Advancing Canada's

ENERGY AND MINING SECTOR

through State-of-the-Art Genomics Applications

A Sector Strategy led by Genome Alberta and the Ontario Genomics Institute, with support from regional Genome Centres across Canada and funded by Genome Canada.

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

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

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

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

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

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

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

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

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

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

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1. EXECUTIVE SUMMARY

As tools for studying biological phenomena improve in capability and cost, a broad range of industries can avail themselves of scientific breakthroughs to advance their own sectors. Mining[1] and energy[2] activities have long employed research to assess and develop various operations, from exploring the microbial basis of well and mine sites, to extraction and processing strategies, and remedial environmental treatments. However, scientific progress since the sequencing of the human genome more than a decade ago now provides modern tools for deeper analysis of sector environments, extraction processes and environmental impacts.

Growing environmental and cost pressures associated with resource development and industry processes compel energy and mining companies to adopt competitive technologies for sustaining international advantages and socially acceptable operations. Opportunity exists for industries to revolutionize their practices and environmental impacts through the manifold enhancements available from application of new biological technologies. While industry sectors like human health, forestry, fisheries and agriculture forge ahead with genomics applications to help unveil and leverage the genetic bases of our environment, the energy and mining sector is still in its infancy. However, this provides tremendous opportunity for Canada to become an international leader in the field, by developing and implementing a unique sector strategy.

Through expert guidance and extensive consultation culminating in a March 2013 workshop and follow-up survey, the energy and mining sector strategy process provided stakeholders from industry, academia, government and the genomics community with a greater appreciation of commercial and environmental needs for targeting with applied 'omics' sciences (genomics, transcriptomics, proteomics, metabolomics, metagenomics, systems biology and bioinformatics).

The time is opportune to advance the energy and mining sector through integration of recent scientific breakthroughs with existing industry operations, and new biotechnological processes. For implementation to be effective, communication and coordination must precede research-industry collaborations, such that commercial challenges are fully understood and biological improvements applied at the correct stage of maturity to attain optimal solutions. The strategy is therefore built on two pillars:

- **Foster improved communication and knowledge exchange.** Representatives from industry, regulatory and academic communities all agreed that information sharing between research and industrial experts must be enhanced to strengthen collaboration and coordination opportunities. Development of a comprehensive communication plan would foster joint understanding of the needs, potential solutions and business case for collaboration. Integration of interdisciplinary teams in energy and mining management could further facilitate and sustain knowledge exchange. Coordinated efforts will help address the identified priorities of capacity building (in research and data analysis) and demonstration projects, having ultimate deliverables within a reasonable timeframe.

[1] For the purpose of this document "mining" refers to industries engaged in the extraction of metals and minerals and does not include coal and hydrocarbon-based energy resources such as bitumen.

[2] For the purpose of this document "energy" refers to industries that extract coal and hydrocarbon-based energy resources such as oil/gas/bitumen.

- **Focus ongoing development of genomics applications on critical broad-interest challenges and opportunities.** Industries across the sector have identified common areas of interest and value for applying omics strategies, including improvements to resource recovery and processing, and environmental remediation. Recommendations for near-term foci additionally included monitoring and biosensing. Mining operators in particular expressed a desire to optimize omics applications in the select areas of bioleaching and biooxidation, and energy industries highlighted the specific challenges of pipeline corrosion, well-souring, hydrocarbon spills and green-house gas emission for biological mitigation.

We look forward to gleaning further feedback from vested stakeholders as the strategy forms a backdrop for ongoing collaboration and cooperation around sector enhancements using genomics. As a sound basis for further dialogue between industry, research and government, it can be considered a comprehensive starting point to determine the best way for moving this innovative agenda forward. With effective consultation involving policymakers, industry operators, scientists and the communities in which sector activities operate, integration of biotechnological advances can offer Canada a leadership position and a competitive advantage for the important industries of mining and energy.

