientific knowledge.

Clearly, and as shown above, there has been successful funding into genomics in Canada. However, would further investment in a genomics strategy for fisheries and aquaculture be good for Canada? Investors look for a select range of key indicators: global market size and growth potential, stable regulatory situation with timely decision approvals, investor certainty, security of tenures, a team with a record of success, commitment from the principals, the ability to differentiate the product from competitors, and in the case of the capture fishery a sustainable supply. As evidenced by production and consumption data and ongoing investments by other nations, the global fisheries and aquaculture sector will continue to exhibit excellent growth characteristics and provide an excellent return on investment.

Canada's track record of research success and excellence in fish genomics has been well supported with investments by industry and government. Genomics can play a major part in breeding the best species for commercial and non-commercial use, and can ensure that this is done in a sustainable manner, protecting and conserving the aquatic ecosystem of Canada's oceans, lakes and rivers. From the national workshop, five key research themes emerged to achieve economic, social and environmental sustainability:

1. **Translational research:** a continued focus on outcome-based genomics research, especially with respect to shellfish, new and invasive species;
2. **Genomics tools:** the development of practical, affordable, and trusted genomic diagnostics;
3. **Health and nutrition:** ensuring the conservation of wild stocks and satisfying the needs of consumers for quality protein, and to understand disease mechanisms and the determinants of stress;
4. **Species sustainability:** safeguarding the survival and conservation of aquatic species—both fin and shellfish—is vital to the maintenance of a thriving aquatic ecosystem and the Canadian fisheries and aquaculture sector; and
5. **Breeding programs:** from high-quality seedstock for hatcheries to elite broodstock for farms, breeding programs are essential for effective management, species planning and control of the outputs.

Genomics in the fisheries and aquaculture sector can, and should, support the balance between the need for economic and production efficiency, with social licence and the consent of the community, and the sustainability of the aquatic ecosystem. It is indeed "*a vital link in the future success of Canadian fisheries and aquaculture*" and a worthwhile investment for Canada.

2. THE IMPORTANCE OF THE FISHERIES AND AQUACULTURE SECTOR TO THE CANADIAN ECONOMY

The majority of the substantial impacts and benefits that fisheries and aquaculture generates for Canada are experienced in and by rural, coastal and First Nations communities—in every province and territory.

2.1 COMMERCIAL FISHERIES

Commercial (sea and freshwater) fisheries, aquaculture and processing contribute $6.4 billion in outputs (landings, production and processing), over 80,000 jobs and a positive trade balance of $1.5 billion to the Canadian economy.[5]

Integration of First Nations Fisheries is a national priority. The *Atlantic and Pacific Integrated Commercial Fisheries Initiatives*[6, 7] are designed to integrate First Nations fishing enterprises into existing commercial fisheries in order to provide economic opportunities for First Nations fishermen and to improve the overall management of fisheries on the Atlantic and Pacific coasts. To date the Government has invested over $730 million to provide First Nations access to commercial fisheries and to assist in building sustainable commercial fisheries enterprises. Canada's *Economic Action Plan 2013*[8] proposes to provide $33.1 million in 2013–14 to Fisheries and Oceans Canada to extend the Atlantic and Pacific Integrated Commercial Fisheries Initiatives.

2.1.1 Commercial Capture Fisheries

In 2011, commercial sea and freshwater fisheries' landings (including shellfish) totalled $2.2 billion and the industry employed over 50,000 fish harvesters and crew. Between 1990 and 2011, Canadian catches from capture[9] fisheries increased in value by 41 percent, but declined 48 percent by weight. The decline in finfish landings was mitigated by an increase of 72 percent by volume, and 220 percent by value, for shellfish landings. Shellfish now account for around 50 percent of the total volume and 77 percent of the value of landings. Lobster, shrimp and queen crab alone account for almost 70 percent of the value of total commercial landings.[10]

In 2011, according to Fisheries and Oceans Canada (DFO), 84.5 percent of value and 82.4 percent of volume of seafisheries (finfish and shellfish) landings originated from Eastern Canada[11] with the remainder from BC. In shellfish landings, 93 percent of value and 98 percent of volume are from Eastern Canada. East coast fisheries have much wider species diversity in comparison to the West coast: around 13 species are the foundation of the East coast fisheries and include groundfish species such as cod, haddock, halibut, redfish (rockfish), flatfishes, Greenland turbot, pollock and hake, and pelagic species such as herring, mackerel, swordfish, tuna and capelin. The highest value finfish in

5 http://www.dfo-mpo.gc.ca/stats/facts-Info-11-eng.htm

6 http://www.dfo-mpo.gc.ca/fm-gp/aboriginal-autochtones/aicfi-ipcia/index-eng.htm

7 http://www.pac.dfo-mpo.gc.ca/index-eng.html

8 http://actionplan.gc.ca/en

9 For the purposes of this paper, "capture" and "wild" are equivalent terms

10 DFO, Ottawa

11 New Brunswick, Newfoundland and Labrador, Nova Scotia, Prince Edward Island and Quebec

Eastern Canada is Greenland turbot, followed by herring and halibut; the species with the highest volume of landings is herring which at 141,929t is almost three times that of hake, its closest rival.[12] West coast fisheries are concentrated on redfish (rockfish), flatfishes, halibut, hake, herring, tuna, and salmon. Hake is the highest volume of landings followed by salmon and redfish, while, by value, salmon remains the leader followed by halibut and tuna. Landings of salmon have declined five-fold, by volume, since 1990, with 2011 figures showing landings at 20,417t with a value of $46 million.[13, 14, 15]

2.1.2 Aquaculture

The aquaculture industry provides 15,000 jobs (direct, indirect and induced) with operations in every province, as well as the Yukon. It has a gross value of more than $2.1 billion and provides around $1 billion toward Canada's gross domestic product.

