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

Genome BritishColumbia

Leading ▸ Investing ▸ Connecting

2018 Revision

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Executive Summary

British Columbia's extensive forests are vital to our environment and resource-based economy. Covering more than 55 million hectares, the second largest forest cover in Canada, BC's forests not only absorb greenhouse gases and provide clean air, water and a host of ecosystem services, they are an economic engine of the province. BC's forest sector employs over 65,000 people and supports over 140 rural and indigenous communities. It generates ~$1.7 billion of tax revenues, contributes to $8.8 billion to the provinces' gross domestic product (GDP) and ~38% (~$12 billion) of Canada's total forest sector exports. BC is also the world's leading exporter of softwood lumber products, and a major producer of pulp, paper, and bioenergy. However, in the recent years, this dominance has been frequently challenged by a changing geo-political and socioeconomic environment.

The forestry sector is facing tremendous pressure to maintain sustainability, especially in the face of climate change, particularly temperature extremes, shifting patterns of disease, and invasive species outbreaks. There are also challenges with respect to competitiveness, from factors such as rising costs, trade issues, and competition from digital media, all of which have negatively impacted BC's forest sector. The result is jobs losses, mill closures, and a decline in demand for key products including newsprint. For the sector to remain globally competitive in the long term, it is imperative to diversify and adopt innovative technologies.

Genomics has emerged as one of the promising technologies to maintaining healthy, resilient, and productive forests. Realizing its potential, Genome BC has significantly invested in genomics and facilitated the development of tools that are leading to: reduction of the costs and time associated with traditional tree breeding, efficient surveillance of forest pests and pathogens, and the development of new bio-based processes.

This document lays out a strategy to expand on previous Genome BC investments in genomics-based research to improve the sustainability and productivity of the forest sector. It places an emphasis on downstream applications to create a zero waste and self-sustaining forest sector by valorizing forest waste residue to produce bioproducts and bioenergy. It also emphasizes the need to develop tools for systemic foresight into the use of new technologies that can guide policy decisions benefiting forest dependent communities and the bioeconomy. The overarching goal of Genome BC's forest sector strategy is to distill knowledge of 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 British Columbia's Forest Sector

Forests are BC's largest renewable resource and a vital part of the provincial economy. Covering close to two-thirds of the province—an area of almost 55 million hectares— BC's world-famous forests weave together the cultural, economic, and political fabric of the province, and are the foundation of many rural communities. Our forests support an industry that is recognized globally as a leader in sustainability with more land certified to internationally recognized sustainability standards than any other jurisdiction in the world[1]. Furthermore, forest products are BC's largest export and generate twice the income of energy products, the next-largest source of revenue.

Since the global economic downturn in 2009, one of the worst years for BC's forestry industry in recent history, the sector has diversified its market and rebounded. In 2016, forestry accounted for almost $14 billion in exports – 35% of the value of all BC goods exported and almost double of the $7.6 billion from 2009[2]. The sector also contributed $8.8 billion in GDP as well as $1.7 billion in total tax revenue[3]. This revenue is a critical source of funding for building BC's infrastructure and providing government services. Accordingly, the sector remains a top priority for the BC government, reflected in various government publications, reports, and initiatives. Continuing with the efforts, particularly those initiated since 2009, and building on the 2012 Forest Sector Strategy[4], BC Government's Ministry of Forests, Lands, and Natural Resource Operations (FLNRO) has recently (2016) developed a Forest Sector Competitiveness Agenda, with an objective to maintain a globally competitive, high value, and sustainable Forest Industry[3].

The overarching goal for BC is to grow healthy, resilient forests and to continue to build a diverse and globally-competitive industry, one that will provide stability for forestry-dependent communities and First Nations.

The forestry sector accounts for nearly a quarter of all direct manufacturing employment in BC and directly employs more than 65,000 people in over 140 communities. Overall, it supports 145,800 jobs, with annual revenue of $15.7 billion[1]. According to one estimate, 40% of BC's regional economies are forest-dependent and work across the breadth of the forestry product value chain. Workers 'upstream' in the value chain are employed in forestry and logging activities such as planning, planting, forest management, road-building, and harvesting. Those employed 'downstream' in the value chain are engaged in: wood product manufacturing; pulp, paper, and bio-refining; and, forest product marketing. BC also hosts a network of forest specialists in government, academia, and industry, who are working to improve forest health, breed better trees, diversify forest products, and extract value from bioproducts. The overall objective is to valorize the entire biomass found in forests, from roots, trunks and branches to their bark, needles, leaves and fruit.

> BC is one of the world's largest exporters of softwood lumber products, and a significant global producer of pulp, paper, and bioenergy.
>
> As a primary industry, forestry contributes 3.5 per cent to provincial GDP and is the foundation for BC's manufacturing sector.
>
> In 2015, the value of Canada's forest production was $32.7 billion. The value of BC's annual forest industry production represents 37% of Canada's annual total.

This strategy is intended to outline a path for the development and application of genomics to support the

forestry sector and address current and future challenges and opportunities. As part of the efforts to promote innovation in forestry sector, Genome BC aims to build new partnerships, while strengthening existing ones, between researchers, industry, and government. Genome BC seeks to play a leadership role by bringing stakeholders together and facilitating the delivery of benefits.