Gijs van Rooijen Ph.D., Genome Alberta and
Alison Symington Ph.D., Ontario Genomics Institute,
on behalf of the Steering Committee

2. ABOUT THE INITIATIVE

As global appetite for energy and commodities expands with the population, Canada's rich natural resource endowments continue to enjoy international prominence. Energy and mining industries also increasingly recognize the potential of recent scientific breakthroughs to improve extraction, processing and environmental management. In its recent strategic plan, Genome Canada added Energy and Mining as the next of the sectors to most benefit from genomics applications; it joins the existing sectors of Human Health, Forestry, Fisheries, Agriculture and Environment. To remain at the forefront of ever-competitive mining and energy exploration, Canada and its industries will have to adopt a leadership position in the development of strategies for innovative and sustainable utilization of these important resources.

Building on past successes, and seeing the potential for omics technologies to substantially enhance mining and energy operations, two of Canada's regional Genome Centres joined to champion this strategy for application of genomics breakthroughs to the sector. Genome Alberta and the Ontario Genomics Institute developed this Sector Strategy Paper under the direction of a Steering Committee comprised of the following individuals:

- Marc Amyot, Professor Environmental Science, University of Montreal
- Soheil Asgarpour, President and CEO, Petroleum Technology Alliance of Canada (PTAC)
- Susan Baldwin, Professor Chemical and Biological Engineering, University of British Columbia
- Alex Bolton, Board Member, Energy Resources Conservation Board
- Eric Cook, CEO, Research Productivity Council, Fredericton, NB
- Elizabeth Haack, Consultant, Worley Parsons Canada Services Ltd.
- Magdi Habib, Director General, CanMet Mining
- Rick Lawrence, Consultant and Professor, Lawrence Consulting/ Mining Department, University of British Columbia
- Douglas Morrison, President and CEO, Centre for Excellence in Mining Innovation
- Andrew Stephens, Genome Alberta Board Member and former Senior VP Suncor Energy
- Gerrit Voordouw, Professor and Industrial Research Chair in Petroleum Microbiology, University of Calgary
- Dan Wicklum, President and CEO, Canadian Oil Sands Innovation Alliance (COSIA)

A DRAFT Sector Strategy Paper was used to inform a broad in-person consultation in Toronto, Canada, on March 7–8, 2013. Representatives from industry, academia, government, policy-makers, regulators and Aboriginal peoples offered input to revise the paper into its current final form.

3. FOREWORD

We live in a world of complex biological phenomena; all physical things manifest from combined chemical and/or biological processes, working together to produce the environment around us. Mining and energy industries operate in such a context, extracting from the natural environment valuable commodities for different purposes: metals and minerals for industrial and commercial use, and hydrocarbons for energy and chemical manufacture. Common to both are the microbial processes acting at the source of extraction, or being put to work as part of recovery efforts. The microorganisms responsible for the biodegradation of light into heavy oil have been within fossil fuel deposits since time immemorial, however today the activity of microorganisms and their associations can be manipulated to prevent well souring or infrastructure corrosion, and can be used to enhance oil recovery. In mining, bioleaching engages select microorganisms to increase output from crushed ore, in some cases improving recovery up to 20-fold[3]. For both sector industries, progressing our understanding of the natural environment from which resources are extracted can help to sustain productivity, improve the rate of recovery and reduce the degree of environmental impact.

Advancing knowledge and taking improvements to the field requires a comprehensive understanding of the industry challenge or opportunity, development of an effective proof-of-principle solution, and scale-up to the point of industrial application. Working together, researchers can aid sector operations with knowledge gained through recent technological breakthroughs, and industry can provide a window through which to view potential applications (and so drive the relevance of research), as well as provide an avenue for direct translation of research outcomes into industrial processes.