Between 2001 and 2011, Canadian aquaculture production increased 40 percent by value to $846M, while production volume increased by just 6 percent. Harvested production has not demonstrated significant growth in the past decade, due in part in British Columbia (BC) to regulatory controls, and has averaged less than 160,000t per year from 2007 to 2011. Industry believes that opportunities for expansion and strong production growth remain, although this assumes a favourable business environment and an appropriate federal legislative framework to restore investor confidence.[16,17]

Salmon remains the main species produced, contributing 63 percent of total (finfish and shellfish) production volume, followed by shellfish (mussels and oysters) at 22 percent. It makes up 83 percent of finfish aquaculture production, and is predominantly located in BC, which accounts for 73 percent of production, followed by New Brunswick (NB), Newfoundland and Labrador (NL) and Nova Scotia (NS). Trout is second, providing 5.3 percent of production in 2011. It has shown 6 percent growth per year since 2007 and is mostly located in Ontario.[18]

Globally, Canada's aquaculture production represents less than one percent of world aquaculture production. It produces 6.25 percent of the Americas' output, ranking 5th behind Chile, the United States (U.S.), Brazil and Ecuador. With respect to high-value species, Canada's performance trends slightly more positively. For example, it accounts for 8 percent of global

[12] Ibid

[13] The decline in the sockeye population in 2008 prompted the setting up in 2009 of the Cohen Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River. The Commission's report was released in October 2012

[14] http://www.dfo-mpo.gc.ca/stats/commercial/sea-maritimes-eng.htm

[15] DFO, Ottawa

[16] Aquaculture in Canada 2012, A Report on Aquaculture Sustainability, DFO

[17] Aquaculture Statistics, 2011, Statistics Canada, November 2012

[18] Aquaculture Statistics, 2011, Statistics Canada, November 2012

farmed-salmon production ranking 4th behind Norway, the United Kingdom and Chile. Given Canada's considerable natural assets, world-class companies, and research excellence, there is little doubt that its aquaculture industry has the potential to surpass its current production.[19, 20, 21, 22]

2.2 RECREATIONAL FISHERIES

In 2010, Canada's recreational fishing contributed $8.3 billion[23] to the national economy and supported over 50,000[24] jobs. It attracts a high level of inward investment, with almost $140 million invested by non-residents and foreign anglers in 2010.

The segment is highly diffuse, located in small clusters with few major players. Overall, the popularity of angling is declining by an estimated 2 percent per year (domestic anglers) and 35 percent (visiting anglers) although this has been compensated for by increased per capita spending.[25] The reason for the decrease in popularity needs quantitative study, but various authors suggest issues such as changing angler demographics, damage or deterioration of the habitat, over-fishing, declining fish populations and an absence of management resources to fully assess status, as contributing factors.

Over 80 percent of freshwater fish landed in 2011 were from five species. In order, these were walleye (yellow pickerel), whitefish, perch, pike and white bass.[26] These and other species such as wild salmon, trout (Brook Trout in particular) and Arctic charr are critical to the sustainability of recreational fishing, which is, in turn, a key component of nature-based tourism in many provinces and the Northern Territories. For example, in 2001, in BC, salmon sport fishing accounted for approximately $231 million in output, contributed $116 million to provincial GDP, and provided 2,280 full-time equivalent[27] jobs.[28,29]

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19 Socio-Economic Impact of Aquaculture in Canada; prepared for Fisheries and Oceans Canada by GardnerPinfold Consulting Economists Ltd., 2010

20 Report to Launch the Aquaculture Sustainability Reporting Initiative, DFO, 2010

21 The State of World Fisheries and Aquaculture, 2012, FAO

22 http://www.canadainternational.gc.ca/norway-norvege/commerce_canada/aquanor07/aquaculture.aspx?view=d

23 This is made up of $5.8 billion in investment and $2.5 billion in direct spending. (It should be noted that the contribution of the commercial fisheries industry is primarily based on landings value and tonnage and hence direct comparison between the recreational and commercial sectors is not possible based on current reporting data.)

24 Likely due to its diffuse nature, there is a lack of up to date information on recreational fishing jobs. However, the Canadian Sport Fishing Association in 2000 put the figure at 47,400 jobs. A 2010 paper *A global estimate of benefits from ecosystem-based marine recreation: potential impacts and implications for management,* Andrés M. Cisneros-Montemayor and U. Rashid Sumaila, J Bioecon, published online August 2010 cited that in the U.S., $43,000 in direct expenditure on recreational fishing generates one full time job. Applying this to Canada's direct spending on recreational fishing of $2.5 billion would suggest about 55,000 jobs created.

25 Survey of Recreational Fishing in Canada 2010, DFO

26 DFO Statistics Branch

27 A full-time equivalent (FTE) job is a better measure of labour inputs to production, i.e., productivity. In Canada, one full-time equivalent is 40 hours per week.

28 Economic Value of the Commercial Nature-Based Tourism Industry in British Columbia. Pacific Analytics and Tourism British Columbia, in cooperation with the Wilderness Tourism Association, 2004

29 Special Committee on Sustainable Aquaculture, Legislative Assembly of the Province of British Columbia, May 2007. Final Report, P.1.

3. CHALLENGES IN THE FISHERIES AND AQUACULTURE SECTOR

The key challenge for Canada is how its fisheries and aquaculture sector can grow economically and efficiently, while managing its aquatic resources in a sustainable manner. A secondary challenge is the generation and application of information and tools to monitor and measure impacts, mitigate uncertainty, and provide decision-makers (government, industry and community) with a sound scientific basis for policies, regulations and programs.

3.1 COMMON CHALLENGES

While they may have differing needs and priorities, it is also true to state that capture, farmed and recreational fisheries have significant economic, biological and ecosystem interfaces and the sustainability of one may have an impact on either or both of the remaining segments. The arrays of challenges that face the overall sector and on which genomics can make a significant impact include:

1. **Understanding of genomics:** a key theme arising from the strategy workshop was that nationally the level of understanding of genomics and genomics tools within the sector is generally poor. Growers and fishers do not understand the science, the tools or their application; industry and academia are not fully informed as to the availability of genomics assets; and the public lacks access to good, independent information and so makes judgments based on the outputs of well-funded, special interest groups. There is also a lack of understanding of the economics of the application of genomic tools, i.e., the cost of development versus the benefits derived;

2. **Meeting market demand:** raises issues such as, increased production efficiency and product quality; sustainable harvesting; species exploitation; and the globalization of food production and distribution;

3. **Ecosystem sustainability:** maintaining healthy and productive ecosystems and animals, monitoring climate change impacts on the aquatic ecosystem, the role of aquatic species in environmental toxicology, species welfare and biodiversity and fisheries management;

4. **Supporting food safety:** product traceability, fish forensics, ensuring safe and healthy products, and understanding zoonotic disease transmission;

5. **Production sustainability and resource efficiency:** monitoring biophysical capacity; stockholding and alternate rearing environments; maintaining animal health and welfare through the development, validation and commercialization of vaccines and understanding host-pathogen relationships; and continuing the reduction of inputs such as feed;

6. **Social licence:** genomics and its related ethical, environmental, economic, legal and social aspects (GE^3LS) approaches need to be applied to a wide range of issues such as: encouraging stakeholder social responsibility and awareness; supporting certification, regulation, policy and national sustainability initiatives; ensuring an economically viable and competitive industry; communicating risk, i.e., ensuring that the public and other user groups understand what can be expected from genomics-based activities and that policy makers are informed of these views; supporting targeted, impactful research through better industry-academia collaborations and ensuring that translation of genomics research excellence benefits Canada; and informing the public and industry of the benefits of genomics-based tools and approaches.

