

FOREST SECTOR

Challenges, Genomic Solutions

A Sector Strategy led by G nome
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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.

Prepared by Dennis Rank and Associates.
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Genome Canada would like to thank the Government of Canada for its continued support.

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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GLOSSARY OF ACRONYMS

\$B	\$ billion
BC	British Columbia
BCIT	British Columbia Institute of Technology
CCFM	Canadian Council of Forest Ministers
CFIA	Canadian Food Inspection Agency
CFS	Canadian Forest Service
CNF	Cellulose nanofilaments
DM	Deputy Minister
DNR	[New Brunswick] Department of Natural Resources
EAB	Emerald ash borer
FTE	Full time equivalent
FPAC	Forest Products Association of Canada
GDP	Gross Domestic Product
GSS	Genomics sector strategy
\$M	\$ million
MAB	Marker-assisted breeding
MAF	Multiple account framework
MAS	Marker-aided selection
MNRF	[Québec] Ministère des Ressources naturelles et de la Faune
MPB	Mountain pine beetle
NB	New Brunswick
NCC	Nanocrystalline cellulose

GLOSSARY OF ACRONYMS

NFPS	National Forest Pest Strategy
NPV	Net Present Value
NRCan	Natural Resources Canada
NS	Nova Scotia
PV	Present Value
R&D	Research and development
RFLP	Restriction fragment length polymorphism
SBM	Spruce budworm
SFM	Sustainable forest management
SNP	Single nucleotide polymorphism
SPS	Sanitary and phytosanitary
UBC	University of British Columbia
U of A	University of Alberta
US	United States
USDA-APHIS	US Department of Agriculture-Animal and Plant Health Inspection Service
USFS	United States Forest Service

1. EXECUTIVE SUMMARY

The forest sector is tremendously important to Canada both as an economic driver and a cultural icon. As Canada's largest renewable natural resource, the forest sector generated about \$54 B in revenues in 2010 and contributed about \$24 B to GDP (or 1.9% of the total). Forestry also provides roughly 234,000 direct jobs, and in some 200 rural Canadian communities this sector makes up at least 50% of the economy. Healthy Canadian forests also play a critical role in providing a host of ecosystem services, including those related to regulating global carbon emissions. Canada enjoys world-class sustainable forest management (SFM) regulations and certifications in all jurisdictions.

Canada's forest sector has recently endured a brutal combination of cyclical and structural adjustment that has resulted in significant job losses and mill closures. As the global forest sector begins to shake off the effects of financial crises and recessions, key challenges continue to revolve around global economic shifts in supply in demand, increased international competition, and threats posed by insect pests and environmental changes to competitive and secure wood supplies. A complication in addressing these challenges is the Canadian tenure system: most forest land is owned by the provinces but harvested by the private sector. Industry requires more (or different) incentives to invest in R&D, especially given the 40 to 75 year production growth cycle on primarily Crown lands (and up to 120 years in northern boreal forests). Fortunately, advances in genomics R&D in the last few years are providing new tools and stimulating new ways of thinking to manage the resource to help assure the long-term security of the fibre source and maintain Canada's position as having the largest sustainably managed forest resource across the globe.

In 2009 and 2012–2013 key stakeholders across Canada were consulted as to forest challenges and genomic opportunities. In the most recent set of consultations, 115 representatives of industry, government, and academia were contacted, and many of these individuals (and others) participated in the National

Forestry Sector Genomics Strategy Workshop held in Ottawa on March 25, 2013, hosted by Genome BC and Genome Québec (as well as Genome Canada and other Genome Centres).

Key representatives of end-user organizations identified two overarching opportunities for genomics. The first is to increase the productivity of Canadian forests, for example by using marker-aided selection in tree breeding programs to increase yield, wood quality, and pest resistance traits. This will require increased collaboration between the provinces, the Canadian Forest Service, and industry and industry associations. This effort would be supplemented by marker-assisted breeding to improve the qualities of lignocellulose feedstocks for manufacturing value-added products such as biofuels and composites, and genomic characterization of harvested fibre to meet specialized industry needs. A mature "genetic barcode" wood sanitation, phytosanitation, and provenance system could promote Canadian lumber and wood products world-wide.

The second overarching topic is to focus on healthy forests. The most important issue is to deal with insect pests, both native species such as mountain pine beetle in the west and spruce budworm in the east, and invasives such as the emerald ash borer threatening eastern urban forests. Genomics can identify molecular targets for pest control, and develop improved tools for tracking pests and emerging pathogens. Identification of resistance marker genes for breeding programs and identification of susceptibility marker genes can guide reforestation policy and practices, from modifying seed zones to developing more resilient planting stock. Investigating genomic traits that influence the adaptation of trees to weather events triggered by a changing climate, and identifying climate-related changes to pest distribution, will allow modified afforestation and reforestation programs to match "best fit" tree genotypes to appropriate climatic and geospatial zones. Overall, genomics-enabled identification and mitigation measures will allow more effective surveillance and rapid response/ramp-up to

support Canada's preparedness for inevitable future pest and disease invasions.

The most recent set of consultations, and especially the 2013 Workshop, showed that there is strong support for four broad topics to address these issues:

- **Leadership:** The time is ripe to initiate a *Forest Genomics Enterprise* led by a national coalition involving organizations such as the Canadian Forest Service, FPInnovations, and provincial and forest genetics councils. This Enterprise would develop a road map for going forward on specific initiatives with concrete practical goals. Developing a coalition with the US Forest Service could leverage resources, and there are already expressions of interest. Possibly groups such as the Forest Products Association of Canada (FPAC) and the Canadian Council of Forest Ministers (CCFM) would also be involved; e.g., the latter to address policy and regulatory issues.
- **Integration:** An integrated, multidisciplinary, multisectoral approach is needed to address forest challenges. This would employ both genomics-based and traditional approaches to key problems, be inclusive of forest issues and research initiatives across Canada, address policy and regulatory reform, support human resource and capacity development, review both upstream and downstream opportunities along the entire value chain, deal with commercialization and application issues, consider public good and intangible benefits, and provide for international cooperation. Stakeholders noted that genomics can bring concrete value to these complex problems, but needs to be better integrated with other disciplines to maximize its potential.
- **Value proposition:** If public and private sector senior opinion leaders are to be engaged in the most effective way, the Forest Genomics Enterprise must construct a single, clear, understandable, and well-coordinated value proposition, especially for industry. One challenge is that, while the technical aspects of genomics are reasonably well-known within industry

at the operational level, the business case for application is not always fully appreciated at the senior management level. Senior industry officials strongly stressed the need for enhanced communication, outreach, and bridging between the research and user communities. Within any value proposition there must be a realistic assessment of the current state of knowledge, proof and validity, ways to measure success, the degree of receptor capability, and potential for meaningful economic return for partners.

- **Proof of concept:** A clear near-term "win" is needed to maintain the current momentum. Many specific opportunities were discussed in the 2013 Workshop, but at a high level there appeared to be most support for pest and pathogen diagnostics. While genomic marker research to enhance tree selection and breeding have great potential to create productivity improvements, respond to climate change, and refine value-added processing, these longer-term outcomes would likely benefit from achieving early wins in other areas first. Although recent advances are speeding translation, for now these lines of inquiry may be better seen as representative of important generational investments. Conversely, a number of non-breeding opportunities might be pursued in the short term, such as pest diagnostics and responses, sanitation and phytosanitation, provenance and traceability, and development of a Canadian brand linked to pest/pathogen-free certification. These candidates must be refined to identify the low-hanging fruit with the most concrete short-term benefits, and that are of most use to Canada as a whole.

An integrated Forest Genomics Enterprise that includes stakeholders from across the value chain, working to realize some early applications, could begin an inclusive process to foster collaborations on specific research initiatives and create mechanisms to ensure that concrete knowledge translation and application occur in a timely fashion.

2. BACKGROUND

Over the last 10 years some \$90 M has been invested in advancing forest genomics research across the country. The bulk of those investments relates to improving the productivity of current and future forests and protecting the health of Canada's forests. The understanding of the science of forest genomics has advanced at an unprecedented pace, and it is now timely to focus more urgently on the needs of users to develop an articulate value proposition for applications.

The timeliness of this initiative is driven by two factors. First, Genome Canada's new 2012–2017 Strategic Plan calls for developing action plans in four resource-based sectors, including the forest sector. Second, there is a growing and shared interest across regional Genome Centres to enhance the integration of genome science from discovery to application, translating results earlier to maximize benefits for forest economic sector and Canadians more generally.

The forest sector strategy process has involved several significant activities. In 2009, an extensive stakeholder consultation process culminated in the Canadian Forest Health Genomics Initiative Workshop held on March 31, 2009 in Toronto, in which 60 participants participated. This led to the first forest genomics sector strategy (GSS) white paper¹. (See Appendix 2 for members of the 2009 steering committee.) During the latter half of 2012 and continuing on into spring of 2013, Genome BC and Genome Québec (supported by Genome Canada and other regional Genome Centres) began developing an inclusive national discussion to refine the 2009 vision. The intent was to gather consensus as to the appropriate focus of future forest genomics investments, discuss how to more effectively apply research results in the field, and take the first steps to develop a practical and effective implementation road map.

Key activities in 2012/2013 included drafting a refined version of a Forest Sector Strategy Background Paper (an earlier version of this document) and circulating it to a select steering committee for comment. Next, Genome BC and Genome Québec initiated an intense period of consultations with 56 senior industry and government executives, as well as key genomics research funders and practitioners across Canada. The consultation process was guided by a Consultation Framework that provided basic background information, and suggested discussion points and optional questions. (See Appendix 3 for the individuals consulted, and Appendix 4 for the Consultation Framework). This input was used to guide the nature of presentations made and breakout sessions conducted during the National Forestry Sector Genomics Strategy Workshop, held in Ottawa on March 25, 2013. This workshop was attended by 69 representatives of industry, academic, and government organizations and included an industry roundtable. (See Appendix 5 for participants in the Workshop.) In addition, representatives of the forest GSS steering committee attended the Canada/US Forest Health Summit II, held March 26–27, 2013 in Ottawa.