Complementing commercial research and development (R&D) efforts, industrial research chairs have been established to focus academic activities in the sector. Industry is aware of potential areas for improvement, and academic researchers have already made advances in biomonitoring and bioremediation. Our growing understanding of environmental processes and their true complexity is helping to inform the most effective omics applications for the energy and mining sector. Following on from recent advances in technological capability and capacity, such as enabled sequencing of the human genome, the field of genomics now has more to contribute than ever. Responsible for decoding many of the processes of life, genomics has developed into a full suite of omics technologies. Biological activity at mine sites and in oil wells, amidst industrial infrastructure and treatment facilities, and at work in remediation efforts can now be identified using these sophisticated tools. Characterization of unique biological processes will continue to progress, aided by partnerships between industry R&D and academic research to ensure future directions remain relevant to applications in the field. Although R&D investments may seem a notional or optional component of the commercial portfolio, their potential to improve key performance indicators has never been better. Collaboration amongst research leaders and industry operators can address limitations to commercial productivity, help control costs, improve environmental performance and assist with greater public credibility.

In an era where climate change awareness has resulted in a heightened focus on efficient recovery and lower environmental footprint, the public is demanding greater corporate social responsibility. Provincial and federal regulatory agencies should be appraised of the benefits to come from scientific developments, since better environmental metrics (with greater resolution) can help improve regulatory guidelines and offer companies the possibility of complying more reliably. Researchers from industry and academia now have much to offer sector operations and environmental outcomes.

[3] McPhee, J. 2011. The little workers of the mining industry. The Science Creative Quarterly 6.

4. SECTOR STRATEGY IN BRIEF

VISION

Substantial improvement in the economic, environmental and societal performance of energy and mining sector operations in Canada and abroad is possible from application of genomics innovations.

GUIDING PRINCIPLES

Leverage. Capitalize on the enterprise of existing industry organizations, and efforts in comparable sectors, to most effectively translate knowledge in all areas of practice and policy.

- **Align.** The strategy will align with identified industry priorities and only support targeted research initiatives that have industry support and participation.
- **Balance.** A measured approach will be taken to short-, medium- and long-term collaborative initiatives, balancing the need for outcomes from foundational research, pilot tests and field studies.
- **Engage.** Initiatives will focus on holistic stakeholder engagement, facilitating collaboration and coordination between the activities of Canadian and international groups, and interfacing with the communities in which industry and research operate.
- **Answer.** Genomics applications will target priority industry challenges and opportunities, and engage relevant community stakeholders to ensure the strategy answers to the call of responsible stewardship.
- **Integrate.** Comprehensive solutions will be derived through an interdisciplinary approach that fosters integration across scientific disciplines, societal paradigms and industry organizations.

STRATEGIC OUTCOMES

The strategy provides a vision and proposed direction for pursuing collaboration in areas of priority technology development. It is intended to:

- Strategically guide genomics research and innovation investments;
- Identify and leverage existing sector strengths, ensuring future activities and investments are complementary; and
- Foster integration of genomics discoveries into existing and future energy and mining operations and regulations to generate environmental, industrial performance and broader societal benefits.

MOVING FORWARD

The sector strategy will advance targeted initiatives in the following areas:

- **Nurture business environments for accelerating genomics improvements to energy and mining operations.**
  - » *Provide leadership.* Foster a broad alliance of thought-leading organizations in the energy, mining and genomics communities to champion and propel the vision.
  - » *Build talent.* Promote greater understanding between researchers and industry, and support development of interdisciplinary teams.
- **Increase collaboration and alignment between research and industry.**
  Demonstrate the impact of genomics on priority challenges and opportunities. Develop mechanisms for identifying, supporting and disseminating outcomes of demonstration projects, such as enhanced recovery, less resource-intensive extraction, accelerated remediation and improved regulatory compliance.
- **Develop Canada's genomics infrastructure and intellectual capital.**
  Create new value through advanced genomics applications. Grow Canada's fundamental genomics knowledge and enhance application to industry for more effective bio-based solutions.