This strategy provides an update of actions consistent with the priorities identified in the Genomics Strategy developed by Genome BC in consultation with sector stakeholders in 2013-2014. It is by its nature designed to complement and align with co-existing sector strategies from industry and government.

BC's Forest Resource

BC has 55 million hectares of forests, of which 95 per cent are publicly owned. They are particularly rich in biodiversity, harboring 49 native tree species that support 33 per cent of the province's flora and fauna at some point in their life cycle. Coniferous, or softwood, species such as pine, spruce, fir, hemlock and western red cedar are predominant, representing about 90 per cent of BC's forests, with deciduous (hardwood) representing a much smaller fraction[5, 6]. Each year, roughly 75 million cubic metres of timber is harvested in BC: about70 per cent from the interior, and the rest from coastal areas[5]. The main species harvested in BC's interior is lodgepole pine followed by spruce, whereas hemlock and Douglas-fir make up roughly two-thirds of the harvest in coastal areas. The wood products and the pulp and paper industries continue to drive forest sales. In 2016, the highest revenue in the sector was generated by wood products (about$10 billion), followed by pulp and paper products (about $4 billion)[1]. The United States of America (U.S.), with 53% of market share, continues to dominate the BC export market; however, in recent years, Asia - particularly China (with Hong Kong), Japan, and India - have emerged as markets with high potential for growth.

The sustainable management and productivity of forest land is shaped by government regulations, market forces, and social factors. Since 2009, the BC government has made continuous efforts to maintain the global leadership and sustainability of the sector. To this end, the 2016 Forest Sector Competitive Agenda, built on the outcomes of previous roundtables as well as BC Forest Sector Strategies, outlines areas considered strategically significant by the government. It identifies three goals: (a) Healthy, Resilient Forests, (b) Diverse, Globally Competitive Industry and, (c) Stable Communities and First Nation Partners. Each goal has been assigned several objectives and associated strategic actions in order to achieve them.

Realizing that traditional advantages alone will not ensure the long-term success of the BC forest sector in the 21st century, the government, in collaboration with FPInnovations, has also developed a Clean-Tech Innovation Strategy for the B.C. Forest Sector[7]. Addressing enhanced economic viability, environmental sustainability, and aboriginal and community technical supports, the Clean-Tech strategy is committed to adapting, adopting, and developing cutting-edge innovations aimed at benefiting BC's forestry sector in the new competitive realities of the global clean-tech and natural resource based bioeconomy. To realize the objectives of these strategies, the following three constituents of the sector will play a critical role:

1.1 Softwood Lumber

BC is one of the world's leaders in terms of softwood lumber products, with exports going to markets in Europe, Asia and the U.S.[2]. However, the lingering softwood lumber trade dispute with the U.S. is having a significant impact on the industry and associated communities in Canada. The BC Government is a key partner to the federal government in ongoing efforts to re-negotiate a trade agreement with the U.S. and Mexico. Another key priority for the province is to continue diversification of softwood lumber exports away from the U.S. and toward Europe, South America, and countries in the Asia-Pacific region. At the provincial level, with the 2009 Wood First Act, BC is promoting a "Wood First" culture to ensure that wood is the material of choice for constructing new buildings and biomaterials. The Forestry Innovation Investment (FII), established in 2003, is also playing a crucial role in implementing these strategies for diversification of domestic and international markets for BC forest products.

1.2 Pulp and Paper

BC's pulp and paper industry processes as much as 50 per cent of the total volume of timber harvested in the province each year[7]. The industry's symbiotic relationship with the sawmills is critical for securing residual chips, shavings, sawdust, and hog fuel as primary inputs for pulp and bioenergy production. The pulp and paper industry complements the lumber industry by generating value from lower quality timber not suitable for manufacture into lumber and other solid wood products. BC's new Forest Fibre Action Plan and the report on pulp and paper sector sustainability prioritize generating more value from the province's forest resources and become a leader in the production of low-carbon, sustainable products. By focusing on maximum utilization of fiber, bioenergy production, and innovative bioproducts, while giving due attention to environmental considerations and engagement with first nations, the industry can implement these priorities.

1.3 Biorefineries

Biorefineries are seen by many as key components of a strong, diversified bio-based economy. These will enable efficient conversion of a broad range of biomass feedstocks into commercially viable biofuels, bioenergy, and other bioproducts that can be used well beyond the premises of lumber and pulp and paper industries. By integrating combinations of feedstock and conversion technologies, the production can be expanded beyond biofuels to speciality chemicals and biomaterials. Although still in its infancy, the concept of biorefineries exist in Canada, including BC. A number of pulp and paper mills have responded to increased international competition and reduced global demand for forest products, such as newsprint, by integrating biomass conversion processes and equipment into their operations to produce a wide range of bio-based, non-traditional products[8]. These mills are already producing biofuels, high value strengthening materials such as Nanocrystalline cellulose (NCC) and cellulose filaments (CF), and a host of other biochemicals. Production of wood pellets is another lucrative option[9].

Active collaboration between government agencies, academia, and industry is critical to the implementation of these priorities and create the deliverables needed to fulfill the BC government's vison of "a vibrant, sustainable, globally competitive forest sector that provides enormous benefits for current and future generations and for strong communities"[3].