3.2 CHALLENGES FOR COMMERCIAL FISHERIES

3.2.1 Capture fisheries

> **"The goals of conservation and a sustainable wild fishery are complementary. Conservation measures are intended to promote abundant, healthy stocks that may in turn permit harvest, while fisheries management activities regulate the catch so that future productivity is assured."[30]**

Specific challenges facing capture fisheries include:

1. **Fish migration:** understanding one of the most complex and intriguing biological phenomena in the animal kingdom is essential for the conservation of species, and its monitoring and management;

2. **Biodiversity:** the rate of loss (species and stocks) is estimated to be 100–1000 times greater than natural rates of extinction and it is estimated that 65 percent are fully- or over-exploited.[31] Biodiversity is essential for species survival, and biocomplexity is important for the stability of ecosystem services;

3. **Population genetics:** local populations should be conserved, as they provide genetic diversity and are often adapted better to local conditions. There is a genetic basis for local adaptation, but until recently these unique traits, including their plasticity, have been difficult to measure;

4. **Conservation genetics:** the conservation of wild fish genetic resources (FiGR) is a sustainability priority. Genetically diverse populations are more likely to survive and adapt to environmental stress and are needed by aquaculture for future breeding programs, e.g., Atlantic salmon and Arctic charr, where there may be a limited genetic base from which to draw;

5. **Economic sustainability:** achieving economic sustainability through the production of strong and sustainable stocks is a key challenge that could be addressed by genomics. However, a further challenge for capture fisheries is justifying investments in genomics when subsequently, due to ministerial discretion, there may be a lack of access to the resource; and

6. **Fisheries and aquaculture interactions:** competition, feral stock replacement, pathogen transmission between fisheries and aquaculture and vice versa, and genetic interactions all potentially impact the evolutionary trajectory of wild fish.[32, 33, 34]

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[30] Cohen Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River, October 2012

[31] Review of the Status, Trends and Issues in Global Fisheries and Aquaculture, with Recommendations for USAID Investments, USAID SPARE Fisheries & Aquaculture Panel

[32] The functional genomics of rapid evolutionary changes between domesticated and wild salmon populations, L. Bernatchez and Christian Roberge

[33] McGinnity.P et al, Fitness reduction and potential extinction of wild populations of Atlantic salmon, Salmo salar, as a result of interactions with escaped farm salmon, Proc. R. Soc. Lond. B (2003) 270

[34] John J. Piccolo and Ewa H. Orlikowska, A biological risk assessment for an Atlantic salmon (Salmo salar) invasion in Alaskan waters, Aquatic Invasions (2012) Volume 7, Issue 2: 259–270

3.3 CHALLENGES IN AQUACULTURE

Canada has recognized sustainability as the principal goal of aquaculture governance. To this end, implementation of Fisheries and Oceans Canada (DFO)'s *Aquaculture Sustainability Reporting Initiative (ASRI)* is seen as a Department priority and consistent with the DFO's lead role in managing Canada's aquatic resources and ensuring "*economically prosperous maritime sectors and fisheries, safe and secure waterways, and sustainable aquatic ecosystems for the benefit of present and future generations*".[35, 36]

A 2011 review of published literature found that, while salmon production may be at the higher end of environmental impact[37], overall aquaculture is more efficient and less damaging to the environment compared to other animal protein production systems such as beef and pork.[38] The industry's key challenges are:

1. **Improving environmental and economic sustainability:** a key challenge is the identification of commercially desirable performance traits, which will deliver increased production efficiency and profitability, and lead to new market opportunities while supporting the socio-economic well-being of coastal communities.

   Other challenges include the interaction between environment and health; minimising the potential impact of aquaculture on wild fisheries and the environment while maintaining fish health and quality; reducing inputs and operating costs; reducing the environmental footprint of production; developing more nutritious, sustainable diets and feeds; and developing and validating better treatments for disease;

2. **The growth of the shellfish industry:** from humble beginnings, shellfish are now an important part of the Canadian aquaculture sector. Production volume has risen rapidly, particularly on the East Coast, but there is a lack of understanding of bivalve genomics. For example, little is known about disease at the molecular level; the impact of invasive species, climate change and ocean acidification; or the production of reliable seedstock;

3. **Site productivity:** is a limiting factor of growth, mostly but not exclusively for shellfish, and overlaps with achieving sustainable development and socio-economic benefit;

4. **Biophysical capacity assessment:** is a challenge when determining suitable locations for industry growth and expansion; and resolving consumer education and awareness issues; and

5. **Informing policy and regulation:** future expansion of the national aquaculture industry may be limited by the lack of clearly defined, and agreed-upon oversight and regulatory environment.

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35 Sustaining Canadian Marine Biodiversity, an Expert Panel Report on Sustaining Canada's Marine Biodiversity: Responding to the Challenges Posed by Climate Change, Fisheries, and Aquaculture, Prepared by the Royal Society of Canada: The Academies of Arts, Humanities and Sciences of Canada, February 2012

36 Report to Launch the Aquaculture Sustainability Reporting Initiative, DFO, 2010

37 Salmon production methods in northern Europe, Canada and Chile are also considered to more efficient than those in China and other Asian countries (in terms of acidification, climate change, energy demand and land occupation).

38 Hall, S.J., et al, 2011. Blue Frontiers: Managing the Environmental Costs of Aquaculture. The WorldFish Center, Penang, Malaysia.

3.4 CHALLENGES FOR RECREATIONAL FISHERIES

In recreational fisheries, opportunities for genomics to play a significant role include addressing challenges such as:

1. **Ecosystem impacts:** there is little understanding of the impacts of climate change, anthropogenic contamination, and ecosystem interactions;

2. **Species selection:** the breeding and/or introduction of high efficiency/low environmental impact fish strains, and monitoring 'catch and release' stresses on the aquatic ecosystem are two challenges that could be addressed by a genomics approach;

3. **Stocking programs:** some of the most important recreational fisheries are supported by massive stocking programs where domestic (captive-reared) fish may interact with their wild counterparts. Yet little is known regarding these interactions, the costs vs. benefits of stocking practices or the effectiveness of hatcheries;

4. **Cultural and subsistence fisheries:** non-commercial species are important from an ecosystem perspective, yet little work has been undertaken to understand their importance in terms of ecological, cultural and subsistence functions and how genomics can support these species.