5. INTRODUCTION

With the world's burgeoning population and rapid urbanization, global demand for energy and natural resources is anticipated to grow by 50% in the next 25 years[4]. Many established and emerging nations are expected to collectively contribute 800M 'middle class' citizens to the world economy[5], requiring significant expansion in energy and commodity production. Canada's stable economic and political climate, generous natural resource deposits, and well-developed industrial processing and scientific research capabilities position it perfectly for technology development and market competitiveness. However, new biotechnologies are already required to address fundamental challenges commonly facing energy and mining industries today. Dwindling reserves of easily accessible resources require new technology to extend the life of aging assets, explore new deposits and increase recovery cost-effectively, and expanded production subject to increasingly rigorous regulations requires innovative technological solutions to address lingering environmental impacts. Genomics enhancement of energy and mining operations presents an opportunity for Canada to boost domestic outputs, and advance international leadership in a field already worth $1.25 trillion[6].

The sector has historically utilized microbial consortia to accelerate leaching and remediate contaminated water in metal mining, and control souring during oil production. Additionally, plants, fungi, algae and other biological species could play a more prominent role in remediating energy and mining sites. The latest genomics breakthroughs enable industry processes to benefit from a deeper knowledge of the indigenous microbial communities involved, and better understand their interaction with the environment. We can now detail the microbial constituents and identify the biochemical pathways of relevant processes, creating the possibility to isolate organisms or their activities for more advanced industrial application and environmental monitoring. The 'omics' sciences responsible for elucidating the molecular detail of natural processes and living things have progressed markedly since the human genome was sequenced in 2001: genomics now enables analysis of the complete DNA of an organism; transcriptomics reviews the pathways to building blocks encoded by the DNA; proteomics studies the resulting building blocks and assembled proteins at the cellular level; metabolomics reviews the full suite of metabolic products from an organism; metagenomics identifies all the genetic material present in an environmental sample; systems biology combines all these technologies to understand the relationship and function of biological components in a system; and, bioinformatics applies informatics to study and verify biological research[7]. Industry could be greatly assisted by application of these technologies to issues such as resource-intensive extraction, large-scale waste management, acid mine drainage, pipeline corrosion, souring of oil production operations, and oil spill management. Omics technologies in the form of biosensors can also assist regulatory agencies with assessment and monitoring. Industry R&D has already partnered with academic researchers using provincial, federal and industry funds to improve resource recovery, waste treatment and site remediation, but more

[4] International Energy Agency. World energy outlook 2007. OECD.

[5] O'Neill, J., Lawson, S. and Purushothaman, R. 2004. The BRICs and global markets: crude, cars and capital. Goldman Sachs CEO Confidential, 2004–09.

[6] Gross domestic product (GDP) at basic prices, by North American Industry Classification System (NAICS). 2012. Statistics Canada. http://www5.statcan.gc.ca/cansim/n26. Accessed September 26, 2012.

[7] The omics sciences (genomics, transcriptomics, proteomics, metabolomics, metagenomics, systems biology and bioinformatics) are further defined in a subsequent footnote on Page 12.

could be done to incorporate the latest genomics advances into sector operations for meeting future demand.

Canada's solid base of omics expertise, infrastructure and track record pave the way to building greater knowledge and technological resources for future applications. Groups across the country have already established foundational informatics databases, designed biological tools for monitoring and remediation, and empowered industry implementation. However, advances and applications beyond previous successes will need to come from coordinated collaboration between industry, academia, government and other relevant stakeholders. This Sector Strategy Paper builds on significant national strengths and investments over the last decade, including the continued strategic and genomics infrastructure support of Genome Canada and others, and was informed by a broad consultation process. To ensure Canada retains its competitive advantage we must determine how to foster collaborative research through public private partnerships, and efficiently translate our improved understanding of microbial and ecological processes into applications that solve industry and environmental challenges. This will position Canada at the forefront of expanding energy and commodities needs, job opportunities and future wellbeing.

6. IMPORTANCE OF THE ENERGY AND MINING SECTOR TO THE CANADIAN ECONOMY

Canada is a world leader in the production of energy, metals and minerals. It possesses the third largest oil and gas reserves and is the third largest energy producer[8]. A wealth of metal and mineral deposits also makes it a top five producer of essential commodities for industry[9]. Already the energy and mining sector generates $126B in exports and contributes 11% of GDP[6]. It employs 1.4M Canadians[10] and is the largest private employer of Aboriginal peoples[11]. In the next 10–20 years, the accelerated industrialization of nations such as Brazil, Russia, India and China (the 'BRIC' countries) will add the needs of 800M 'middle class' citizens to current world demand for energy and resources. This growth will double the appetite for fossil fuels and expand the market for metals and minerals,[5] making this important Canadian sector indispensable to the projected needs of global development.