2. Sector Challenges and Opportunities

To realize the many opportunities for growth and investment in the sector, it is necessary to examine the challenges BC's forest sector is exposed to in the context of a fluid socioeconomic and geo-political environment. Innovative thinking and collaboration are required to address such challenges and to maintain the productivity of BC's forests, build sustainable opportunities for adding value through the sector's value chain, and for BC to remain globally competitive. Following are some of the key challenges faced by the forestry sector in BC and opportunities associated with those:

Sustainable Forest Management in the Face of Climate Change

Natural disturbances, including fire, insects, disease, and drought affect forests on an ongoing basis and climate change impacts them all. Fire activity has increased in many regions; incidents of severe insect infestation are increasing; both trees and pests are responding to warmer temperatures by dispersing into more climatically-suitable habitats, ands; drought conditions are resulting in reduced tree growth, productivity, and increased mortality[10].

However, opportunities to mitigate the impact of climate change lie in: selecting trees resistant to drought, insects, and fire; assisting the migration of the trees by moving species to more suitable habitats; utilizing and enhancing the carbon capture capability of forests, and; using wood products as substitute to those derived from fossil-fuels.

Globalization and Market Diversity

Canada and BC have thrived in a globalizing world, particularly in the forestry sector. However, shifts in global investment to regions with low cost production, cheaper natural resources, and lower regulatory burdens for environmental performance are challenging our leadership role. Moreover, recent global economic uncertainty and trade disputes, particularly those with the U.S. on Canadian softwood lumber, have specifically impacted BC's economy. BC was hit particularly hard in April 2017, when the U.S. Department of Commerce imposed countervailing and antidumping duties on Canadian softwood lumber exports to the U.S.[11]. The sector and government are working to reduce the reliance on U.S. markets, which has reduced from 82 per cent in 2001 to 59 per cent in 2015, but it still remains a major consumer of BC's forestry products ($4.6 billion in sales in 2016)[2]. Opportunities lie in further diversifying BC's forest product market as well as in developing innovative forest bioproducts as new sources of revenue.

Increasing Demand for Wood Products in Asia and Europe

Fast-growing economies in Asia and Europe are aiding market diversification efforts and present significant opportunities for BC forest products. Realizing the potential, national and provincial governments have made several successful efforts to present increased opportunity in these markets, which are aimed at reducing dependence on the U.S.. Since 2002, Canada has increased exports to China by more than 25 times to $1.6 billion; and exports to South Korea, Southeast Asia and the United Kingdom have increased by more than 200 percent to over $700 million.

Increasing Demand for Bioenergy, Green Building Materials, other Bioproducts

Forest harvesting operations seek to maximize the collection and removal of commercially valuable fiber from sites. In BC, the fiber volumes on forest sites are some of the highest in the country; however, the low value of this fiber to the marketplace provides little or no commercial incentive to transport these

residues to a processing facility. Substantial opportunities lie in upgrading wood waste and residue to produce high-value products as new source of revenue. These products can be used to generate clean energy, biomaterials, and speciality chemicals. Export markets for bioproducts, which have global market of over $400 billion, are growing quickly, creating opportunities for BC technologies and products. As a natural choice for constructing green buildings, wood is on the rise for non-residential and mid-rise residential buildings. With our abundant forest resources, high environmental standards, and innovative approaches to design and construction, BC is exporting forest products, knowledge and construction technology to other countries. In the non-residential market (including commercial, industrial, recreational, and institutional), wood currently holds less than a 20 per cent share across Canada and the U.S.. With a significant portion of non-residential construction in the one- to three-storey range, there is considerable growth potential.

Mid-Term Timber Supply and Maintaining Sustainability

The volume of Crown timber sold at auction has decreased over the last three years, mainly due to the mountain pine beetle infestation and other factors impacting timber supply[12]. According to the 2017-2018 business BC Timber Sales seeks to maximize short and mid-term timber supply by ensuring its share of the harvest is auctioned, thereby supporting forest sector employment jobs and industry sustainability. The Clean-Tech Innovation Strategy also stresses the implementation of advance processing technologies for harvesting, such as step slope harvesting with access to full allowable annual cut and increased utilization from the land base to increase value from cutblocks[7].

Workforce transformation

BC's forest sector has a critical requirement for a high-quality workforce trained on state-of-the-art contemporary technologies to drive continued success in this highly competitive industry. Labour Market Information studies by BC's forestry and logging, silviculture, solid wood manufacturing and pulp and paper sectors, have estimated a total demand for up to 27,000 workers over 10 years (excluding seasonal silviculture workers)[13]. The sector is improving awareness of career opportunities and relevant work search tools for key audiences, such as current forest industry employees, youth, First Nations, women, and immigrants. It is also prioritizing investment in training and creating business capacity, particularly among First Nations, to rebuild a skilled, innovative, and sustainable forestry industry in BC. A BC Government priority is to increase First Nations participation in the forest sector, to provide jobs and economic benefits and obtain the social licence to operate the industry. Since 2002, the province has signed forestry agreements with 177 of 203 First Nations, providing $382 million in revenue-sharing and providing access to 180 million cubic metres of timber, giving communities a stronger role in forest and land stewardship.