4. THE ROLE OF GENOMICS IN MITIGATING THE CHALLENGES AND CREATING THE OPPORTUNITIES

Expansion of the global library of scientific knowledge is a valid output of research, however an applied focus is needed to integrate Canada's academic research excellence in fisheries and aquaculture genomics with corporate innovation and technology deployment, and to achieve aquatic ecosystem and resource sustainability.

4.1 EXPANDING FISH GENOMICS KNOWLEDGE AND ITS USE

The Precautionary Approach adopted by the Government of Canada seeks to classify the status of a fish stock based on a scientific analysis of biological indicators. This is a driver in support of better and timely genomics information to help achieve Canada's conservation and management goals. For industry, the application of genomic research is no less important although its main driver is economic sustainability.

The timely access to research databases, dissemination of tools, expertise and assets is a key criterion for good science. High quality reference genome sequences, and high density marker development, validation and application continue to be critical to the translation of genomic discovery to improved animal production and health. Genetic stock identification technologies and databases need to be developed and populated, and basic genomic information is required for novel and exotic species before their role in production, conservation or ecosystem sustainability can be understood. The link between genotype and phenotype is not well understood.

4.2 FOOD PRODUCTION

Food production is a real opportunity for Canada's research capacity to work with industry in an area that can produce long-term impacts and benefits. The application of the genome sciences and genomics tools to the identification of valuable performance traits, and their incorporation into selective breeding programs (SBPs); managing disease; optimizing diets and feed; and ensuring hatchery effectiveness are clear opportunities.

The economic argument for SBPs using marker assisted selection (MAS) is very strong, with investments in efficient breeding programs having benefit to cost ratios ranging from 8:1 to 60:1.[39] Yet 90% of global aquaculture is still based on wild and genetically unimproved animals. Norway has a national aquaculture breeding program that now includes economically important traits such as age at sexual maturation, resistance to disease, fillet colour, fillet fat content and distribution, and body shape. SBPs in Canada are led by companies such as Cooke Aquaculture[40], Marine Harvest Canada[41], Icy Waters[42], Grieg Seafood and Mainstream Canada[43] who has the longest running, most advanced Atlantic salmon breeding programs in Canada. Other key genomics impact areas related to food production are:

[39] Development of Breeding Programs for Aquatic Species Should Be Given High Priority, Trygve Gjedrem and Karl Kolstad, September 2012

[40] http://cookeaqua.com/

[41] http://www.marineharvestcanada.com/

[42] http://www.icywaters.com/

[43] http://www.mainstreamcanada.com/

- **Human health:** supporting the establishment of industry standards, monitoring and product traceability to ensure biosecurity, and the health impacts arising from consuming contaminated products;
- **Resource efficiency and benefit:** fish feed is the largest single input in terms of cost. Genomics, and the emerging field of nutrigenomics, are integral to the development of new aquatic (seaweed) and crop-based feeds that move away from the unsustainable use of fishmeal;[44] and
- **Biophysical capacity:** investigating the efficiencies of land, marine and freshwater based systems in conjunction with targeted species/strains, and assessing opportunities for both land and offshore-based production.

4.3 FISH HEALTH

Fish resistance or tolerance to disease, pathogens and stress is not fully understood. Thus, research is urgently needed on infectious diseases and parasites, therapeutics and vaccine development, interactions between farmed and wild fish, and fin and shellfish host/pathogen relationships.

Fish in the wild generally have the ability to select favourable environments, whereas farmed fish do not and tend to be more vulnerable to disease and stress situations. The transmission of disease or infection from wild fish to farmed, and vice versa, tends to be a very 'charged' subject area and is in need of objective research, which will enable all stakeholders to understand and base their positions on current scientific knowledge.

One argument in favour of selective breeding programs is that high genetic gain is achievable for disease resistance. Examples of this are seen in the Infectious Pancreatic Necrosis (IPN) virus in Atlantic salmon, and bacterial cold water disease in rainbow trout. Application of genomics and genomics tools to better understand and identify secondary hosts of the MSX (Multinucleated Sphere Unknown) parasite in shellfish would have a direct economic impact on the farmed oyster industry in Aboriginal and rural communities such as those in the Bras d'Or Lakes region of Cape Breton.

4.4 CONSERVATION AND POPULATION GENOMICS

The coupling of genomics/functional genomics with telemetry has already made a significant impact on our understanding of wild fish migration and established real-time genotyping for fish migration. The combination of watershed-scale biotelemetry and functional genomics has yielded key information of survivorship of wild salmon. An example is the use of the salmonid microarray developed by the GRASP project to look at factors that may influence migration success in Fraser River sockeye. This microarray has also been used to look at impacts of pathogen carrier status (sea lice and IHNv) on wild salmon.[45, 46]

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[44] Based strictly on the improvement of feed utilization, it has been estimated that gains made through the national SBP for Atlantic salmon in Norway has saved the Norwegian salmon aquaculture industry $230M p.a. Clearly, the economic gain to the aquaculture sector in Norway is many times this figure when taking into consideration the gains made in growth rate, the reductions in mortality and the other performance and quality improvements that can be attributed to the Norwegian selective breeding programs

[45] Developing a Mechanistic Understanding of Fish Migrations by Linking Telemetry with Physiology, Behavior, Genomics and Experimental Biology: An Interdisciplinary Case Study on Adult Fraser River Sockeye Salmon, S.J. Cooke et al., Fisheries, Vol. 33, No. 7, July 2008

[46] Genomic Signatures Predict Migration and Spawning Failure in Wild Canadian Salmon, Kristina M. Miller et al., Science 333, 214 (2011)

In order to better understand, predict and manage impacts and benefits in recreational fishing, it is essential that more is learned about the differences at the genome level between domestic/stocked fish vs. wild populations.

The lack of genome information in wild fisheries limits the application of genome technologies in the assessment of the status and conservation of FiGR. For some species, the limited genetic base from which to draw on for breeding programs and importation or collection of new genetics from the wild is impeded by lack of regulatory clarity on these issues. Other opportunities for genomics interventions in the area of conservation and population genomics include:

- **Wild stock management:** monitoring population health, species abundance and local population groups is essential in wild fisheries to avoid overfishing, yet allow a sustainable harvest, and to conserve the integrity of the ecosystem; and
- **Impacts of aquaculture on wild stocks and vice versa:** genomics can play a major role in determining impacts and finding solutions for factors such as disease and parasites, escapement, the introduction of novel species, impact of therapeutics, competition for resources and genetic interactions.