Fossil fuels currently provide 80% of the world's energy supply[12], and are the source for 90% of industrial chemicals produced[13]. Although Canada is the sixth largest oil producer and currently supplies 25% of US need, conventional reserves topped out in 2003. However, if the contained crude oil were all technically recoverable from the world's largest hydrocarbon deposit in the Athabasca oil sands, Canada would place ahead of the Middle East in terms of future global petroleum supplies[14]. While the world's oil needs grow almost 40% over the next 25 years (to 116M barrels per day[15]), the Canadian government will reap approximately $500B in provincial royalties as it generates nearly 5% of global demand[17]. Technological breakthroughs in unconventional shale gas extraction have increased Canada's energy capacity beyond the previous 70 year natural gas supply[16], but further innovation is needed to develop these resources sustainably. Currently, the oil industry employs 75,000, the gas industry employs 172,000 and a further 800,000 employees work in the oil and gas services industry. Together, these sectors engage more than 5% of the Canadian workforce[9, 17, 18]. Pursuit of further advances will ensure employment opportunities continue to grow with the development of competitive sustainable extraction and recovery processes.

Coal constitutes two-thirds of Canada's fossil fuel deposits[12]. In addition to coal, Canadian mineral production operations in 2011 produced $45B from

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[8] Canada. 2012. U.S. Energy Information Administration. http://www.eia.gov/countries/cab.cfm?fips_CA. Accessed September 29, 2012.

[9] Mining in Canada: Opportunities through Mergers & Acquisitions. Deloitte & Touche LLP. Accessed October 4, 2012.

[10] Oil and gas services sector profile. Industry Canada. http://www.ic.gc.ca/eic/site/ogt-ipg.nsf/eng/og00199.html. Accessed September 16, 2012.

[11] Meyes, R. 2012. The Importance of Research and Development Investing for Canada's Mining Industry. Mining Association of Canada.

[12] Clean coal – clean coal roadmap. 2008. Natural Resources Canada. http://canmetenergy.nrcan.gc.ca/clean-fossils-fuels/clean-coal/810. Accessed September 16, 2012.

[13] DeBruyn, R. et al. Residual oil deposits as a substrate for methane geobioreactors. Luca Technologies LLC. Presentation, accessed September 27, 2012.

[14] Reynolds, N. 2012. Even Canadian's don't comprehend what they're sitting on. The Globe and Mail, September 6, 2012.

[15] Future fuels and emissions. 2009. Natural Resources Canada. http://canmetenergy.nrcan.gc.ca/oil-sands/1634. Accessed September 16, 2012.

[16] Stringham, G. 2011. Canada's oil & natural gas. Presentation, Canadian Association of Petroleum Producers.

commodities such as potash, uranium, nickel, cobalt, titanium, aluminum and platinum. Ranking first in global exploration spending, more than 800 operations account for almost 20% of Canadian exports (eight times more than forestry, and twice the contribution of agriculture). A quarter of the 360,000 Canadians employed in mining possess a university degree, and have developed considerable expertise through industry's substantial investment in R&D.[9, 19]

Continued advances will be required to address acute environmental pressures arising from increased production[5]. Already, Canadian scientists and industry are working to improve management of waste tailings from 170km^2 of ponds in the Athabasca oil sands[20], and are devising ways to mitigate toxic releases from mining operations. Heightened energy demand is likely to result in a corresponding 60% increase in CO_2 emissions[15], for which Canada's leading-edge work on climate change emissions management could also offer the world much-needed policy solutions; Alberta companies exceeding maximum allowable emissions can attain regulatory compliance through contribution to a fund that supports technological innovation and deployment. As well as providing a scalable incentive for corporate reduction of emissions, funded project proponents must demonstrate utility for reducing greenhouse gases.[21] Due to the inherent involvement of microbial constituents in energy and mining processes, both industry and researchers recognize the promise of omics sciences to help solve the global challenges resulting from sector operations. As easily accessible hydrocarbon, metal and mineral deposits decline and new ways are needed to secure ongoing supplies, it will be necessary for Canada to expand technology development in the sector in order to better understand the complex operating environments and maintain essential energy and commodity outputs with minimum impact.