This white paper integrates the results of all consultations and activities to date, makes some observations based on the information gathered, and suggests options for going forward. It is intended to provide a framework for a process that will build critical mass and capacity, and establish concrete national and international possibilities for translating genomics research into practical applications for Canadian industry and society.

The main text discusses key findings, while Appendix 1 has a detailed discussion of recent data that the text is based upon.

¹ *Canadian Forest Health Genomics: Canadian Strengths Address Forestry Challenges*. July 2009.

3. KEY MESSAGES

1. THE IMPORTANCE OF THE FOREST SECTOR TO THE CANADIAN ECONOMY

Forests are Canada's largest renewable natural resource, and forestry is one of Canada's major economic engines. Canada contains 10% of the planet's forests, and is one of only three countries in the world still retaining vast areas of unaccessed, untouched stands. Canada is the world's leading exporter of forest products such as softwood lumber, newsprint, and wood pulp, which together account for close to 10% of Canada's exports. The forest sector generated about \$54 B in revenues in 2010 and contributed about \$24 B to GDP (or 1.9% of the total) in 2011². Forestry also provides roughly 234,000 direct jobs, and in some 200 rural Canadian communities this sector makes up at least 50% of the economy³. Healthy Canadian forests also play a critical role in the global carbon cycle, and both forests and forestry are key elements of Canada's culture.

In recent years, Canada's forest sector has been struggling for competitiveness, recently reflected by a 30% decrease of its contribution to GDP due to a combination of market and environmental factors. Genomics⁴ can play a key role in reversing this trend by leveraging past longer-term research investments into shorter-term forest health solutions, and maintaining the generational investments needed to properly understand and manage this enormous pool of natural resources, including maintaining preparedness⁵ to deal with future environmental and economic challenges.

2. CHALLENGES IN THE FOREST SECTOR

Market forces. Over the last few years the global forest industry had endured significant challenges, including the downturn in global economies, a general decline in demand for wood products, emerging low cost competitors, and a major contraction in the availability of financing. Domestically, this grim global picture resulted in significant job losses and mill closures, exacerbated by the decline in newsprint demand, a collapse in US housing markets, and a strong Canadian dollar. However, after years of shedding excess labour and lowering production costs across Canada, the forest sector is now far better positioned to compete into the future.

Environmental challenges. There have been changes in the frequency and severity of environmental disturbances such as insect and disease outbreaks, wildfires, droughts, storms, and changes to average temperatures and timing. In some regions, these disturbances have triggered reductions in allowable harvesting levels along with changing environmental regulations and newly established protected areas. The changing climate suggests that these issues will accelerate over time and adaptive management practices will increasingly be needed.

Insect pests. In 2009 and 2010 about 15.2 M and 12.7 M hectares of forest, respectively, were killed or defoliated by insect pests⁶. For example, the mountain pine beetle (MPB) killed more than half of BC's commercial pine inventory from 1998 to 2011 and affected 1.3 M hectares of forest in Alberta. Climatic shifts are allowing the MPB to significantly increase its

² In constant 2002 dollars.

³ *The State of Canada's Forests, Annual Report*. Natural Resources Canada, 2012.

⁴ The genome sciences (also called "genomics" here) include: genomics, transcriptomics, proteomics, metabolomics, metagenomics, systems biology, and bioinformatics.

⁵ National preparedness is seen as a critical outcome of public R&D investment in several countries. In Australia, for example, see: [Australian government] *Productivity Commission Research Report*, March 9, 2007.

⁶ *Op cit*. Natural Resources Canada, 2012.

range across BC and Alberta and threaten Canada's boreal forests, with potentially devastating economic, community, and ecological impacts. In eastern Canada, heavy spruce budworm (SBW) infestation severely affects the lumber, pulp and paper, and associated industries, as well as disturbing fire cycles from Alberta to the Atlantic. The invasive emerald ash borer (EAB) has killed millions of ash trees in parts of Ontario and Québec and continues to spread. While the economic impacts associated with increased incidence and severity of pest infestation are easily measured, the impacts on environmental services (watershed protection, habitat for native flora and fauna, etc.), while more difficult to quantify, may in fact be even more significant.

Public forest policy. Unlike our neighbours to the south, the vast majority of Canadian forest land is publically owned and made available for use by private interests within a framework of specifically defined obligations (forest products, mining, energy, etc.) in return for royalties paid to governments. Unlike private forest land that is exploited with few restrictions, operations on public land are regulated by legislation, regulation, policy, guidelines and directives that not only create a financial burden, but are often "time bound" and offer limited incentives for firms to make the kind of large and long-term investments in the forest as they do in their manufacturing facilities. The Canadian public is of course the ultimate end-user, but while it has little direct input into forest policies the public still retains very high expectations regarding the economic benefits and protection of forests.

Growth cycle. Canada's forests are generally more slow-growing than many of its international competitors, facing rotation cycles of 40 to 75 years (and up to 120 years for northern boreal forests of black spruce). This makes reaping short-term benefits from R&D more difficult, again influencing the ability to compete for public and private research investment.

Understanding of genomics. Knowledge of, and interest in, genomics have increased dramatically among key end-users over the past five years, from it being almost invisible to it being at least "on the radar". However, the way in which genomics can affect the sector is still not well understood by many stakeholders. The 2013 consultations found that there was good understanding of the technical aspects of genomics at the operational level within industry. However, the closer to the top of the corporate hierarchy, the less well understood was the potential for practical applications of genomics that could affect their business. (The opposite appears to be true within government forest ministries.) During the 2013 Workshop this finding was reinforced, as several senior industry officials commented that they had only a vague understanding of the value of potential genomics applications. These findings have implications for improving the nature of outreach, policy education, and ways to influence industry/public perception, to ensure that genomic innovations are implemented in the sector.

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

The two main broad opportunities for using genomics to address sector challenges can be summarized as "Productive Forests" and "Healthy Forests". Productive forest R&D would focus on increasing forest productivity through tree breeding for increased yield, quality, pest resistance, suitability for value-added products and processing, and trade issues such as those related to provenance and certification. Healthy forest R&D would address sustainability issues related to maintenance of the fibre supply, pest and pathogen management, and tree adaptability and regulatory responses to climate change.

These two overarching topics are nevertheless intimately related: there will be no productive forest sector without healthy forests, and no healthy forests without sustainable forest management practices. Within both, emphasis will need to be put not only on knowledge development

but also on knowledge transfer and practical implementation. A translation-focused approach that uses genomics to integrate the various sector problems, stakeholders, and disciplinary approaches is possible. This can provide a breakthrough in how the sector's stakeholders collaborate and function, providing a higher chance of success than the often-piecemeal approach now used.

4. VISION

Overview. The 2013 consultations and Workshop identified the need for a common vision within the future forest genomics sector strategy, and articulated four clear elements that should underpin this vision:

- development of a road map for going forward, initiated and championed by a collaborative Forest Genomics Enterprise operating within a purpose-built national coalition;
- use of an integrated, multidisciplinary, multisectoral approach;
- construction of a clear, easily-understandable value proposition for industry; and
- pursuit of proof of concept through a clear near-term “win”.

Development a national coalition for going forward. The consultations demonstrated significant support for development of a national coordinated coalition to facilitate translation and application of forest genomics R&D. This might also include some form of application/commercialization capacity and/or technology platforms. While national in scope, of course both regional and international engagement would be required.

The newly created coalition would be guided by a road map to be developed in going forward. This road map would provide a framework for forest GSS activities that will take stock of the current status of genomics R&D, consider early candidates for practical applications (as part of the value proposition building process), build critical mass and capacity, and establish national and international R&D possibilities. Stakeholders believe that genomics tools are now advanced enough to

make significant contributions in the near- to mid-term, can help solve some of the difficulties discussed herein. Given the many challenges in the sector and the still-uncertain level of knowledge, this level of support is highly encouraging.

Such a roadmap will be incomplete without a functional deployment strategy that has consistent funding available, and that lays out explicit roles and responsibilities, timelines, and milestones. See below.

Use of an integrated approach. An integrated approach would take into account multidisciplinary and multisectoral issues and expertise, use both genomics and traditional sciences, and deal with infrastructure and human resource issues. Several key stakeholders referred to this as a holistic approach that would include:

- Canada-wide initiatives and priorities;
- provincial initiatives and priorities;
- industry initiatives and priorities;
- policy and regulatory development;
- research, commercialization, and public good intangible opportunities;
- upstream and downstream issues affecting the entire value chain, and including value-added opportunities;
 - » within value-added processing and manufacturing, it is recognized that many beneficiaries will be large multinationals—the strategy must identify clear Canadian opportunities;
- ways to leverage the scientific and technical expertise gained across the many Canadian climate zones, species, and jurisdictions—this breadth of knowledge may provide a unique Canadian strength;
- traditional tree breeding and scientific approaches (in addition to genomics), such as phenotypic studies and whole ecosystem and microbiome approaches (e.g., the point was made that the “best fit” phenotypes for adapting to climate changes are still poorly known, making marker-aided selection, or MAS, techniques premature); and

- human resource requirements, including capacity building from training to leadership.

Construction of a value proposition for industry.

If only one industry message had to be taken from the most recent consultations, it is that some industry players are skeptical about the short-term potential of genomics (especially for productivity), and the readiness of the science. In particular, there is currently no compelling and easy to understand value proposition for Canadian industry. Industry representatives commented that, in many cases, this means finding ways to reduce costs, not necessarily to increase the value of forest harvests. It must be noted that there is considerable variation among management officials, firms, and even regions in terms of how engaged they are with genomics, so outreach and communication efforts must be tailored to individual people and situations. Further, it is not that value propositions do not exist already, so much as that there are perhaps too many, but without clear linkages and priorities amongst them.