Species at Risk

The rich biodiversity of BC's open forests and grassland ecosystems is not immune to the challenges facing the forest sector. Many of the provinces forest-species are at risk of extirpation due to improper human use of land and resources. Moreover, climate change, which has been linked to extreme events, such as forest fires, droughts, and invasion of alien species, is compounding the situation. Already this has resulted in loss of economic, social, and cultural value, not just for the forest communities, but also for the province and the country. The BC government is making efforts to maintain and improve ecosystem health and resilience through the recovery of open forest and grassland ecosystems, prescribed burning, and other measures. The opportunities lie in: improving resilience to climate change

and habitat for species; increasing natural forage for wildlife; increasing availability of First Nations' traditional use plants and habitats; protecting potable water resources; and, improving overall forest health.

Ecosystem Restoration

FLNRO's commitment to ecosystem restoration to re-establish structural characteristics, species composition and ecological processes is aimed towards mitigating the risk faced by BC's open forests and grassland ecosystems. The ministry's draft plan for ecosystem restoration strategy is forming the foundation for a multi-agency provincial strategy[14].

Another focus is on phytoremediation – a type of ecosystem restoration, which refers to the use of plants and associated soil microbes to reduce the concentration or toxic effects of contaminants in the environment[15]. This restoration technology is emerging as an alternative to engineering procedures that are usually more destructive to the soil; moreover, phytoremediation can be used for various environments and a range of contaminants. Phytoremediation aligns with the provincial government's efforts to track and clean over 14,000 sites in BC[16], which are contaminated with heavy metals (lead, arsenic, cadmium, and mercury), organic chemicals, chlorophenols (resulting from wood treatment operations), and polychlorinated biphenyls, during past industrial or commercial uses.

Urban Forestry

Increasing urbanization of global societies, increasing populations and a corresponding social desire for green space is forcing our cities to adopt a forestry strategy that can provide tools for growing and maintaining healthy, resilient urban forests for future generations[17, 18]. Urban forestry is equally significant in the efforts to adapt to climate change impacts, and to the rise of a diverse forestry sector. It provides substantial opportunities for the application of genomics by selecting trees with traits such as larger canopy, drought tolerance, and enhanced carbon sequestration. It is also tied to the quality of life and socioeconomic dynamics of cities, and provides a basis for engaging urban communities with the forestry sector and obtaining social license.

Many of these challenges and opportunities are derived from or intimately associated with trees, tree characteristics or bi-products, or the surrounding ecosystem. As such, genomics offers potential to provide solutions to these challenges and help seize opportunities. For the sector to remain globally competitive in the long term, it is imperative to diversify and adopt innovative technologies.

3. Genomics in the Forestry 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, agri-food, 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.

Within BC and across the globe, the forestry sector has been one of the pioneering natural resource sectors to rapidly adopt this innovative technology. Canada, U.S., European Union (EU), and several other countries have invested in research to adopt genomics into the sector. Genome Canada and Genome BC have invested in several large-scale, applied research programs focused on tree genomics and breeding, as well as forest health. To the south, the U.S. Department of Energy has initiated several programs focused on the application of genomics in different areas, such as generation of the first tree genome (poplar), wood biochemistry, climate change, and development of biofuels and bioproducts from forest biomass[19]. National U.S. laboratories, such as Oak Ridge, Lawrence Berkley, Pacific Northwest, and National Renewable Energy Laboratory have made significant progress in developing next-generation genomics-driven technologies to derive value added products from forest biomass.

Similar initiatives have also been adopted by EU, where European Forest Genomics Network was established as part of European Cooperation in Science and Technology[20]. Investments were made in projects aimed at producing ultra-high density maps of conifers, adoption of systems biology for identification of adaptive traits, and efficient management of breeding stocks while maintaining long term diversity[21]. Heavily-forested Scandinavian countries like Finland, Sweden, and Norway have also invested in forest genomic research. With the majority of forests on private land, these countries are actively pursuing the development of integrated biorefineries in collaboration with academia and private partners. For example, Borregaard, one of the world's most advanced biorefineries, has partnered with RISE's (Research Institutes of Sweden AB) Paper and Fibre Research Institute AS in Sweden to use genome-wide mining for developing enzyme technologies for forest biomass processing[11].

Elsewhere, Brazil has adopted genomics to maintain its leadership in eucalyptus breeding[22].International Papers, a large paper and packaging company in Brazil, is collaborating with researchers to use genomic selection methods for quicker, more efficient genetic gains at lower costs relative to traditional selection based on phenotypic data. In the Asia-Pacific region, India is using exome sequencing to develop genetic markers for eucalyptus[23]; China has applied genomic tools to study bamboo, the most important non-timber forest product in the world[13]; and SION – New Zealand's crown agency - has invested significantly in the application of genomics across the entire forest sector value chain[12].

A landmark in forestry genomics research was the publication in 2006 of genome sequence of poplar – a fast-growing perennial tree recognized for its economic potential in biofuels production[24]. It established the tree as a true model organism and led to many novel findings, including the recent Genome-Wide Association Study (GWAS) dataset comprising over 28 million single nucleotide polymorphisms (SNPs) promising for biofuels, materials and metabolites[19].

Despite these advances, the full application of genomics in forestry remains in its infancy. Much of the primary motivation for genomics research stems from the need to create breeding programs for genetic improvement of trees and develop tools for the conservation, restoration, and management of natural populations. However, the technology has the potential to develop tools for process optimization, new product development, and international trade facilitation. One of the largest future impacts of forest genomics is anticipated in addressing climate change, where it can be harnessed to help solve complex issues, such as conservation management, efficient use of forest trees as carbon sinks, and feedstocks for biofuels and bioproducts.