4.5 ECOSYSTEM INTEGRITY

> **"The idea that a single event or stressor is responsible for the 1992-2009 decline in Fraser River sockeye is appealing, but improbable. DFO should develop and carry out a research strategy to assess the cumulative effects of stressors on Fraser River sockeye. DFO science managers should encourage innovation and new research into novel diseases and other conditions affecting wild fish."[47]**

Species survival and ensuring genetic variation, as well as the sustainability of coastal and inland water ecosystems, is a topic well-suited to a genomics approach. The aquatic ecosystem is subject to a wide range of impacts such as pollution, water salinity, oxygen and acidity levels that in turn place stress on fish. For example, salmon reproduction is strongly affected by riverine and estuarine habitat degradation decoupling resource requirements and resource availability through anthropogenic impacts of agriculture, logging, urban expansion, mining, and energy development.

Genomics can support the achievement of Canada's sustainability and aquatic biodiversity goals.[48] An example is using a metagenomics approach to understanding biodiversity in coastal areas and the effect of different environmental stressors, such as finfish and shellfish aquaculture, integrated multitrophic aquaculture (IMTA), agricultural run-off, and coastal urban

[47] Cohen Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River, October 2012

[48] Sustaining Canadian Marine Biodiversity, an Expert Panel Report on Sustaining Canada's Marine Biodiversity: Responding to the Challenges Posed by Climate Change, Fisheries, and Aquaculture, Prepared by the Royal Society of Canada: The Academies of Arts, Humanities and Sciences of Canada, February 2012

development. Furthermore, the role that fish, shellfish and other organisms play as sentinel species brings together for investigation areas such as environmental health, industry impact and ecosystem integrity.

4.6 SOCIAL LICENCE

Topics such as the economics of sustainability, societal risks, perceived risks and benefits of aspects of the fisheries sector, cultural ties and traditions and/or the role of First Nations, West versus East coast cultural, economic and social priorities, social justice, human adaptation to the changing environment, the integration of local and traditional ecological knowledge, raising stakeholder awareness and information dissemination all come under the banner of 'social licence'.

Hence, genomics and its related ethical, environmental, economic, legal and social aspects (GE^{3}LS) are integral to the successful application of genomics in the fisheries and aquaculture sector. A GE^{3}LS approach can address issues such as awareness, engagement, education and communications and how genomics information can contribute to informing policy. It can inform and prepare the dissemination of evidence-based information, prompt outreach to address public perceptions bridging the gap between perception and reality, and provide a channel for public feedback on key issues related to the application of genomics. It can also support the achievement of common understanding between diverse communities and cultures. Finally, a GE^{3}LS approach can address the economics of genomics tools and their application through cost-benefit study and analysis.

5. CANADA'S LEADERSHIP AND STRENGTHS

Canada's industry and government continues to show a commitment to large and small-scale genomics research in the fisheries and aquaculture sector. Industry continues to show its support and confidence in the sector through investments by many companies. Investment by federal and provincial government has been substantial, with public programming contributing over $130 million to date, largely to aquaculture- and capture-based projects. Despite the important economic value of recreational fisheries, relatively little has been invested with respect to supporting genomics research.

5.1 CANADA'S INVESTMENT

Genome Canada has invested $21.3 million in four internationally acclaimed projects. This investment has leveraged private sector, and other federal and provincial government program and international funding to achieve a project total of $43.6 million. In addition, with the support of industry and economic development partners, Genome Atlantic, Genome BC and Genome Quebec have raised an additional $23M for projects of importance to both capture and farmed fisheries.

Biotechnology and genomic tools and products contribute to the achievement of DFO's priority outcomes and the Department has strategically developed expertise and capabilities in biotechnology and genomics. The vision for DFO's *Aquatic Biotechnology and Genomics Research and Development Strategy*[49] is:

> **"A successful, innovative, dynamic biotechnology and genomics program to enhance the sustainability of our aquatic resources and the ecological health of our aquatic ecosystems, that is characterized by strong partnerships and stakeholder involvement; innovative research programs; the application of effective biotechnology and genomics tools and products; and funding to maintain required expertise."**

To support this vision, the DFO has invested millions of dollars in federal genomics R&D since the late 1990s. Furthermore, the DFO's *Aquaculture Collaborative Research and Development Program* (ACRDP)[50] from 2010 to 2011 contributed $32.5 million towards 326 projects with a total value of $70.0 million—many of which had a major genomics component.

Other programs have supported fisheries and aquaculture projects with genomics content. For example, the Natural Sciences and Engineering Research Council contributed $24 million, and the National Research Council's IRAP program has contributed $3.2 million in support of aquaculture SMEs.

[49] Aquatic Biotechnology and Genomics Research and Development Strategy, DFO

[50] http://www.dfo-mpo.gc.ca/science/enviro/aquaculture/acrdp-pcrda/index-eng.htm

5.2 CANADA'S LEADERSHIP

Canada's investments in large-scale genomics projects have resulted in Canada being recognized as a global leader in the genomics of fish and shellfish, and has contributed significantly to the ranking of the quality of Agriculture, Fisheries and Forestry research as second in the world—behind the U.S.[51] This research excellence and capacity is supported by a first rate research infrastructure that encompasses universities, research institutes, federal research labs, companies and technologies.

Cutting-edge research continues to be conducted on the application of genomics to traditional species such as cod, halibut, salmonids such as Pacific and Atlantic salmon, trout and whitefish, eels, and emerging species of economic importance such as Arctic charr, Brook charr and sablefish. It also continues to be applied to cross-cutting projects that impact both wild and farmed stocks such as the DFO's SLICE® project and Genome BC's GiLS project. Advances and application developments in biotechnology and genomics present the potential of low-cost biotechnology applications with greater sensitivity, accuracy, faster results and increased efficiency.

Canada's research capacity, by supporting high-growth strategies through the application of next generation genomics technologies; improving product quality, production efficiency, and environmental sustainability of farmed species; and ensuring wild species conservation and protecting ecosystem biodiversity, works to give Canadian fisheries and aquaculture a competitive advantage in the global market.