Developing a strong value proposition will affect all types of impacts now being discussed, whether they be from increased productivity (e.g., how can long growth cycles be dealt with, and how can genomics best improve upon traditional breeding methods?), healthy forests (e.g., under the current tenure and allowable cut system, how can a given firm be assured that its investment will benefit them specifically?), value-added products (e.g., how can the economics be maximized?), pests (e.g., control of pests has not been possible to date, but are there other nearer-term opportunities such as in sanitation and phytosanitation?), and climate change (e.g., how robust are the models, and how can the time to identify and grow “best fit” phenotypes be reduced?). Industry respondents frequently commented that they need to hear one single message that demonstrates a clear economic return on their investment, that would occur within the easily foreseeable future, and that would accrue to their specific firm (not just Canadian industry in general).

The points above were stressed in the recent consultations and, as noted earlier, some senior industry officials have limited exposure to forest genomics research and are understandably unaware of its potential value. Thus any value propositions need considerable input from industry in developing them, but also substantial interactions to explain and disseminate information if engagement is to be assured. Some specific points are that the process must:

- engage users earlier and more actively in project development, design, delivery, coordination and application (bridging the gap);
- develop common and more understandable language related to genomics to make it more understandable and less intimidating for end-users; and
- realistically assess the state of knowledge, the ability to validate and replicate key findings, develop means for proof of and metrics for success, and assess industry receptor capability.

Pursuit of proof of concept for a near-term “win”.

Many respondents noted that genomics has been oversold in the past. Although concrete applications and examples of industry applications have begun to come on line within the past five years, a clear economic “win” was believed to be required within relatively short timeframes to maintain this momentum. In other words, build on existing practical applications and opportunities to focus on some specific “low hanging fruit”.

Many specific opportunities were discussed in the 2013 Workshop, but at a high level there appeared to be most support for pest and pathogen diagnostics. This could include a national pest/pathogen survey complemented by the use and refinement of genomics tools, both of which fit well with the topics discussed in the Canada/US bilateral workshop as noted earlier. This suggests that a collaborative synthesis of Canadian and US efforts would be welcomed.

The improved diagnostics should be accompanied by considering how to develop options for responses. These ideally would include integration of Canadian, US, and provincial/territorial responses, including

certifications, sanitary and phytosanitary (SPS) techniques, and trade regulations. There would be a need for considerable effort to develop the exact nature of these responses (cross-border harmonization of regulatory and management responses can be a daunting challenge), as well as appropriate metrics for measuring progress and success, including impacts on intangibles. For the moment, many policy gaps exist in these areas.

Other possibilities such as improving productivity through genomics-enabled breeding programs for more commercially attractive wood traits and/or reduced selection and rotation cycles, although seen as highly important in the long term, may be too far down the road to fit the “near-term win” criterion. Value-added processing opportunities likely suffer the same basic problem, although the degree to which processing using nanocrystalline celluloses (NCCs) or cellulose nanofilaments (CNFs) might be improved short-term through genomic means are unknown. In both cases, however (and especially for productivity) there have been substantial scientific and technical advances recently, to the point that a few selected near-term opportunities might be identified in these areas as well.

A suggested focus for a near-term “win”. The discussions above demonstrate that the forest sector requires two different strategic approaches: (1) genomics-enabled tree breeding and selection, and (2) non-breeding opportunities. To arrive at a short-term “win” we argue that non-breeding opportunities may represent the best opportunity for an early win:

- Tree breeding, whether it be for productivity, quality, climate adaptation, pest resistance, value-added, will inevitably take many years, albeit with some variation by species. Though recent genomic advances mean the selection process can be considerably speeded up, deployment in replantation and harvesting will still be slow, certainly too slow to fit industry’s need for a concrete value proposition, right now.
 - » The implication is that tree breeding (for *any* downstream reason) may not represent the lowest hanging fruit. Most genomics R&D effort

to date has been on breeding programs, and these fit the most seamlessly into existing industry practices. However, we must accept that—while still of critical importance for long-term forest health and industry productivity—breeding approaches may not be what are needed *right at the moment*.

- Opportunities other than tree breeding, on the other hand, represent several potentially important applications that are actually doable in the foreseeable future. Possibilities include; e.g.,
 - » pest diagnostics and *non-genomic* containment methods;
 - » sanitation and phytosanitation;
 - » provenance and traceability, linked to certifications, regulations, and trade policies and export initiatives—combined with the two elements immediately above, there is potential for branding Canadian wood products as uniquely pest- and pathogen-free that could provide significant competitiveness advantages for Canadian producers; and
 - » improving *existing* value-added processing (i.e., not through breeding better-suited trees, but through techniques such as better genomics-enabled microbial processing techniques).

Fewer examples of non-breeding opportunities were discussed in the 2009 and 2012-2013 consultations because of the heavy focus on improved breeding opportunities—but the latter were always discussed in the context of significant, and often “deal-breaking” problems. In going forward, we therefore suggest re-thinking how the Canadian Enterprise could achieve short-term benefits and industry buy-in. Of course, genomics-enabled selection and tree breeding efforts would need to be continued, but accepted as generational investments. But for the near-term, think creatively about non-breeding opportunities.

5. PROCESS

A Forest Genomics Enterprise. Genome Canada and the associated Genome Centres must be congratulated for generating the momentum to date around

forest genomics, including funding, strategies, workshops and outreach. It is timely that the forest sector stakeholders become more engaged by coordinating and facilitating a coalition across Canada—creating a purpose-built Forest Genomics Enterprise that can develop a road map that builds on the work to date. The Forest Genomics Enterprise would champion the road map, develop priorities for applications, identify national/regional projects to fill gaps, and facilitate an ongoing dialogue among researchers and users in industry and government to build concrete application considerations in all future investments.

The 2012–2013 consultations suggest that this Forest Genomics Enterprise might involve a coalition of all relevant stakeholders, including the CFS, FPIInnovations, and provincial and forest genetics councils. Developing a coalition with the USFS would also be beneficial in a number of arenas, including leveraging of resources, capabilities, and outreach around specific initiatives. Possibly groups such as the Forest Products Association of Canada (FPAC) and the Canadian Council of Forest Ministers (CCFM) would also be involved; e.g., the latter to address policy and regulatory issues.

Near term actions. The 2012–2013 consultation process and Workshop brought together (virtually or in person) over 115 influential senior opinion leaders across the national forest sector. While embryonic in its development, this network asset should be nurtured, developed and consulted through regular communications as an appropriate national coalition is formed and the “go forward” road map is developed. One result is an expectation within the sector that concrete actions will happen and we will deliver on the promise. Ongoing engagement with individuals within this network, whether allies or skeptics, will be critical to communicating and realizing the vision for the sector.

Furthermore, it is expected that this road map, developed in consultation with this network of sector stakeholders, will provide a useful tool for funders, policy makers

and other stakeholders working to support innovation within the sector. In this regard, the most recent consultations identified two key messages: (1) narrowing the application gulf and creating clear value propositions imply a strong focus on creating an early win, and (2) stakeholders noted the inconsistency of the current funding mechanisms, including those accessed through Genome Canada for individual research projects; support for a national coalition and new funding mechanisms⁷ might help address this challenge and provide much-needed, more consistent resources for the sector strategy.

Long term. The long-term intent is to develop an integrated genomics-enabled forest sector initiative. This initiative will close the gap between the genomics potential within the academic sphere (the “push”), and what end-users in government and industry believe is feasible, most important, and timely (the “pull”). It will be an inclusive initiative involving all key stakeholders, and taking into account economic impacts as well as other important intangible effects such as those on the environment, forest communities, First Nations, and general Canadian society. Although the initiative is pan-Canadian, it is recognized that some specific regional priorities and capabilities will differ and need to be addressed, and that international (especially US) participation is almost certainly required.

Within a foreseeable planning horizon, outputs from the initiative are intended to be put into practice by end-users in the private sector (both traditional and value-added), provincial and territorial Forest ministries, the CFS, regulatory agencies, forest communities, and First Nations. This means not only that the results are useful enough to encourage uptake by end-users, but also that mechanisms are put in place to foster knowledge and technology transfer (e.g., to deal with receptor capacity issues, fund intermediary steps such as proof of concept and demonstrations, address policy and regulatory hurdles, etc.)

⁷ For example, a Check-off type of R&D funding mechanism as used in sectors such as agriculture may be useful.

APPENDIX 1: DETAILED DISCUSSION

THE IMPORTANCE OF THE FOREST SECTOR TO THE CANADIAN ECONOMY

Forests are Canada's largest renewable natural resource, and forestry is one of Canada's major economic engines. At more than 400 M hectares, Canada contains 10% of the planet's forests, and is one of only three countries in the world still retaining vast areas of virgin, untouched stands. Canada is the world's leading exporter of forest products such as softwood lumber, newsprint, and wood pulp, which together account for close to 10% of Canada's exports. The forest sector generated about \$54 B in revenues in 2010 and contributed about \$24 B to GDP (or 1.9% of the total) in 2011⁸. Exports are strong, at about \$26 B in 2011. Forestry also provides roughly 234,000 direct jobs, and in some 200 rural Canadian communities this sector makes up at least 50% of the economy⁹. Healthy Canadian forests also play a critical role in the global carbon cycle, and both forests and forestry are key elements of Canada's culture.

In recent years, Canada's forest sector has been struggling for competitiveness, recently reflected by a 30% decrease of its contribution to GDP due to a combination of market and environmental factors. This is having a considerable impact for the many communities in which the forest industry has traditionally been the main economic driver. Genomics¹⁰ can play a key role in reversing this trend through a two-pronged strategic approach: leveraging past longer-term research investments into shorter-term forest health solutions, and maintaining the generational investments needed to properly understand and manage this enormous

pool of natural resources, including maintaining preparedness¹¹ to deal with future environmental and economic challenges.