Impact of Genome BC's Investment in Genomics

Genome BC has made strategic investment to advance the application of genomics in BC's forestry sector since 2000. The organization has invested $107M in 28 projects and continuously supports the efforts of BC researchers to develop genomic tools for application in the sector, including mitigating the impact of climate change; designing next generation breeding programs; detecting of pests, pathogens and invasive species; tracing BC's timber; and producing value-added bioproducts for forest biomass valorization. With funding support from Genome BC and Genome Canada, BC researchers have established productive partnerships with leading institutes at the national and international level, such as FPInnovations, Canadian Food Inspection Agency, Natural Resources Canada, BC Ministry of Forest, Land and Natural Resources Operations, Joint Genome Institute, Joint Bioenergy Institute, and the National Renewable Energy Laboratories.

Genome BC's forestry project portfolio extends from discovery to applied research. While most new investment in the forestry value chain has been geared towards maintaining healthy and productive forests under a changing climate ('upstream' research), there are additional opportunities for investment in value-added bioproducts ('downstream' research). Previous investments have transformed the landscape for forest genomics internationally, generating much-needed genomic resources that are now being used in translational research studies and applications. With this foundation in place, BC's forest sector is well positioned to realize opportunities for applied and translational research likely to deliver a tangible impact in the short and medium term.

In Canada, the potential socioeconomic impact of these investments is significant. For example, by applying marker-assisted selection (MAS) to just 20 per cent of Canadian spruce plantations, wood yield could increase by 1.5 million cubic meters per year, boosting GDP by $300 million[25]. The detection of detrimental forest pests and pathogens using genomic tools could generate economic benefits of $800 million annually by protecting Canada's forest resources and up to $2.5 billion by maintaining export markets[26]. Valorization of lignin has the potential to help BC capture a significant share of global bio-product markets whose combined value is estimated to grow to over $700 billion by 2021[27]. In addition, these investments create jobs, support education and bring a skilled workforce to the sector and the province. Overall, the investment in applied technologies within the forestry sector will maintain a sustainable and productive industry that is ready for current and future challenges.

4. Opportunities for BC:

Creating Opportunities for Genomics in BC's Forest Sector

Genome BC's investment in numerous genomics projects has helped the forestry sector adopt and realize the benefits of genomics, which has positively impacted the social and economic well-being of the province. Within BC's expanding bioeconomy, the forest sector provides significant opportunities related to clean energy production, development of value-added products, and climate change mitigation. Application of practical genomics across the forestry value chain (upstream and downstream), from breeding better trees for forest health to extracting value from bioproducts, has the

potential to create substantial opportunities for the forestry sector in BC. To capture these opportunities, several short- and long-term projects are underway in the following areas:

Tree Breeding Programs

Over the last 30 years, BC has been a leader among Canadian provinces in investing and seeing the benefits of conventional tree breeding and testing procedures. With the application of genomic MAS, these gains can now be enhanced, broadened, and realized over considerably shorter time frames and at lower cost. Genomic selection can improve wood quality, wood quantity, resilience, and environmental adaptation more rapidly and accurately than traditional methods. Workers can use improved tree breeding programs to better understand the genetic mechanisms of disease, pest resistance and adaptability to climate change, to effectively address these challenges. For example, information about the conifer (an important feedstock for biofuels) genome gathered in the Conifer Hybrid Zones as Genomic Laboratories for Adaptation to New Climates project are helping tailor future plantings in response to climate change along the coastal and in the interior of BC.

Pest and Pathogen Diagnostics

Prevention is the best defence when it comes to invasive pests and pathogens that may harm BCs forests or reduce export opportunities. To limit pest and pathogen introduction, spread and subsequent damage, genomic tools can be used for their detection at point of entry. For example, poplar and cereal rust comparative genomics and identification of pathogen determinants can predict and prevent epidemics. Within the province, an increased understanding of the interactions between pathogens and their hosts (e.g. Mountain pine beetle on lodgepole pine) can help reduce future infestations and develop robust mitigation strategies.

Traceability of BC Timber

BC is in the enviable position of providing excellent wood-based products to the global market. To enable BC timber to be recognized by trading partners and ensure a buyer is receiving a high-quality product, a genomics-based system can be employed to track and authenticate trees and wood products.

Value-Added Bioproducts

Genomics tools are being employed to provide new 'downstream' opportunities for processing of wood and wood products. They are also being used to produce advanced, high value-added bioproducts from fibre, improving sustainability and using more forest residues. Ideally, by modifying existing processes for producing these value-added bioproducts, genomics tools will reduce the cost of production by, including pre-treatments before production or treating effluents post-production.

Wildlife Conservation and Species- at- Risk

Genomics tools can be employed for accurate characterization of individuals to the subspecies or population level. This information is critical for developing forest and ecosystem management tools and informing policy as it can identify rare or at-risk populations. For example, genomic tools are being used to differentiate the *laingi* subspecies of the northern goshawk, inhabiting Haida Gwaii and possibly other areas off the BC coast, from

the *atricapillus* form of goshawk. The outcome of the research will inform the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) recommendations to the Federal Minister of Environment and Climate Change whether the subspecies should be listed as threatened or endangered under the Species at Risk Act (SARA).