[51] The State of Science and Technology in Canada, 2012, Council of Canadian Academies

6. SUCCESS OF PAST CANADIAN INVESTMENTS IN FISHERIES & AQUACULTURE GENOMICS

The genomic sciences continue to form a significant component of Canada's research program and Canadian genomics research can point to important successes in:

- **Disease Resistance:** the development, through marker-assisted selection, of IPN resistant strains of Atlantic salmon was achieved through the genomic identification of quantitative trait loci (QTL) that confer resistance;
- **Population Health:** the identification of a genomic signature associated with increased mortality in migrating Fraser River Sockeye salmon;
- **Stock Management:** the microarray chip developed by the GRASP and cGRASP projects is used in over 70 labs worldwide and by the DFO to monitor wild salmon stocks; and
- **Production Efficiency:** a 20% reduction in grow out time to market for halibut came as a direct impact from the Pleurogene project.

Genome Canada, in partnership with Genome Atlantic, Genome BC and Genome Quebec, as well as regional economic development agencies and industry, has supported:

- **The Atlantic Cod Genomics and Broodstock Project (CGP)** has contributed to cod aquaculture through the identification of genetic markers, and the construction and development of genetic maps and tools for marker-assisted selection (MAS);[52]
- **The Genomics Research on Atlantic Salmon Project (GRASP)** and Consortium for Genomic Research on all Salmonids Project (cGRASP) projects, which have produced many genomics tools and resources for salmonids, including gene lists, genetic markers and microarrays. The Atlantic salmon genome sequence will also act as a reference genome for other salmonids;[53, 54] and
- **Pleurogene–Flatfish genomics: enhancing commercial culture of Atlantic halibut and Senegal sole** was a partnership between Genome Canada and Genoma España and produced the world's first genetic linkage map of Atlantic halibut. This gave Canadian producers a key tool for improving productivity and competitiveness by increasing broodstock development capabilities.[55]

Smaller-scale research projects continue to be undertaken and demonstrate a mix of innovation, leading-edge expertise, industry partnering, the use of advanced genomics technologies, and diversification of the range of species. Examples include:

- **Genomics in Lice and Salmon (GiLS):** Sea lice infections of salmon populations threaten an important economic and environmental resource in BC. GiLS made use of genomics to understand the host-pathogen interaction between different salmon populations and lice;[56]

[52] http://www.genomeatlantic.ca/projects/view/8-The_Atlantic_Cod_Genomics_and_Broodstock_Development_Project_CGP

[53] http://www.genomebc.ca/portfolio/projects/fisheries-projects/completed/genomics-research-on-atlantic-salmon-project-grasp/

[54] http://www.genomebc.ca/portfolio/projects/fisheries-projects/completed/consortium-for-genomic-research-on-all-salmonids-project-cgrasp/

[55] http://www.genomeatlantic.ca/projects/view/6-Pleurogene_Flatfish_genomics_enhancing_commercial_culture_of_Atlantic_halibut_and_Senegal_sole

[56] http://www.genomebc.ca/portfolio/projects/fisheries-projects/genomics-in-lice-and-salmon-gils/

- **TREAT2–the development of sustainable treatments targeted at sea lice infestations in cultured salmon:** supported with funding by the Atlantic Canada Opportunities Agency's Atlantic Innovation Fund and led by Novartis Animal Health Canada with partners Atlantic Veterinary College - University of Prince Edward Island, University of Guelph and the University of Victoria;
- **Atlantic salmon:** Mainstream Canada, Simon Fraser University (SFU)[57] and CIGENE, Norway[58] are working on MAS to identify quantitative trait loci (QTL)[59] associated with body-weight traits;[60]
- **Arctic charr:** Icy Waters Ltd. has developed a strong broodstock program in collaboration with SFU. The company's current focus is the discovery of genetic markers associated with disease and stress; the Institut de recherché sur les zone côtières, Université de Moncton[61] was awarded funding under the 2011 Round of the Atlantic Innovation Fund to create a national Arctic charr genetic improvement program;
- **Sablefish Genomics:** sablefish is an economically important species in commercial fisheries of the North Pacific and an emerging species in aquaculture. The industry is valued at over $300 million in North America, yet, to date, little was known about its genetics. This project undertook a preliminary characterization of genetic markers. The resultant genetic map is thought to represent the first linkage map for a member of the Scorpaeniformes and will allow for the successful development of future broodstock and mapping of phenotypes of interest;[62, 63, 64]
- **Genomic Tools for Fisheries Management (FishMan Omics):** this project will identify biomarkers and use them to assess the overall health and condition of migrating wild salmon fish stocks;[65]
- **Development of a health assessment tool for marine mussels (Myt_OME):** the project developed genomic resources and tools for two commercially important species of marine mussels, thus enabling more accurate health assessments of coastal zones

57 http://www.sfu.ca/

58 http://www.cigene.no/

59 Quantitative trait loci (QTLs) are stretches of DNA containing or linked to the genes that underlie a quantitative trait.

60 Genetic Mapping of Quantitative Trait Loci (QTL) for Body-Weight in Atlantic Salmon (Salmo Salar) Using a 6.5K SNP Array, Aquaculture 358-359 (2012) 61-70

61 http://www.umoncton.ca/

62 Application of Genome Science to Sustainable Aquaculture, Proceedings of a special session held at Aquaculture Canada, 2009

63 http://www.genomebc.ca/portfolio/projects/fisheries-projects/completed/sablefish-genomics/

64 Genomics of sablefish (Anoplopoma fimbria): expressed genes, mitochondrial phylogeny, linkage map and identification of a putative sex gene, Rondeau et al. BMC Genomics 2013, 14:452

65 http://www.genomebc.ca/portfolio/projects/fisheries-projects/genomic-tools-for-fisheries-management-fishman-omics/

and facilitating the ability to monitor the effects of the changing environment;[66] and

- **GreenSNPs: an enabling technology for environmental genomics in aquatic or land animals and plants:** one of the activities of this project is centered on the American eel with impacts on the management of exploited stocks, aquaculture development, and environmental health related to effects of pollutants.[67]

In other innovative developments, DFO's *National Aquatic Animal Health Program* (with laboratories in Moncton, Winnipeg and Nanaimo) uses molecular techniques to develop validated tests for diseases, including MSX, listed as reportable or immediately notifiable in the Health of Animals Act[68]; the Aquatic Wildlife Division (AWD, Quebec) has started to include genomic tools in its current practices and has put in place the mapping and monitoring of Quebec's salmon and trout populations using population genetics; Genome BC has partnered with Chile and Norway in an International Cooperation to Sequence the Atlantic Salmon Genome; and Genome Atlantic has supported the *Camelina: Developing Canada's Next Oilseed Project,* which aims to develop a crop-based, low-cost alternate to fish meal.