CHALLENGES AND OPPORTUNITIES IN THE FOREST SECTOR

Key Challenges

Market forces. Over the last few years the global forest industry had endured significant challenges, including the downturn in global economies, a general decline in demand for wood products, emerging low cost competitors, and a major contraction in the availability of financing. Domestically, this grim global picture resulted in significant job losses and mill closures, exacerbated by the decline in newsprint demand, a collapse in US housing markets, and a strong Canadian dollar. However, after years of shedding excess labour and lowering production costs across Canada, the forest sector is now far better positioned to compete into the future.

Environmental challenges. There have been changes in the frequency and severity of environmental disturbances such as insect and disease outbreaks, wildfires, droughts, storms, and changes to average temperatures and timing. In some regions, these disturbances have triggered reductions in allowable harvesting levels along with changing environmental regulations and newly established protected areas. The changing climate suggests that these issues will accelerate over time and adaptive management practices will increasingly be needed.

⁸ In constant 2002 dollars.

⁹ *The State of Canada's Forests, Annual Report*. Natural Resources Canada, 2012.

¹⁰ The genome sciences (also called "genomics" here) include: genomics, transcriptomics, proteomics, metabolomics, metagenomics, systems biology, and bioinformatics.

¹¹ National preparedness is seen as a critical outcome of public R&D investment in several countries. In Australia, for example, see: [Australian government] *Productivity Commission Research Report*, March 9, 2007.

Insect pests. Insect pests in Canada's forests have been part of the biological cycles since their existence. However, as demand for economically accessible wood fibre approaches the limits of supply, the tolerance for losses has declined. In 2009 and 2010 about 15.2 M and 12.7 M hectares of forest, respectively, were killed or defoliated by insect pests¹². For example, the mountain pine beetle (MPB) killed more than half of BC's commercial pine inventory from 1998 to 2011 and affected 1.3 M hectares of forest in Alberta. Climatic shifts are allowing the MPB to significantly increase its range across BC and Alberta and threaten Canada's boreal forests, with potentially devastating economic, community, and ecological impacts. In eastern Canada, heavy spruce budworm (SBW) infestation recurs roughly every 35–40 years, and severely affects the lumber, pulp and paper, and associated industries, as well as disturbing fire cycles from Alberta to the Atlantic. The emerald ash borer (EAB) has killed millions of ash trees in parts of Ontario and Québec and continues to spread. In the context of climate change, challenges related to such insect infestations are expected to accelerate. While the economic impacts associated with increased incidence and severity of pest infestation are easily measured, the impacts on environmental services (watershed protection, habitat for native flora and fauna, etc.), while more difficult to quantify, may in fact be even more significant.

Public forest policy. Unlike our neighbours to the south, the vast majority of Canadian forest land is publically owned and made available for use by private interests within a framework of specifically defined obligations (forest products, mining, energy, etc.) in return for royalties paid to governments. Unlike private forest land that is exploited with few restrictions, operations on public land are regulated by legislation, regulation, policy, guidelines and directives that not only create a financial

burden, but are often “time bound” and offer limited incentives for firms to make the kind of large and long-term investments in the forest as they do in their manufacturing facilities. The Canadian public is of course the ultimate end-user, but while it has little direct input into forest policies the public still retains very high expectations regarding the economic benefits and protection of forests.

Growth cycle. Canada's forests are generally more slow-growing than many of its international competitors, facing rotation cycles of 40–70 years. This makes reaping short-term benefits from R&D more difficult, again influencing the ability to compete for public and private research investment.

Understanding of genomics. Knowledge of, and interest in, genomics have increased dramatically among key end-users over the past five years, from it being almost invisible to it being at least “on the radar”. However, the way in which genomics can affect the sector is still not well understood by many stakeholders. The 2013 consultations found that there was good understanding of the technical aspects of genomics at the operational level within industry. However, the closer to the top of the corporate hierarchy, the less well understood was the potential for practical applications of genomics that could affect their business. (The opposite appears to be true within government forest ministries.) During the 2013 Workshop this finding was reinforced, as several senior industry officials commented that they had only a vague understanding of the value of potential genomics applications. These findings have implications for improving the nature of outreach, policy education, and ways to influence industry/public perception, to ensure that genomic innovations are implemented in the sector.

¹² *Op cit.* Natural Resources Canada, 2012.

Broad Opportunities

Tangible benefits for Canada. Challenges related to market forces, wood supply, pests/pathogens, and environmental issues offer a number of opportunities in which genomics R&D can help assure the long-term security of the fibre supply (e.g., through additional forest area suitable for production, more trees grown per hectare, and fewer losses due to biotic and abiotic stress), increase its intrinsic value (e.g., from increased wood quality), and provide the foundation for numerous value-added products (e.g., by tailoring fibre characteristics for specific end-uses). Genomics & Society research¹³ can investigate some implications of the resource's ownership and long-term growth cycle, as well as ensure non-quantifiable benefits such as intrinsic value, cultural and community significance, recreational uses, and environmental values of Canadian forests.

A catalyst for innovations in sustainable forest management. Genomics is providing a new lens through which to view sector challenges and powerful new tools for developing novel solutions to these challenges. Through this lens, we can envision using genomics to be more efficient in our plantation choices, so less pest management energy is required, and we can imagine greater efficiency in the mills through tree breeding targeted at increased productivity and specific value-added needs, all of which will have a net positive impact on our sustainable forest management performance.

ROLE OF GENOMICS IN MITIGATING THE CHALLENGES AND CREATING THE OPPORTUNITIES

The vast majority of stakeholders believe that the most appropriate strategy is to create a few large-scale projects that catalyze the necessary critical mass to address major issues, and develop these programs on a national scale to make them relevant Canada-wide. It is recognized, however, that there will be some regional variation in priorities and relevant partnerships.

The two main broad opportunities for using genomics to address sector challenges have been summarized as “Productive Forests” and “Healthy Forests”. These two overarching topics are nevertheless intimately related: there will be no productive forest sector without healthy forests, and no healthy forests without sustainable forest management practices. Within both, emphasis will need to be put not only on knowledge development but also on knowledge transfer and practical implementation. A translation-focused approach that uses genomics to integrate the various sector problems, stakeholders, and disciplinary approaches is possible. This can provide a breakthrough in how the sector's stakeholders collaborate and function, providing a higher chance of success than the often-piecemeal approach now used.

Productive Forests

Improved forest productivity. An important opportunity for industry and government is the development of marker-aided selection for yield, wood quality, and pest resistance traits to be used in tree improvement

¹³ Genomics & Society research focuses on understanding those factors lying at the interface between science and society that influence the extent to which genomic technologies are taken up by society, the uses to which they are put, and the benefits therefrom. Genomics and Society research is typically conducted by researchers from a wide range of disciplines including; social sciences, law, philosophy, bioethics, anthropology, business ethics, commerce, economics, education, environmental and conservation sciences, animal welfare, communications and journalism studies, political science and public policy.

programs. Such work has been done in the past using genetic markers and research has recently delivered significant new results. Now is the time to use genomics approaches to improve efficacy even more. There is a number of existing provincial, federal, and private sector collaborations around tree breeding initiatives (e.g., the Province of Québec with the Canadian Forest Service [CFS] and FPInnovations around tree breeding; and the Province of BC with CFS and Québec around the SMarTForest project). Such collaborations may be bolstered by additional focus on genomics-enabled opportunities. In cases where the private sector has ownership and incentive (e.g., JD Irving), significant in-kind support is available through their extensive phenotype libraries.

Within this effort, it will also be useful to investigate how refined forest management methods can maximize genomics-enabled gains. For example, plantations in many countries are more intensively managed than in Canada, with explicit strategies for growth, yield, and quality (but often operating under significantly different ownership and public policy regimes from Canada's). Some nations are also managing harvesting levels according to strongly integrated vertical value chains; e.g., daily harvesting based on individual customers' species/quality/quantity requirements. These nations have seen impacts at many scales, ranging from traditional forestry to fast-growing purpose-grown energy crops like willow or poplar for which it is easier to take advantage of genetic gains (but which may not offer high value/high margin economic impacts). Canada has traditionally been well-served by natural regeneration and less extensive forest management. However, there is now a recognized need in some regions and markets for more intensive and targeted forest and silviculture management, shifting away from a focus on low cost forest management towards more

explicit user pull based on market needs and, increasingly, higher quality wood and value-added products. This might include both breeding programs for specific lignocellulose traits required in value-added products and processes (e.g., biofuel production), as well as genomic characterization of harvested fibre to ensure compatibility with specialized end-uses.

Value-added processing¹⁴. Value-added processes such as bioconversion and chemical production are increasingly using wood fibre as a base material, for example because of cost/effectiveness advantages, to address supply limitations foreseen for other feedstocks such as agricultural, or to capitalize on the “green” sustainability advantage of feedstocks from forests. Genomics-enabled improvements can be made to the base material used in these processes (at present, usually the residue streams resulting from solid wood product processing), or to improve the bioprocessing itself, in particular focusing on:

- advanced materials – identifying wood-derived factors that more efficiently produce compounds that may be used in manufacturing novel composite materials, for example by using nanocrystalline cellulose (NCC), cellulose nanofilaments (CNF)¹⁵, or lignins; and
- bioenergy – identifying enzymes with enhanced cellulolytic properties that more efficiently convert wood waste to fuels, and marker assisted breeding of trees to foster improvements in carbohydrate conversion.

Many of these value-added processes are currently driven mainly by engineering advances. There is considerable scope for more collaborative engagement between government and industry on how to leverage forest genomics capability to maximize the effectiveness and efficiency of these efforts.