A Roadmap for Genomics in BC's Forestry Sector

Genome BC is continuing its efforts to realize the benefits of genomics across the entire value chain of the forestry sector. After strategically focusing on and investing in the upstream portion of the value chain, Genome BC is now widening its scope by including opportunities in the downstream segment of the value chain. Strategically, this means pursuing the application of genomics to support production of value-added products from wood fiber and forest biomass residue and facilitating development of tools to effectively assess the new and emerging technologies, leading to informed policy decisions benefiting forestry-dependent communities and the bioeconomy.

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 forest sector value chain:

Pilot Project	***Impact***	
	Short term	***Long term***
• *Genomic Tools for forest inventory and monitoring*	*Adoption of precision genomics; sustainable forest management practices; increased competitiveness and jobs*	*Global leadership for the BC forest sector; diversification of markets*
• *Valorization of pulp and paper mill waste to produce high value bioproducts*	*Adoption of synthetic and systems biology for biocatalysis; increased competitiveness and jobs*	*Market diversification; new revenue sources; components of future biorefineries; lowering carbon foot print; reducing dependence on non-sustainable products; mitigation adoption of climate change*
• *Bio factories for platform chemicals (chemicals derived from biomass and used to make other chemicals)*		
• *Upgrading lignin into bioplastic and plastic resins*		
• *High-value extractives from forest trees*	*Adoption of systems biology for biomining; increased competitiveness and jobs*	*Market diversification; forest-derived natural products as new revenue sources*
• *Application of genomics in urban forestry*	*Partnering with BC's cities to support a healthy urban forestry strategy*	*Healthy and resilient urban forest: greater canopy, drought tolerance, resistant to invasive species/pests, enhanced carbon sequestration to mitigate climate change and pollution*

• *Role of forest genomics in shaping the future of Canadian bioeconomy* • *Tools to assess the impact of genomics and associated technologies in the forestry sector*	*Develop tools for assessment of societal benefits; engagement with First Nations and forestry-dependent communities*	*Realizing socioeconomic benefits of genomics research in forestry; guiding policy decisions for sustainable and efficient management of next generation of forestry*

4.2 Forestry Sector Innovation Centre

Given the maturity of genomics in the forest sector and wide-ranging engagement and dialogue that exists between different stakeholders, Genome BC sees opportunities to support development of a Forestry Sector Innovation Centre. In consultation with Genome BC's Forestry Sector Advisor Committee and working with key sector partners, such as FPInnovations, the pulp and paper industry, and FLNRO, Genome BC intends that the Sector Innovation Center will provide a forum for identifying and articulating the challenges faced by industries across the value chain and catalyze development of genomic solutions to these challenges. One early focus of the Forestry Sector Innovation Centre may be technology development to support zero waste operations for mills by transforming mill waste into energy and/or high value-added bioproducts. This approach will also help the lumber industry, upstream in the value chain, by creating value from wood fiber waste and diversifying to address market challenges. The long-term objectives of the Forestry Sector Innovation Centre would be to integrate genomics-driven technologies across the entire value chain of BC's forestry sector and help it remain innovative and future-ready.

4.3 Community Engagement

While cutting-edge technology opportunities and genomics applications are well known among BC researchers engaged in forest genomics, gaps exist between research and the activity of some forest managers and executives in public and private companies whose responsibilities are to relate to broader issues of public policy, land management, or competitiveness. To increase the adoption of genomics-based tools and achieve high impacts in industry sooner, it will be important to bridge these gaps and connect research to decision-makers. Whether the gaps in dialogue arise from premature promotion of genomics potential, or use of language that is too technical or inaccessible, it is important that forest sector decision-makers find common language to understand and address opportunities. The opportunities presented by applications of genomics need to be embraced and fundamental dialogue gaps between providers and users of genomics technologies must be closed to see real progress. Genome BC will help address this opportunity by pursuing a coordinated approach to stakeholder engagement, dialogue and collaboration on critical issues related to forest sector innovation.

5. Advancing the Implementation of Genomics

This document lays out numerous opportunities for practical applications of genomics in BC's forest sector including: tree breeding for healthy and resilient forests; pest and pathogen diagnostics; traceability of BC timber; value-added bioproducts; genomic tools for accurate characterization of

species at risk; utilize genomics to restore and/or improve wildlife habitat; and, genomic selection of trees for environmental remediation of contaminated sites.