[66] http://www.genomebc.ca/portfolio/projects/fisheries-projects/genomic-tools-for-fisheries-management-fishman-omics/

[67] http://www.genomequebec.com/en/your-environment.html

[68] http://laws-lois.justice.gc.ca/eng/acts/H-3.3/

7. THE SOCIO-ECONOMIC IMPACT OF SUCCESSFUL GENOMICS ENABLED SOLUTIONS

The fisheries and aquaculture sector is vulnerable to often competing natural, socio-economic, political, environmental and technological forces. The successful application of genomics, whether in breeding programs, stocking management, population genetics, reduced inputs, disease management and prevention, conserving biodiversity or ecosystem management, will have a direct impact on provincial and national economies, and the Canadian aquatic ecosystem.

Genomics research, and the application of genome-based tools, can provide insights to complex aquatic challenges and support the sustainable development and management of this important resource. In doing so, it will contribute to: rural, coastal and Aboriginal community economic development; industry growth and international competitiveness; an understanding of the interactions and impacts between recreational, capture and farmed fisheries; an informed policy and regulatory environment resulting in effective fisheries management planning; and a thriving and sustainable national aquatic resource.

Furthermore, in the specific area of social licence, the GE^3LS component is a critical mechanism for ensuring that all stakeholders fully understand their roles and responsibilities and the social, ethical, regulatory and environmental impacts of genomics-based approaches; that the data is seen as transparent and objective; and that the evidence of these impacts are widely available.

7.1 COMMERCIAL FISHERIES

7.1.1 Capture Fisheries

Capture fisheries provides employment for over 50,000 people, largely in rural, coastal and Aboriginal communities. Key to a stable capture fishery is the management and conservation of a diverse range of capture FiGR while simultaneously exploiting, in a sustainable manner, the potential of indigenous crustacean, shellfish and finfish populations such as Arctic charr, trout, whitefish, walleye and sablefish. This is a key socio-economic impact and a driver of genomics research.

To accomplish this, good information on areas such as species origin, population genetic diversity, and population migration is vital. Research is needed to provide reliable information that will help address serious issues such as escapement and disease transfer, and can support the promotion of evidence-based dialogue between capture and farmed fisheries.

7.1.2 Aquaculture

The genome sciences can directly impact the socio-economic well-being of Canadians by supporting the efficient and profitable production of high-quality protein in a safe, secure and sustainable manner. In 1986, Canadian aquaculture production amounted to only 10,488 tonnes, valued at $35 million; by 2006, production had grown to 171,829 tonnes with a value of over $912 million. Aquaculture now accounts for 14% of total Canadian fisheries production and 33% of its value. Farmed salmon is British Columbia's largest agricultural export product, and the largest crop in the New Brunswick agri-food sector. Over 8,000 Canadians are directly employed in aquaculture—most of them full time. The aquaculture supply and services sector creates an additional 8,000 jobs. Two-thirds of all workers are under the age of 35.[69]

In a highly competitive market, finding the most efficient manner to operate profitably while being environmentally and socially responsible will ensure the long-term viability of the Canadian farmed fish and shellfish industry.[70] Successful genomics-based applications, such as SBPs and MAS, will provide industry with the tools needed to support production growth and enable it to compete with greater success for global market share. The application of the genome sciences to the complexities of the aquatic ecosystem will also provide hard data for the management and regulation of the industry.

Aquaculture has proven economic benefits within each province and nationally. An increased economic benefit in one province will therefore have substantial economic impacts nationally.[71] The industry has positive socio-economic impacts, particularly in rural, coastal and Aboriginal communities such as Charlotte County, NB, and Ahousaht (Ahousaht First Nation), Tsaxana (Mowachaht Muchalaht First Nations), and Klemtu (Kitasoo First Nation) in BC, among many others.[72] Much of the employment growth in communities such as these can be attributed to the expansion of the aquaculture industry as other sectors have stabilized or declined. A successful aquaculture industry attracts investment, increases social well-being within rural and coastal communities, and helps retain and attract young people to the community by offering a wide range of skilled employment opportunities.

7.2 RECREATIONAL FISHERIES

Recreational fisheries is a highly dispersed, community-based activity with international appeal and a clear source of wealth, jobs and investment for rural communities as well as tax revenues for provincial and federal governments. To ensure continued socio-economic benefits from this sector, our lack of understanding of anthropogenic, climate change, stocking, 'catch and release', and biodiversity (local population groups) impacts on the aquatic ecosystem, will need to be addressed.

[69] Canadian Aquaculture: An Important Economic Contributor , http://www.aquaculture.ca/files/economic-benefits.php

[70] Report to Launch the Aquaculture Sustainability Reporting Initiative, DFO, 2010

[71] Socio-Economic Impact of Aquaculture in Canada; prepared for Fisheries and Oceans Canada by Gardner Pinfold Consulting Economists Ltd., 2010

[72] http://www.dfo-mpo.gc.ca/aquaculture/ref/aqua-es2009-eng.htm#ch22

8. NEXT STEPS TOWARD SUCCESS

"Genomics–a vital link in the future success of Canadian fisheries and aquaculture"

From the fisheries and aquaculture workshop, there was a consensus among industry and academia that Canada needs a national strategy for the fisheries and aquaculture sector. Such a strategy would address challenges such as sector fragmentation and coordination, sustainability for each stakeholder unit, an economic model for fisheries, the need for a long-term funding model, and realistic expectations and timelines for the impact of key drivers, such as genomics. While recognizing that this may be a longer-term aspiration, what can be achieved in the short-term is an agreed Genomics Strategy for Canadian Fisheries and Aquaculture.

This national genomics strategy should focus on giving industry, academia and government the tools to propel Canada to sustainable international leadership in the essential, but highly competitive, global fisheries and aquaculture sector. Building on the capacity and infrastructure generated through previous investments, the genome sciences can help support and maintain Canada's competitiveness against jurisdictions such as Europe and Chile, who continue to invest heavily in the use of genomics in national aquaculture breeding programs, and in capture fisheries through projects such as AquaTrace[73], FishTrace[74], and SALSEA[75].

To be effective in defending and exploiting Canada's aquatic ecosystem, there will need to be productive collaborations between a diverse range of stakeholders and interest groups including industry, academia, government, First Nations, consumers and the general public, underpinned by compelling communications and education.

Nationally, genomics can make a beneficial social and economic impact by supporting sustainable sector growth. This growth should balance the needs of industry for efficient and profitable protein production, with the management and conservation of wild stocks—commercial and non-commercial, and associated marine ecosystems.