¹⁴ Here we do not mean manufacturing value-added products such as paper, cardboard, glued panels and beams, etc. directly from wood.

¹⁵ Both are useful in providing high reinforcement strength in composite materials far more inexpensively than using carbon fibres. NCCs are at the nanotechnology scale, while CNFs are at the micro scale.

Trade issues. Identification of pathogens and pests through “genetic barcoding” will allow for rapid identification, monitoring and mitigation of species of concern by the Canadian Food Inspection Agency (CFIA) and the provinces and territories. Trade issues such as potential trade sanctions against Canadian wood products may be dealt with through programs targeted at genomics-enabled wood provenance and pathogen testing, certification and chain of custody, and with implications for phytosanitation (e.g., protocol development, validation, certification).

Industry and government end-users are best positioned to identify the highest priority topics that can significantly affect imports and exports (e.g., traceability). Genomics research programs will develop mature, commercially-ready technologies such as single nucleotide polymorphism (SNP) chips and other genomics-based tests that can improve traceability and provenance, for example focusing on restriction fragment length polymorphism (RFLPs) and multi-locus genotyping. As is the norm for the development of other specialized tools and methods used in trade, certification bodies will likely be active partners to ensure that the genomics technologies and standards are accurate, validated, and accepted by the international community. The CFIA currently issues phytosanitation certificates, for example, and cooperates through the International Plant Protection Convention with international bodies such as the European Plant Protection Organization and the US Department of Agriculture to develop protocols and standards related to specific pests and pathogens¹⁶. Canadian sanitation and phytosanitation, traceability, and provenance standards, tied to Canada’s reputation in SFM, can then be promoted world-wide as a marketing tool for Canadian wood products.

Healthy Forests

Insect pests. Sustainable forest management includes the management of pests to minimize their impact on forest productivity and protect silviculture investments. The priority candidates for genomics-enabled solutions are seen to be biotic and abiotic factors affecting MPB, SBW, and EAB. Genomics approaches can determine baseline genetic diversity of pests and pathogens and host-parasite interactions at the molecular scale, which can lead to identification of molecular targets for pest management (e.g., natural pathogens and diseases), and new tools for pest/pathogen tracking. Investigation of host specificity, distribution (including variability in natural resistance and species/hybrid susceptibility to pests and pathogens), and transmission, will lead to the identification of resistance marker genes which can be used in breeding programs, and identification of susceptibility marker genes can guide reforestation practices. Better identification and mitigation measures will support Canadian preparedness for future invasive disease and pest invasions (e.g., Asian longhorn beetle, European and Asian gypsy moths).

Climate change adaptation. Silviculture and tree breeding practices can leverage genomics research that investigates the adaptation of trees to weather events triggered by a changing climate (such as droughts, floods, and changes to average temperatures and timing), and changing pest distributions (some of which are climate-related).

This will match “best fit” tree genotypes to appropriate climatic and geospatial zones, and map these against models now being developed to anticipate the timing and spatial distribution of future forest challenges. Modifications to afforestation and reforestation policies such as those governing seed transfers, planting

¹⁶ For the CFIA see: <http://www.inspection.gc.ca/plants/exports/phytosanitary-certificates/eng/1299872808479/1299872974262>. For the IPPC see: <http://www.ippc.int/IPP/En/default.htm>.

zones, functional genetic diversity in planting stock, and plantation management, will maximize the regeneration success and sustainability of future forests, with the boreal forests being a priority target. The sheer diversity of Canadian ecosystems allows researchers to conduct comprehensive investigations not possible in most other countries, providing Canada with unique research and application advantages.

Risk and benefits assessment

Analysis of risks and potential pay-offs can determine in which sub-sets of these topics genomics can provide the highest ROI to industrial and provincial end-users, be faster than traditional approaches (e.g., in tree breeding programs), deal with unique challenges, and/or leverage more Canadian capability. Such risk analysis may be combined with existing mechanisms such as the risk framework developed by the Canadian Council of Forest Ministers in collaboration with CFIA and the CFS in their National Forest Pest Strategy (NFPS)¹⁷. There are both qualitative and quantitative approaches possible.

A multiple account framework (MAF)¹⁸ is a qualitative approach that may assist high level decision-making, as it provides a relatively simple way to assess trade-offs among impacts on different key “accounts” that include both quantitative and qualitative metrics, and that apply to different end-users. For example, one might consider the impacts of R&D initiatives against forest sector accounts such as: short-term national income, regional employment, long-term forest health and sustainability, First Nations, and national and regional “preparedness” for future challenges. Trade-offs among different options are then easier to

evaluate; e.g., one package of initiatives might provide the greatest short-term GDP impacts but fall short on preparedness; another might be the opposite. The end result of MAF is usually a short list of candidate projects.

Quantitative approaches are useful to drill down on the specifics of these candidates to identify those with the greatest economic potential. Standard benefit-cost techniques can be used, applying these to hypothetical models of anticipated cost and benefit streams, the timing of costs and benefits, likelihood of scientific and commercial success, estimates of take-up, need for capitalization, ability to quantify public good impacts, etc. And since many benefits may accrue offshore, the models can take into account what specific proportion of impacts may benefit Canada (and consider how such impacts can be assured).

SUCCESS OF PAST CANADIAN INVESTMENTS IN FOREST GENOMICS

Forest genomics research has proven itself through development of many complementary technologies and management tools, a selection of which are described below.

Productive forests

Selective breeding practices have been used for as long as plantation management and reforestation programs have existed. More recently, the importance of single gene and whole genome effects has become recognized, along with an emerging understanding of the increase in the system complexities (e.g., gene interactions, gene regulation, epigenetic effects). As genomic studies become mainstream in the study of

¹⁷ <http://cfs.nrcan.gc.ca/pages/345>. A fully implemented NFPS would include monitoring, risk analysis, coordinated national responses to risks (including R&D), information management, and decision-making tools.

¹⁸ See, for example, *Considerations Involved in Developing an Economic Assessment Framework for the Prince Albert Model Forest Region*. S.N. Kulshrestha, B.F. Moriarty, and H.V. Walker. A report prepared for The Prince Albert Model Forest Association Inc. Prince Albert, Saskatchewan. July 1994. Available at: <http://www.pamodelforest.sk.ca/pubs/PAMF1700.pdf>

all living systems (e.g., within personalized human health and medicine), we are on the cusp of a natural advance from breeding based on single gene to genomic profiles that are linked to phenotypes. While this work is relatively early, some specific examples of projects in progress are discussed in section 5.2 (e.g., POPCAN, SMarTForest).

Healthy forests

Over the recent years, genomics studies have led to the development of innovative tools and practices leading towards healthier forests. Some specific examples are noted below.

Sudden oak death. A kit was developed by the CFS to monitor the canker that causes sudden oak death before the disease moved from the US to Canada. It is being used by the CFIA and US Department of Agriculture-Animal and Plant Health Inspection Service (USDA-APHIS) to certify that Canadian nurseries are free of the disease, thereby allowing Canadian producers to export their materials¹⁹.

Balsam fir sawfly. Using genomics, the CFS characterized and commercialized via Sylvar Technologies the naturally occurring insect nucleopolyhedrovirus as a forest pest management product (Abietiv™). About \$750,000 worth of Abietiv™ was sold and sprayed over large parts of Newfoundland and Labrador against balsam fir sawfly in 2006²⁰,

and the product is still in use. The virus not only resulted in the collapse of infestations, but an epizootic was established that kept the insect under control for a number of years²¹. Furthermore, Sylvar employs research scientists as well as laboratory and field support personnel, adding high value jobs in Fredericton, New Brunswick. This approach has been studied to see if it would be amenable to other pests such as SBW.

Blister rust resistance. The CFS has identified blister rust resistance genes in western white pine, and pollen from major gene resistant (Cr2) trees is now used to create “clean” seedlings for use in coastal reforestation in BC²².

Pest/pathogen sensitivity. The CFS is currently working on roughly 50 molecular targets using array-based tools developed jointly with FPInnovations, and about ten of these are close to application. Examples include tools meant to test hybrid poplars for pest/pathogen sensitivity and genetic transmission, and on ash die back. The CFS is moving completely away from earlier ELISA-based tests in these areas.

Dutch elm disease. Researchers have identified the genetic basis of elicitor compounds induced in elm trees when attacked by Dutch elm disease carried on European elm bark beetles and their fungal symbionts. Scientists have used the information to develop ‘vaccine’ tactics to immunize healthy elms with non-virulent disease strains. This strategy is currently undergoing

¹⁹ Seeing the forest through the genes. Natural Resources Canada. <http://canadaforests.nrcan.gc.ca/articletopic/133>.

²⁰ Cuddeford V. Good news for Canadian biocontrol: Registration of Abietiv, a new made-in-Canada bioinsecticide. *BioControl Files: Canada's Bulletin on Ecological Pest Management* 2006; November. www.biocontrol.ca/pdf/Bio8EN-Final.pdf; www.sylvar.ca/content/13058. Accessed May 6, 2009.

²¹ Arif B. Genomics of the spruce budworm and its viral pathogens, and the pursuit of bioactive molecules as spinoffs. Genomics for future forests symposium report. Natural Resources Canada Canadian Forest Service. 2006; 41-44.

²² Zeglen, S., Hunt R, Cleary M. British Columbia's forests: White Pine Blister Rust Forest Health Stand Establishment Decision Aid. *BC Journal of Ecosystems and Management* 2009; 10(1):97–100. www.forrex.org/jem/ISS50/vol10_no1_art9.pdf. Accessed May 28, 2009.