To achieve these targets, Genome BC consults with stakeholders within BC's forest sector and across 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 forest sector is to distill knowledge of the challenges and opportunities facing the sector; the previous investments, results, and strengths; and to distill 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 across 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 outreach programs, public talks BGH
- Stakeholder engagement
    - All stakeholders: Bringing together and supporting the life sciences community to a 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 demonstrate the practical and cost-saving value of genomics.
    - Genome BC: Funding for partners, 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 Forest Sector Advisory Council, as at March 1, 2018

- Brian Barber, Chief Executive Officer, SelectSeed Co. Ltd.
- Judi Beck, Director General, Natural Resources Canada (NRCan) - Canadian Forest Service (CFS), Pacific Forestry Centre
- Jim Farrell, Vice-Chair, Genome Canada Board of Directors, Consultant to Genome BC and former Assistant Deputy Minister (ADM), Natural Resources Canada (NRCan) - Canadian Forest Service (CFS)
- Mark Feldinger, Senior Vice President, Forestry/Environment and Energy, Canfor Corporation
- Bob Fleet, Vice President, Environment & Forestry, Tolko Industries
- James Gorman, Vice-President, Corporate and Government Relations, West Fraser
- John Innes, Dean of Forestry, University of British Columbia (UBC)
- Diane Nicholls, Assistant Deputy Minister, Chief Forester, BC Ministry of Forests, Lands and Natural Resource Operations (MFLNRO)
- James Olson, Associate Dean for Research and Industrial Partnerships, Faculty of Applied Science, UBC
- Dave Peterson, Assistant Deputy Minister, BC MFLNRO
- Ian de la Roche, Member and former Chair, Genome BC Board of Directors
- Jack Saddler, Professor and Dean Emeritus, Faculty of Forestry, UBC, and Task Leader, IEA Bioenergy Task 39, Liquid Biofuels
- Ric Slaco, Vice President and Chief Forester, Interfor
- Trevor Stuthridge, Executive Vice President, FPInnovations

Appendix 2. List of Key Projects

043FOR - Conifer Forest Health Genomics (2006-11)

Total Budget: $19.9M

Program: Large Scale Applied Research Program

Project Leaders: Profs. Joerg Bohlmann and Kermit Ritland, UBC

Canada's forest economy is largely based on conifers, such as spruce, pines, and western red cedar. Application of genomics to observe and maintain conifer forest health can contribute towards forest stewardship and resource management benefits. With this objective, Drs. Bohlmann and Ritland aimed to identify the genetic traits of Spruce – one of the dominant conifer species valued for its use in the construction industry, making musical instruments, as well as by aboriginal people for medicinal purposes. Their team developed massive resources, such as new conifer genomics, proteomics and metabolomics research platforms, large-scale data resources, and genetic markers for improving resistance to pests, like the spruce weevil, as well as increasing the ability to adapt to changing climate. This knowledge was also transferable to other critical conifer species including pines, true firs, douglas fir, and western red cedar. The project, also called Treenomix-II since it followed up Treenomix – a successful large-scale Canadian forestry genomics program, provided platform for Canada's spruce genome sequencing project (SMarTForest) and other conifer genome projects funded in Canada, the U.S., Sweden, and Spain. It established several partnerships between academia, industry, and government as well as laid foundation for other follow-up projects and collaborations. Besides publishing 60 research articles and 8 book chapters, several highly qualified personals were also trained during the project and policy related documents were created as part of the GE3LS research. This highly successful project demonstrated the significance of genomics in improving forest management practices and enhance socioeconomic benefits.

243FOR - Spruce-Up - Advanced spruce genomics for productive and resilient forests (2016-20)

Total Budget: $10.4M

Program: Large Scale Applied Research Program

Project Leaders: Prof. Joerg Bohlmann, UBC and Prof. Jean Bousquet, Université Laval

Continuing with their success from Treenomix-II, Dr. Bohlmann continued his forestry focused genomics research, this time in collaboration with Dr. Bousquet from Université Laval, to address the impact of climate change and its related epidemics of insects and droughts. These factors are causing losses of millions of dollars annually due to reduced productivity of spruce forests. The research team wanted to use genomics to accelerate spruce breeding programs to ensure future forest health, wood quality and productivity. The Spruce-Up project is aimed to solve exactly these challenges. The project will deliver leading knowledge, socioeconomic decision support tools and applied genomic tools to significantly enhance conventional breeding programs. By involving end users in government and industry in its work, the project will accelerate the development and deployment of genomics-improved spruce stock that is more resistant to insects and drought, uses nutrients efficiently and results in improved wood quality and productivity. The project is estimated to more than double the net economic output value of spruce forests relative to conventional breeding. It will leverage existing spruce breeding and reforestation programs by increasing the value of new trees and reducing losses due to environmental disturbances.

SOF113 - Conifer Hybrid Zones as Genomic Laboratories for Adaptation to New Climates (2009-10)

Total Budget: $270K

Program:

Project Leader: Profs. Sally Aitken and Kermit Ritland, UBC

This small-scale project, another follow-up from Treenomix, continued the work on identifying variability in adaption of spruce. Dr. Aitken's team tested the utility of biomarkers for managing a range of spruce species in a changing climate. The deliverables allowed to assess whether artificial selection can provide natural and breeding populations adapted to new climates, in particular whether trees with novel profiles from more extreme environments can be effectively grown in BC. The findings of this study led to new local and international collaborations and foundation for a follow-up LSARP – CoAdapTree.