New provincial and federal policies have also created opportunity for increased hydrocarbon and commodity exploration, especially as access opens in Canada's sovereign north. Canada owns the second-largest Arctic shoreline, and new information and tools are needed to compete there in the emerging international race for natural resources[22]. Despite humble beginnings, where myths of plentiful hydrocarbon deposits were dispelled by harsh geological realities, fresh inspiration for Arctic deposits has arisen in response to more accessible exploration and new technologies that might bridge previously insurmountable hurdles[23]. In anticipation of this potential, the Canadian government in 2012 auctioned 905,000 hectares of northern

[17] The facts on oil sands. Canadian Association of Petroleum Producers. http://www.capp.ca/UpstreamDialogue/OilSands/Pages/default.aspx. Accessed October 4, 2012.

[18] The facts on natural gas. Canadian Association of Petroleum Producers. http://www.capp.ca/UpstreamDialogue/NaturalGas/Pages/default.aspx. Accessed October 4, 2012.

[19] Canadian trade by industry (NAICS codes). 2011. Trade Data Online/Industry Canada. Accessed September 16, 2012.

[20] Campbell, D. 2012. How tiny bacteria could cleanse oil sands tailings: researchers look to biofilms for help with reclamation. Alberta Oil – the business of energy. http://www.albertaoilmagazine.com/2012/03/detox/. Accessed September 17, 2012.

[21] Climate Change and Emissions Management (CCEMC) Corporation. The CCEMC grand challenge: innovative carbon uses. http://ccemc.ca/. Accessed May 30, 2013.

[22] Lytvynenko, A. 2011. Arctic sovereignty policy review. Ad Hoc Committee of Deputy Ministers on the Arctic.

[23] Jaremko, G. 2008. Arctic fantasies need reality check. Edmonton Journal, April 4, 2008.

offshore exploration rights, a 30% expansion to the area already under lease (historic bids have yielded up to $1.2B for drilling rights there)[24]. However, these prospects are tempered by a regulatory requirement for comprehensive disaster management protocols, which remain elusive in the severe climate of the Arctic. Recent scientific advances offer key opportunities to explore the full potential of Canada's energy and mining sector through the implementation of technology optimized to these extremes. Application of such advances can improve extraction from existing and future deposits in the High North, providing Canadians with a mechanism for secure employment and revenue generation in the face of exponential global demand for accessible commodities.

[24] Vanderklippe, N. Reviving Arctic oil rush, Ottawa to auction rights in massive area. The Globe and Mail, May 16, 2012.

7. TECHNICAL CHALLENGES AND OPPORTUNITIES FOR GENOMICS APPLICATIONS TO ADDRESS

Increasingly stringent regulatory and societal standards for energy and mining operations have accelerated the need for more sustainable alternatives to traditional approaches. Canadian provinces are responding to public concern over resource-intensive processes by issuing stricter industry regulations, such as Alberta's recent *Directive 74* that requires an aggressive change in the management of oil sands tailings to accelerate the closure of existing and future tailings ponds[25]. In turn, industry is being technologically enabled through endowed federal and industrial research chairs, federal research agencies like CanmetENERGY, and collaborative industry consortia like the Mining Association of Canada and Canada's Oil Sands Innovation Alliance. However, no agency alone has the capacity to fully develop the biotechnologies required by the sector. In addition to the informatics, biomonitoring and industry-enabling innovations emerging from Canada, previous international advances in Switzerland (bioleaching), South Africa (bioaccumulation),[26] India[27], Netherlands[28] and Japan[29] (bioremediation) have been expanded more recently to include important developments in Finland (first commercial bioleaching in Europe), China (biohydrometallurgy research) and Chile (industrial-scale rapid thermophilic processing)[30]. Tremendous value could come from coordinating the efforts of global leaders in academia and industry. Further international collaboration could facilitate more sustainable energy and commodity supplies overall. Already in Europe, 27 partners from 11 countries (representing 70% of European metal production) have formed a consortium to explore industry enhancements for overcoming heavy dependence on imports[31].