²³ Scheffer RJ, Voeten JGWF, Guries RP. Biological control of Dutch elm disease. *Plant Disease*. 2008; 92, 192-200; Nasmith C, Jeng R, Hubbes M. A comparison of *in vivo* targeted gene expression during fungal colonization of DED-susceptible *Ulmus Americana*. *Forest Pathology*. 2008; 38(2): 104-112; Coghlan A. A jab for trees—A vaccine will make it easier to control Dutch elm disease. *New Scientist*. 1998;160 (2164):7; Trees to be vaccinated against Dutch elm disease. CTV. Updated Sat. Jun. 6 2009 10:02 PM.

commercial development through field trials on the leading edge of the Dutch elm disease infestation to prevent impacts in western Canada²³.

White spruce quality. There has been recent interest and uptake by the Quebec provincial government of white spruce molecular markers for improved wood characteristics.

THE SOCIOECONOMIC IMPACT OF GENOMICS-ENABLED SOLUTIONS

Genomics can address important socio-economic needs of the forest sector that cannot easily be solved through other means, because genomics can unravel the fundamental biological mechanisms underlying many critical challenges. To be fully effective, some changes may be required to provincial forestry policies, and so there is a significant Genomics & Society component to many solutions. Many genomic research programs will address more than one factor simultaneously, as seen in the concrete examples below drawn from existing Genome Canada projects (although not all are yet fully implemented). For example, all projects addressing forest health will have significant implications for resource sustainability, carbon cycles, and environmental quality (land, water, and air, and including wildlife, public good, and consumer surplus values), while all projects addressing forest productivity will have significant implications for customer needs and market pull, rural community health, culture, and job creation and sustainability.

Examples related to a productive forests agenda

Harnessing Microbial Diversity for Sustainable Use of Forest Biomass Resources. This project is producing three major inter-related classes of deliverables: (1) new lignin-based products, including biofuels;

(2) biocatalysts to transform lignin; and (3) improved forest management practices. All three will have major economic, social and environmental (“green”) benefits by helping to sustainably and economically unlock and exploit the considerable potential of Canadian forest biomass, and providing new opportunities and jobs for forest community development.

- *Resins for plastic production.* Lignin-derived resins for Canadian plastics production will be worth up to ~\$300 M per year if 25% of Canadian resins become lignin-based.
- *Increased pulp production.* Increased pulp production is possible by removing excess lignin, and will be worth \$300 M per annum to Canadian Kraft mills if 10% of lignin can be removed.
- *Replacement of petroleum feedstocks.* Production of monocyclic aromatic hydrocarbons (e.g., BXT and styrene) from lignin will be worth \$217 M annually if 25% of Canada’s petrochemical production from petroleum feedstock is replaced by biomass feedstocks.
- *Other value-added products:* these will include lignin-based carbon fibres, and cellulosic biofuels (which are more environmentally sustainable than agriculturally derived biofuels).
- *Improved environment.* Compared to traditional chemical production, biocatalyst-enabled production of resins and pharmaceuticals will use significantly less energy, produce less mass (excluding water), and create lower photochemical ozone and acidification, and uses no toxic metal catalyts.

AdapTree: Assessing the Adaptive Portfolio of Reforestation Stocks for Future Climates. This project assesses the impacts of climate and pest challenges on lodgepole pine and interior spruce, the two most important sources of fibre and wood in

²⁴ Wang, T., Hamann, A., Yanchuk, A., O’Neill, G.A., and Aitken. S.N., 2006. Use of response functions in selecting lodgepole pine populations for future climate. *Global Change Biology*. (12: 2404-2416)

western Canada and the most common reforestation species. Pest and climate challenges are anticipated to lead to a 10% to 35% reduction in lodgepole pine productivity if not mitigated²⁴, with significant implications for communities depending on this resource, and for Canada's carbon sequestration potential. Modified reforestation policies and practices based on genomics information will allow reforestation efforts using selected "best fit" genotypes matched to changing growth environments. This will require changes to current provincial seed transfer policies and genetic resource management for lodgepole pine and interior spruce (which in BC and Alberta grow almost exclusively on public lands), allowing the genetic potential of replanted forests to respond to climate change to be maximized²⁵:

- Even a 5% to 20% relative mitigation of the anticipated productivity losses caused by these challenges will result in annual impacts of \$23 M–\$363 M, with a Net Present Value (NPV) of \$1.2 B to \$20 B over the next 125 years, representing two growth/harvest cycles²⁶.
- Over the next 200 years (the standard timeframe used by the Forest Genetics Council of BC), the NPV rises to \$3.5 B–\$50 B, and will affect about 500–8,000 FTEs of employment.
- Not included in either of these estimates is the value of other impacts such as ecosystem health, increased forest productivity, or First Nations cultural sustainability.

Climate-based revisions to seed zones and seed transfer guidelines are being made in BC²⁷; and in Alberta there are calls for scientific guidance on managing seed movements and genetic diversity in reforestation programs²⁸.

SMarTForest: Spruce Marker Technologies for Sustainable Forestry. This project is providing forest managers with genetic marker systems and biomarkers to enable Marker Assisted Selection (MAS) in tree breeding and forest management programs for spruce plantations and forests. The major users will be spruce improvement programs, starting with those in British Columbia, Québec, Ontario, Alberta and New Brunswick. The major benefits are:

- *Insect pest resistance.* The present value (PV) expected from the use of resistant interior spruce planting stock in British Columbia alone could reach up to \$123 M over a long-term planning horizon²⁹; However, a safe "intermediate" estimate from this analysis is ~\$50 M³⁰.
- *Wood quality and value recovery.* For a typical Canadian sawmill, improving the average grade of lumber by 15% would add \$1.5 M per year to product value. This objective could be met if 50% of the saw-logs came from trees selected for wood traits related to stiffness. At a national scale this represents a \$300 M annual margin.

²⁵ Current policies are based on risk-avoidance strategies that mimic natural processes through restricting seed movement and maintaining natural patterns of genetic diversity. These policies are no longer valid as climates change, requiring climate-based refinements to seed transfer guidelines and seed zones that provide a better "fit" of each species' genotype suitability to changing environments and geographic distributions.

²⁶ Using a 2% discount rate.

²⁷ O'Neill, G.A., Ukrainetz, N.K., Carlson, M., Cartwright, C.V., Jaquish, V.C., King, J.N., Krakowski, J., Russell, J.H., Stoehr, M.U., Xie, C.Y., and Yanchuk, A.D., 2008; Assisted migration to address climate change in BC: recommendations for interim seed transfer standards. *Technical Report 048*. Victoria, BCV. BC Ministry of Forests and Range.

²⁸ AFGRC, 2007. *Alberta Forest Genetics Resource Council—Research Priorities*.

²⁹ Schwab O., T. Maness, G. Bull, D. Roberts 2009. Modeling the effect of changing market conditions on mountain pine beetle salvage harvesting and structural changes in the British Columbia forest products industry. *Canadian Journal of Forest Research*. (39:1806-1820).

³⁰ A. Yanchuk, pers. comm.

- *Growth and yield.* MAS selection is projected to increase Canadian wood supply by about 1.5 M m³ per year at harvest, with an impact of \$300 M per year on Canadian GDP.

POPCAN: Genetic Improvement of Poplar Trees as a Canadian Bioenergy Feedstock. The genomic platforms produced in POPCAN is generating a suite of powerful molecular tools (SNPs) to support marker-assisted breeding (MAB) in poplars for rapid improvement of biomass, biofuel, and disease resistance traits, allowing poplars to be deployed as efficient and sustainable bio-energy feedstocks:

- *Bioenergy and Biorefinery Industries.* These advances will facilitate rapid improvement and development of an alternative, highly productive forest tree species and bioenergy feedstock appropriate for many Canadian landscapes, and help ensure a place for Canada in the emerging carbon economy. When these feedstocks are deployed at the scale required to meet the ethanol supplement target in the Canadian Renewable Fuels Strategy³¹, it will save 0.75 M tons of feedstock annually and increase annual production of ethanol by 240 M litres.
- *Benefits to Traditional Forest Industry.* Deployment of elite genotypes with improved cell wall chemistry traits and optimized adaptation to local climate will improve traditional cellulose manufacturing processing such as in the pulp, paper and specialty cellulose industries. The impact of a 5% increase in wood cellulose content in a single poplar plantation producing 10 dry tons of cellulose/hectares/year would be approximately \$1 M per year.
- *Environmental Benefits.* Energy crops will play a key role in carbon cycling, and as such will increasingly

be targeted as a means to reduce emissions. Recently, the Province of BC released a draft Forest Carbon Offset Protocol³², and projects meeting protocol requirements will generate offsets that can be sold on the carbon offset market.

Traceability. Québec has found that the number of markers for effective tree traceability during the production process is fewer than what is required to do genomic selection (perhaps 20–40 markers vs. more than 100, respectively), suggesting that traceability may be a more effective short-term avenue to pursue.

The province is very close to practical genomics traceability applications for white spruce. Last year, and in Quebec alone, 32 M white spruce seedlings were produced, of which 98% came from the breeding program. More than 3 M of these seedlings are produced via a clonal production system (somatic embryogenesis and root cuttings), and for black spruce about 40% out of the 92 M seedlings produced came from the breeding program. The province believes they will be able to develop a genomics-enabled traceability system that is more universal and applicable to other living systems (e.g., aquaculture, other plant production systems). When genomic selection is implemented, development of certification methods and standards will assure credibility and governance.

Examples related to a healthy forests agenda

Genomics-Based Forest Health Diagnostics and Monitoring. This project is developing diagnostic tools for forest pathogens. These tools will also assist the forest and nursery industries with plant and product certification, offering Canada's corporations a competitive edge in the international forest sector. Secondary benefits are expected in the form of

³¹ <http://www.gazette.gc.ca/rprp/p1/2010/2010-04-10/html/reg1-eng.html>. This strategy aims to reduce greenhouse gas (GHG) emissions by mandating a nation-wide minimum 5% renewable fuel content in gasoline for transportation (some provinces have targets of 10% renewable content).