Discussions at the national fisheries and aquaculture workshop generated a fertile base of research ideas, as well as identifying, confirming and augmenting the sectoral challenges and opportunities previously identified in the consultation process and strategy development. The content of these dialogues provide a solid platform that the fisheries and aquaculture sector can build on and identify as its "*next steps towards success*". While the diversity and range of research proposed was considerable, five key themes where an investment in genomics would ensure sustainable sector growth and national leadership were apparent:

1. **Translational or outcomes-based research:** industry and academia agree that there is a requirement for understanding the genomes of traditional, novel and invasive species. This ranges from determining reference genomes that provide the foundation for future work, to the identification of biomarkers for desirable traits such as disease susceptibility, species origin, and carcass quality in commercial and non-commercial fisheries. Basic research also extends to understanding organisms in the associated ecosystems and their ecosystem interactions.

   There is a lack of understanding of the genomics of shellfish (including lobster). Given the rapid rise in shellfish production and its increasing importance as an industry sector, there is a priority need to address this knowledge gap, especially with respect to broodstock development, early maturation and disease resistance;

[73] https://aquatrace.eu/

[74] https://fishtrace.jrc.ec.europa.eu/fishtrace/composite.action

[75] http://www.nasco.int/sas/salsea.htm

2. **Genomics tools:** practical, affordable, and trusted "in-field" genomic diagnostics are needed at all levels of the sector. Such tools would have wide application not only in wild, capture, recreational and farmed stock monitoring, tracking and management, but also in the regulatory field, e.g., by DFO;

3. **Health and nutrition:** health and nutrition is a cross-cutting research theme that can ensure the conservation of wild stocks and satisfy the needs of consumers for quality protein. Investment is needed to understand and determine the genomics of disease and parasite infestation and the production of targeted, environmentally friendly treatments, e.g., vaccines; to optimize sustainable diet and nutrition characteristics; and to understand the causes and socio-economic impacts of environmental and production stress on species. Health and nutrition is a needed focus with practical application in the short- and longer-terms;

4. **Species sustainability:** ensuring the survival and conservation of aquatic species—both fin and shellfish—is vital to the growth of the Canadian fisheries and aquaculture sector and a thriving aquatic ecosystem. Key focus areas for research highlighted by the workshop include: understanding population management units and stock structure; the interaction between wild and farmed species; disease, parasite and pathogen transportation; tracking species mortality; and the impact of climate change and anthropogenic stressors on the aquatic environment—oceans, rivers and inland waters; and

5. **Breeding programs:** breeding programs are essential for effective management, species planning and control of the outputs from farms. This applies to the production of high-quality seedstock for hatcheries, to elite broodstock for the aquaculture industry and to restocking programs in recreational fisheries. Selective breeding programs allow the validation of biomarkers for key production, stress and disease susceptibility traits, and the elucidation of phenotype-genotype linkages. Understanding and alleviating the stress of fish populations was identified of particular importance for aquaculture.

To underpin and increase the effectiveness of the application of genomics to fisheries and aquaculture, there are a select number of areas that need to be considered:

- **Communications and education:** at all levels of the sector value chain, and within many stakeholder or interest groups, there is a low level of understanding of the utility or value of genomics. A comprehensive, ongoing public communications, dissemination and education strategy is required to support social licence, highlight benefits and dispel inadequate and/or misinformation. Such a strategy will require a commitment to identifying and responding to the priorities and needs of the public, and other user groups.
- **Building trust:** to be effective, genomics research, and its application, has to be seen as objective by industry, academia, the public and government. Achieving this will entail creating a platform to encourage transparency in the generation, publication and use of data, and for data sharing. It will also require the development of models for structured collaboration, particularly between industry and academia, and the recruitment of committed, sector champions.

In conclusion, the consultation process that has accompanied and provided a mine of goodwill, information, and comment for the **Fisheries and Aquaculture Genomics Sector Strategy Paper** has been a positive, constructive step in the evolution of an impactful national strategy that makes the best use of Canadian genomics expertise and industry leadership, while building social licence through effective communications and education.

ACKNOWLEDGEMENTS

Thanks are due to the members of the national steering committee of government, academic and industry representatives, which was assembled to support the development of the Fisheries and Aquaculture Genomics Sector Strategy Paper. The committee members were:

- Louis Bernatchez, Chaire de recherche du Canada en Génomique et Conservation des Ressources Aquatiques, Université Laval, QC,
- Brian Blanchard, VP and General Manager, Scotian Halibut Ltd., NS,
- Jason Cleaversmith, Head of Aqua Health PEI, Novartis Animal Health,
- William S. Davidson, Professor, Department of Molecular Biology and Biochemistry, Simon Fraser University, BC,
- Jessy Dynes, Chef de Service, Service de la faune aquatique, Ministère des Ressources naturelles et de la Faune du Quebec, QC,
- Ben Koop, Professor, Faculty in Biology, University of Victoria, BC,
- Jay Parsons, Director, Department of Fisheries and Oceans—Aquaculture and Science Branch, ON,
- Debbie Plouffe, Vice President Research, Center for Aquaculture Technologies Canada, PEI,
- Brian Riddell, Chief Executive Officer, Pacific Salmon Foundation, BC,
- Ed Safarik, Former President and CEO, Ocean Fisheries Ltd., and Board Member of Genome BC,
- Brian Skinner, ingénieur forestier, Ministère des Ressources naturelles et de la Faune du Quebec, QC, and
- Mary Ellen Walling, Executive Director, BC Salmon Farmers Association, BC.

We deeply appreciate the support and input from industry, academia and government who attended the national workshop and to those who provided feedback during the workshop pre-consultation.

The Genome Centre contributors to the management of the strategy development process and the organization and delivery of the national workshop were key to the success of this initiative. They include:

- Steven Armstrong, President and CEO, Genome Atlantic,
- Shelley King, VP Research and Development, Genome Atlantic,
- Sue Coueslan, Director of External Relations, Genome Atlantic,
- Gabe Kalmar, Vice President, Sector Development, Genome British Columbia,
- Tony Brooks, Chief Financial Officer, Genome British Columbia,
- Rachael Ritchie, Director, Business Development, Genome British Columbia, and
- Catalina Lopez-Correa, VP Scientific Affairs, Genome Quebec.

Finally, our thanks to David Millar, Executive Chairman, Haisley Millar Consulting Group, TX who provided support in the researching and drafting of the paper and delivery of the pre-consultation process; and to the staff from Genome Atlantic (David Spurrell and Kim Johnstone) who assisted in providing reference sources and publications.

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