241REF - CoAdapTree - Healthy trees for future climates (2016-20)

Total Budget: $5.8M

Program: Large Scale Applied Research Program

Project Leaders: Prof. Sally Aitken, UBC; Prof. Richard Hamelin, Université Laval; Prof Sam Yeaman, University of Calgary

The current standard procedure to use seeds from local tree populations to re-grow forests is under threat due to changing climate. The procedure is losing its efficiency due to inability of local trees to adapt to a changing environment that includes not just warmer temperatures but also new diseases and new pests. This would negatively impact the economic and environmental benefits, such as wood, jobs, habitat protection and carbon sequestration, forests provide to Canada. Dr. Sally Aitken and her colleagues are using genomic tools to develop three options to deal with this problem. Thus, they are collecting seeds of the same species of trees that are better adapted to warmer climates; sowing seeds further north or at higher elevations; or selecting and breeding trees that can withstand climatic stresses or disease. All of these strategies can be successful if they result in trees better able to withstand a changing climate and the accompanying stresses. The goal of the project is to develop better reforestation options for high-value tree species such as Douglas fir and lodgepole pine, as well as western larch and jack pine. This work will provide policy and reforestation recommendations to support tree breeders and foresters in selecting and planting trees that will be healthy in new climates in western Canada. The team's work may result in up to 30% greater timber yields, with a proportional impact on the economy and employment, as well as sustain the ecological and environmental benefits of our forests.

164DIA - Genomics-Based Forest Health Diagnostics and Monitoring (2011-15)

Total Budget: $4.25M

Program: Large Scale Applied Research Program

Project Leader: Prof. Richard Hamelin, UBC

Canada's forests are increasingly under threat by pests and pathogens, resulting in annual losses of about $2 billion. Dr. Hamelin used The Tree Aggressors Identification using Genomic Approaches (TAIGA) project to develop diagnostic tools for detection of pathogens. The project developed DNA tests covering 44

species of tree pathogens attacking 45 tree species and built a reference collection of over 700 pathogenic species and generated 1600 DNA barcodes. A total of 82 DNA tests were transferred to the Canadian Food Inspection Agency (CFIA), the end-user, and several were quickly deployed operationally by the agency to detect deadly pathogens, such as Dutch elm disease and ash dieback. The success of this project led to a follow-up GAPP project, which applied the TAIGA approach to the Asian Gypsy Moth problem. It also generated commercial interest from groups such as Biopterre, a technology transfer group, to bring TAIGA to agricultural crop pathogens.

244DIA - BioSurveillance of Alien Forest Enemies (bioSAFE) (2016-20)

Total Budget: $8.7M

Program: Large Scale Applied Research Program

Project Leaders: Prof. Richard Hamelin, UBC; Dr. Cameron Duff, Canadian Food Inspection Agency, Prof. Ilga Porth, Université Laval

Continuing their focus on invasive alien species and diseases, such as the Asian longhorned beetle, Dutch elm disease, sudden oak death and Asian gypsy moth, which causes losses to the amount of billions of dollars and threaten our forests, Dr. Hamelin collaborated with Dr. Porth and the CFIA, to address this challenge. They are now developing an earlier detection system for biosurveillance. The team is harnessing the power of genome sequencing and bioinformatics analysis to develop a new suite of tools to rapidly and accurately detect these four detrimental forest enemies. The early detection will help eliminate the invasive alien species before they establish themselves. Their work will enable forest health professionals to track and determine the source of these threats, enabling the development of measures to prevent further invasions. Once applied, these tools could have positive economic impacts of ~$800 million annually by protecting Canada's forest resources and ~$2.2 billion by maintaining export markets.

162MIC: Harnessing microbial diversity for sustainable use of forest biomass resources (2011-15)

Total Budget: $7.8M

Program: Large Scale Applied Research Program

Project Leaders: Profs. Lindsay Eltis and Bill Mohn, UBC

In order to remain competitive and sustainable, Canada's forest industry must develop both better forest management and extract forest biomass related products that are of value to customers in Canada and around the world. Drs. Eltis and Mohn used genomic tools to study soli microbial communities with an objective to identify biocatalysts that can be used to valorize forest biomass. In one part, the team used metagenomcis to study soil microbial communities and found that these are affected by harvesting and, that some ecosystems are more resistant to organic matter removal than others. The team further developed a high-throughput biosensor based functional screen to identify enzymes from metegenomic libraries representing the microbial communities and established the potential of bacterial enzymes and strains in lignin valorization. The expertise developed for metagenomics analyses in this project facilitated the development of two companies, Microbiome Insights Inc. and Metemixis Inc. The project also established several key collaborations with industry, government, as well as US national labs, such as National Renewable Energy Laboratories (NREL). These have served as foundation for follow-on projects to further develop biocatalysts for industrial processes.

SIP004: Microbial activities for lignin valorization (2017-19)

Total Budget: $0.25M

Program: Sector Innovation Program

Project Leaders: Profs. Bill Mohn and Lindsay Eltis, UBC

Using the previous LSARP as the foundation, the research team of Drs. Mohn and Eltis, is advancing their efforts to discover and implement biocatalysts for biomass valorization. In particular, they are focused on transformation of lignin, the most abundant aromatic biopolymer on earth, into higher value products by using microorganisms and enzymes that naturally degrade woody biomass. With the help of these enzymes and engineered pathways that degrade lignin depolymerization products, the team will develop bioprocesses to valorize woody biomass and to commercialize those bioprocesses. A number of industrial and government collaborators, including FPInnovations, Fibria, the NREL and AB Enzymes, will enable the project to reach the objectives. The technologies arising from this project will have the potential to help BC capture a significant share of global markets whose combined value is estimated to grow to $100 billion by 2024. The knowledge and innovations emerging from this project will contribute to revitalizing BC's forest industry, driving its sustainability, growth, productivity and global competitiveness.

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