³² <http://www.env.gov.bc.ca/cas/mitigation/fcop.html>

improved trade relations and reputation in international markets due to Canada's proactive preventative approach to diagnostic testing and export certification, and demonstrated leadership role in industry, policy, and research regarding forest health management. Benefits will be substantial:

- *Current losses.* Canadian resources equivalent to at least \$66 M (and possibly as much as \$690 M in full market value) are currently lost annually to invasive forest pathogens³³.
- *Cost savings.* This project is expected to generate a at least a 1% reduction in volume lost to forest pathogens annually, and (following broader application of the diagnostic tool after testing and validation), a reduction of up to 2% resource loss nationwide. This would translate into from \$22 M–\$44 M in losses avoided per year.
- *Revenue generation.* Distribution of the diagnostic to Canadian publicly-funded and private test sites will conservatively generate annual revenues of up to \$4 M.

Tria 2. This project uses genomics to study the interactions between invasive bark beetles, fungal pathogens, and host pine trees to improve forest ecological risk models. These genomics-based forecasting tools will anticipate the available supplies of lignocellulosic feedstock suitable for bioenergy production. Accurate prediction of bioenergy opportunities will allow modification of forest policies and planning tools to focus more on value-added opportunities rather than traditional forest products.

Two major challenges are being addressed: (1) MPB, especially as the pest spreads beyond its historic range (e.g., into Alberta) and into new hosts such as jackpine; and (2) climate change. These two challenges currently make it difficult for policy makers, resource managers, communities, and industry to identify the “right time” and “the right place” for investment in bioenergy facilities. The tools will also feed into Canada's NFPS to allow prediction of the occurrence and severity of MPB outbreaks and estimate bioenergy feedstock supply opportunities under various MPB outbreak scenarios.

CANADA'S LEADERSHIP AND STRENGTHS

World-Class Scientific Leadership

Canada's forestry genomics researchers are world leaders, particularly in the area of conifer and forest pest research. The Arborea³⁴ and Treenomix³⁵ projects were early, large-scale, international, and integrative forest health genomics projects led by Canadian researchers. Furthermore, the CFS has a strong network of scientists working on insect population dynamics, climate change research, and carbon budget modeling. CFS research in New Brunswick, Quebec, Ontario, and BC covers pest insect genomics and applied tree resistance genomics.

The excellence of Canadian forest genomics researchers has been recognized by other countries with major forest assets, such as Brazil, Norway, Sweden, and the US, as well as Austria, Belgium, China, France, Germany, Italy, the Netherlands, Spain, South Africa, Thailand, and the

³³ (1) Pimentel, D., Lach, L., Zuniga, R. and Morrison, D., 2000, Environmental and economic costs of nonindigenous species in the United States, *Bioscience* (50: 53-65). (2) Rossman, A. Y., 2009, The impact of invasive fungi on agricultural ecosystems in the United States, *Biological Invasions* (11: 97-107).

³⁴ <http://www.genomecanada.ca/medias/pdf/en/Arboreall.pdf>.

³⁵ www.treenomix.ca.

³⁶ Krell P. Canadian research involvement in international insect pest and pathogen projects. *Genomics for future forests symposium report*. Natural Resources Canada Canadian Forest Service. 2006; 37-39.

³⁷ Tuskan, G.A. et al. The genome of black cotton wood, *Populus trichocarpa*. *Science*. 2006; 313: 1596-1604.

UK³⁶. Large scale collaborative projects have been conducted with, among others, Umea Plant Sciences Centre (Sweden), the UK Forestry Commission, the University of California Davis, and the Max Planck Institute for Chemical Ecology (Jena, Germany). Canadian scientists have been or currently are involved in global projects related to two major tree species in Canadian forestry, spruce and poplar, and participated in the recent international sequencing of black cottonwood genome³⁷.

Forestry Genomics Capacity from the Atlantic to the Pacific

Genome Canada, the regional Genome Centres³⁸, the CFS, the Canadian Wood Fibre Centre (which provides FPInnovations with forest-level “upstream” research services), the CFIA, and the provincial ministries of forests have actively supported large-scale forestry genomics research over the past 10 years. Investments from universities, research institutes, the Natural Sciences and Engineering Research Council, other federal departments and agencies, companies, and others have created additional genomics capacity and expertise applicable to forestry. Capabilities are underpinned by Canada’s internationally competitive large-scale technology platforms and R&D centres. The research has resulted in basic structural and functional data that are now being applied to novel tools that can be used in conjunction with traditional forest management techniques, as indicated above.

Linkages with the US

Many issues facing Canadian forests are equally relevant in the United States. The March 2013 bilateral Canada/US Forest Health Summit II showed that many of the key topics proposed in the Genome

Canada workshop for enhanced investigation would fit within a collaborative trans-national model; e.g.

Overarching topics:

- develop a joint inventory of highly novel forest inventory technologies and applications to be vetted at a bi-national conference.

Trade-related topics:

- develop genomics-based diagnostics/detection tools for use at borders or with shippers to survey for plant pathogens and certify wood origin; and
- develop a shared agenda to keep invasives out of both countries by establishing perimeter security and start by targeting a specific pest and use that as a pilot for the secure perimeter concept.

Pest/pathogen-related topics³⁹:

- develop a working Emerald Ash Borer “tool box” for municipal managers that includes best practices including: sanitation; identification; surveys; pheromones; treatment; etc; and
- investigate a joint synthesis of current diagnostic/detection tools and capacities around invasive pests with a view to identifying gaps and sharing best practices.

The heads of the CFS and the United States Forest Service (USFS) currently anticipate pursuing two to four projects immediately, with others perhaps following later. It will be important for any initiatives arising from the forest GSS consultation process to integrate with these collaborative ventures in order to maximize effectiveness and efficiency.

³⁸ Genome BC, Genome Alberta, Genome Prairie, Ontario Genomics Institute, Genome Québec, Genome Atlantic.

³⁹ These are also trade-related, but more focused on the pests/pathogens themselves.

APPENDIX 2: PARTICIPANTS IN THE 2012 ADVISORY COMMITTEE

The discussions in this paper were developed with the support of a Forest Genomics Sector Strategy (GSS) advisory committee struck by Genome Québec and Genome BC.

The members of the Forest GSS advisory committee (October 2012) are:

- Greg Adams, Manager, Research and Development, JD Irving Limited
- Michel Campagna, Direction de l'environnement forestier, Ministère des Ressources naturelles et de la Faune
- Dave Davies, Managing Director, Forest Protection Limited
- Ian de la Roche, Genome BC Board member, former President, FP Innovations
- Yvan Hardy, GC Board Member and Chair, UNEP International Panel for Sustainable Resource Management
- Keith McClain, Program Lead, Mountain Pine Beetle Program, Foothills Research Institute
- Mary Mes-Hartree, Director General, NRCan Canadian Forest Service (CFS) National Capital Region
- David Nanang, A/Director General, NRCan CFS, Great Lakes
- Alan Pelman, former VP Technology, Weyerhaeuser Canada
- Steve Price, Executive Director, Alberta Innovates Bio Solutions
- Larry Stanley, Manager, Forestry Development, Saskatchewan Ministry of Energy and Resources

- Paule Tetu, Génome Québec Board member, FPIInnovations Senior Advisor – University Strategic Partnerships

This group advised on new consultations and refinement of targets developed during the March 31, 2009 Canadian Forest Health Genomics Initiative Workshop that resulted in a 2009 white paper⁴⁰.

The authors of the 2009 report were:

- Brian Aukema, Canadian Forest Service, Natural Resources Canada & University of Northern British Columbia, Prince George, British Columbia
- Jörg Bohlmann, University British Columbia, Vancouver, British Columbia
- Anne-Christine Bonfils, Canadian Forest Service, Natural Resources Canada, Ottawa, Ontario
- Daniel Doucet, Canadian Forest Service, Natural Resources Canada, Sault Ste. Marie, Ontario
- Ismahane Elouafi, Canadian Food Inspection Agency, Ottawa, Ontario
- Nadir Erbilgin, University of Alberta, Edmonton, Alberta
- Armand Séguin, Canadian Forest Service, Natural Resources Canada, Quebec City, Quebec
- Sandy Smith, University of Toronto, Ontario
- And with the assistance of Sue Kingsley, Vancouver, British Columbia.

⁴⁰ *Canadian Forest Health Genomics: Canadian Strengths Address Forestry Challenges*. July 2009.

APPENDIX 3: FOREST GENOMICS STAKEHOLDER CONSULTATIONS (2012–2013)

INDUSTRY

- Ric Slaco, VP Forestry, Interfor (BC and US)
- Mark Feldinger, VP Forestry and Environment Canfor (BC, AB, QC and US)
- David Lehane, VP Forestry WestFraser (BC, AB, US)
- Brian Merwin, VP Strategic Initiatives, Mercer International (BC, Germany)
- Alan Pelman, former VP Research Weyerhaeuser
- Ian de la Roche, former President and CEO FPIInnovations
- Pierre Lapointe, Pres and CEO FPIInnovations
- Jean-Pierre Martel, VP Strategic Partnerships FPIInnovations
- Mark Hubert, VP Environmental Leadership, FPAC
- Blake Brundson, Chief Forester, JD Irving, St John (NB, NS, US)
- Greg Adams, Tree Improvement Manager, JD Irving, St John
- Jack Woods, Program Manager, Forest Genetics Council of BC/CEO SelectSeed Ltd.
- David Davies, Managing Director, Forest Protection Limited, Fredericton, NB
- Fred Dzida, National Director, Forestry, Weyerhaeuser Co Ltd (BC, AB, ON, US)
- Jason Linkewich, VP Strategic Fibre Supply, Tembec, (ON, QC)
- Martin Lorrion, VP Forestry & Environment, Domtar, QC
- Kevin Belanger, VP Forestry and Woodlands, Domtar, (ON, QC, US)
- Andre Tremblay, President & CEO, Quebec Forest Industry Council
- Catherine Cobden, Executive VP, Forest Products Association of Canada, Ottawa
- Brian Nicks, Sr VP, Forest Management & Operations, Eacom Timber Corp (ON)
- Bob Fleet, VP Forestry and Environment, Tolko (BC, AB, SK, MN)
- Helen Nemeth, Assistant to the Executive Chair, Tolko
- Michael O'Blenis, VP, Fibre Supply and Gov't Relations, Aditya Birla, (NB)
- François Dumoulin, VP, Forestry, Resolute Forest Products (ON and QC)
- David Lindsay, President and CEO, Forest Products Association of Canada, Ottawa
- Jon Flemming, VP, Industry Affairs, BioTech Canada (Ottawa)
- Michel Lessard, VP Forest Resource Management, Tembec (ON and QC)

GOVERNMENT

- Tony Ritchie, Executive Director, Plant Health CFIA
- Beth MacNeil A/DG Science CFS-NRCan
- Kami Ramcharan DG, Pacific Forestry Centre, CFS-NRCan
- Jacinthe Leclair, DG, Laurentian Forestry Centre, CFS-NRCan

- Bill Anderson, Sr Policy Advisor, Atlantic Forestry Centre, CFS-NRCan
- George Bruemmer, Executive Director, Canadian Wood Fibre Centre
- Mike Fullerton, Director, Science Branch CFS-NRCan
- David Bailey, CEO and President, Genome Alberta
- Tim Karlsson, A/DG, Manufacturing and Life Sciences Branch, Industry Canada
- Tom Bedford, Sector Analyst, Manufacturing and Life Sciences Branch, IC
- Saeed Khan, Business Analyst, Manufacturing and Life Sciences Branch, IC
- Brad Feasey, Senior Sector Analyst, Manufacturing and Life Sciences Branch, IC
- Richard Savard, DM, MRN&F, Quebec (by e-mail)
- Robert Jobidon, Director, Forest Research, MRN&F, Quebec
- Doug Konkin, DM, Ministry of Forests, Lands and N.R. Operations, BC
- David O'Toole, DM, Ontario Ministry of Natural Resources
- George Ross, DM, Ontario Ministry of Northern Development and Mines
- Bill Thornton, ADM, Forests, Ontario Ministry of Natural Resources
- Tom MacFarlane, ADM, Renewable Resources, New Brunswick DNR
- Julie Towers, Executive Director, Natural Resources Branch, NS DNR

RESEARCH COMMUNITY

- Richard Hamelin, UBC
- Jörg Bohlmann, UBC
- Sally Aitken, UBC
- Janice Cook, U of A
- Jack Saddler, UBC
- John McKay, Laval

OTHER

- Roger Foxall, Founding CEO of Genome BC
- Don Wright, former BC Forestry DM and former President BCIT, Vancouver
- Angus Livingstone, Director, UBC Industry Liaison Office

APPENDIX 4: THE CONSULTATION FRAMEWORK FOR A NATIONAL FOREST GENOMICS STRATEGY (2012–2013)

BACKGROUND

Over the last 10 years some \$90M has been invested in advancing forest genomics research across the country. The key themes around those investments relate to improving the health and productivity of current and future forests and creating more effective diagnostic tools to protect Canada's forests. The understanding of the science of forest genomics has advanced at an unprecedented pace and it's timely to focus more urgently on the value proposition of applications. In advance of a March 25th workshop in Ottawa, a consultation process is being undertaken to solicit views from a wide range of interested parties to help inform the workshop discussion and explore key drivers, issues and opportunities around accelerating applications to help guide future investments.

DISCUSSION POINTS

A changing climate is having (and will continue to have) substantial impacts on Canada's forests. It is unlikely that natural tree adaptation will occur fast enough to keep pace with these environmental changes. What are your thoughts around investing now in forest genomics to improve the odds of a more resilient and healthy future forest? Who should invest and who should apply these new genomics tools?

A consequence of a changing climate along with significantly increased global trade is the ever increasing incidence of invasive pests, a challenge that all trading nations are faced with. How significant is this issue and what priority should genomics applications have in addressing it?

As we have seen with the Mountain Pine Beetle epidemic, a changing climate has played a role in facilitating an unprecedented expansion of domestic

pest populations with catastrophic results. Forest genomics is playing a role in unravelling the pest/host/pathogen interaction to produce tools for better forecasts, more effective control and ultimately better protection for future forests. What are some of the applications possible with this new knowledge?

Canada is only just starting to harvest trees from a second generation forest and for centuries has enjoyed the value, diversity and available volume of the third largest forest endowment on the globe. A future commercial forest will be smaller, more regulated (by government and public expectations), less valuable (ie: fewer large trees in dense stands) and generally more costly to manage. What role can forest genomics play in moving from the "volume model" of the past to a "value model" of the future? Who should invest and what is the potential for applications?

OPTIONAL

In your view, what are the early wins in terms of applications of forest genomics?

The use of genomics in accelerating classic tree breeding and targeting preferred traits around resistance to pest and drought appears very promising; however, it is unclear the application can be scaled up to produce the millions of seedlings required annually. Any views on this?

What are some of your views on the economics around applications of forest genomics in fields such as diagnostics, accelerated tree breeding and pest control?

Do you have any views on (negative or positive) public perceptions around use of genomics in forest applications?

APPENDIX 5— PARTICIPANTS IN THE NATIONAL FORESTRY SECTOR GENOMICS STRATEGY WORKSHOP, HELD IN OTTAWA ON MARCH 25, 2013

LAST NAME	FIRST NAME	JOB TITLE	ORGANIZATION/COMPANY
Adams	Greg	Manager, R&D, Nurseries and Tree Improvement	J.D. Irving Limited
Aitken	Sally	Professor	University of British Columbia
Arif	Basil	Senior Research Scientist	Great Lakes Forestry Centre
Bailey	David	President & CEO	Genome Alberta
Barker	Christopher	Senior Project Manager	Genome Prairie
Baross	Agnes	Manager, Sector Development	Genome BC
Barsi	Debby	Manager—Forest Genomics Program	CFS-NRCan
Beaulieu	Jean	Research Scientist	Natural Resources Canada
Belanger	Kevin	Vice President, Wood Fiber Procurement	Domtar
Bell	Cindy	Executive VP, Corporate Development	Genome Canada
Bohlmann	Jörg	Professor	University of British Columbia
Bonfils	Anne-Christine	Research Program Manager	National Research Council
Bousquet	Jean	Professor	Université Laval
Bruemmer	George	Executive Director, Canadian Wood Fibre Centre	CFS-NRCan

LAST NAME	FIRST NAME	JOB TITLE	ORGANIZATION/COMPANY
Bull	Gary	Professor	University of British Columbia
Campagna	Michel	Manager	Ministry Natural Resources Quebec
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Chaffre	Sébastien	Program Manager	Génome Québec
Cooke	Janice	Associate Professor	University of Alberta
Coueslan	Sue	Director of External Relations	Genome Atlantic
Cusson	Michel	Research Scientist	Natural Resources Canada
Dambrowitz	Chris	Director, Bioindustrial Strategic Initiatives	Biorefining Conversions Network, University of Alberta
de la Roche	Ian	Director	Genome BC
Ensminger	Ingo	Professor	University of Toronto
Farrell	Jim	Advisor	Consultant
Flemming	Jon	VP, Industry Affairs	BIOTECanada
Fullarton	Michele	Tree Improvement Coordinator	Dept.Natural Resources
Gelinas	Nancy	Professor	Université Laval

LAST NAME	FIRST NAME	JOB TITLE	ORGANIZATION/COMPANY
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Hamelin	Richard	Research Scientist	Natural Resources Canada
Hardy	Yvan	Board Member	Genome Canada
Isabel	Nathalie	Research Scientist	Natural Resources Canada
Jobidon	Robert	Director	Ministère des ressources naturelles du Québec
Kalisz	Michael	Project Manager	Trent University
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King	Shelley	VP Research & Business Development	Genome Atlantic
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Leclerc	Jacinthe	Director General	Laurentian Forestry Centre of Canadian Forest Service
LePage	Marc	President and CEO	Genome Quebec
Lindsay	Kate		Forest Products Association of Canada
Livingstone	Angus	Managing Director	UILO, UBC
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Mansfield	Shawn	Professor	University of British Columbia
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Martin	Vincent	Associate Professor	Concordia University
Meulien	Pierre	President and CEO	Genome Canada
Morin	Karine	Director, National GE3LS Program	Genome Canada
Nelson	Harry	Assistant Professor	UBC
Nemeth	Helen	Assistant to the Executive Chair	Tolko Industries Ltd.
Orsborne	Victoria	Director, Policy & Industry Affairs	BIOTECCanada
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Rank	Dennis	Senior Partner	Dennis Rank and Associates
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LAST NAME	FIRST NAME	JOB TITLE	ORGANIZATION/COMPANY
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Swan	Kate	Associate Director, Genomics Programs	Genome Canada
Thomas	Barb	Geneticist & Poplar Farm Research Coordinator	Alberta-Pacific Forest Industries Inc.
Tsang	Adrian	Professor	Concordia University
Uzunovic	Adnan	Senior Research Scientist/mycologist	FPIInnovations
Vanier	Raymond	Forestry & Harvesting Superintendent	Domtar
Whetten	Ross	Associate Professor	North Carolina State University
Wilson	Richard	Forest Program Pathologist	Ontario Ministry of Natural Resources
Winter	Alan	President and CEO	Genome BC
Woods	Jack	Program Manager, Forest Genetics Council of BC/CEO SelectSeed Ltd.	Forest Genetics Council of BC and SelectSeed Ltd.

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