Collaborations between industry and research in public private partnerships have resulted in a range of integrated tools, including software for geochemical modeling, calculators for environmental risk assessment, designs for bioreactors, and identification of effective phytoremediation agents. Of course, implementation of any tool depends on ultimate cost-effectiveness, as determined by market demand, installation expense, ease of operation and feasibility within the actual ecological setting, as well as any regulatory or societal constraints[29, 32]. Industry has historically employed microbial processes to enhance many energy and mining activities. However, their effectiveness varied widely, since technologies were often developed without a comprehensive understanding of the microbial participants or their interaction with industrial processes and the environment.

The full genetic potential of microbial constituents can now be analyzed through recent advances in the omics sciences (genomics, transcriptomics, proteomics, metabolomics, metagenomics, systems biology and

[25] Louie, J. 2009. New directive on tailings ponds sets the bar high for oilsands mining companies. AirWaterLand.

[26] Rawlings, D.E. 2002. Heavy metal mining using microbes. Annual Review in Microbiology 56:65-91.

[27] Mathiyazhagan, N. and Natarajan, D. 2011. Bioremediation on effluents from magnetite and bauxite mines using Thiobacillus spp and Pseudomonas spp. Bioremediation & Biodegradation, 2(1):1000115.

[28] Kuyucak, N. 1997. Minerals bioprocessing, biorecovery and bioremediation in mining. Mineral Processing and Extractive Metallurgy Review, 19(1):1-4.

[29] Heavy metals and acid rock drainage: a select literature review of remediation and recommendations for applied research. 2004. EBA Engineering Consultants Ltd.

[30] Biohydrometallurgy 2012 Conference Diary http://min-eng.blogspot.co.uk/2012/06/biohydromet-12-conference-diary.html. Accessed December 16, 2012.

[31] The ProMine Project. http://promine.gtk.fi/index.php/about. Accessed December 16, 2012.

[32] Dosh, S.M. 2006. Bioremediation of acid mine drainage using sulfate-reducing bacteria. US Environmental Protection Agency.

bioinformatics)[33]. The complexities of natural processes can be better understood, and more effective biotechnologies developed to make operations increasingly efficient, effective and environmentally benign. A deeper understanding of the microbes responsible for processes such as the iron and sulfur cycles that affect mining operations[26], or the methanogenic transformation of hydrocarbons[34], can aid development of bioleaching, bioaccumulation and beneficiation for better extraction of metals and minerals, and can help enhance hydrocarbon recovery, prevent biocorrosion of infrastructure, or abate environmental impacts through biomonitoring and bioremediation. For modest investment, integration of biological applications can often return percentage-wise improvements worth exploring, such as 5–10% enhanced oil recovery[35, 36], 20-fold increased yield for gold biooxidation[3], 50% reduced greenhouse gas emissions from tailings ponds[37], or a 10% correction toward a more desirable pH for contaminated soils[38].

The following lists of sector challenges detail opportunities for Canadians to spearhead genomics solutions to common issues of low recovery, high water and energy consumption, and potential adverse environmental effects, among others. Mindful of revisiting promises that could not be fulfilled by previous technologies, Canada must leverage the latest omics advances and successful preliminary applications through integration with existing technologies, and under the oversight of interdisciplinary collaborators, for the substantial benefits of competitive natural resource extraction and environmental stewardship to be realized.

COMMON SECTOR CHALLENGES

- **Enhancing recovery.** Although not all microbial manipulations currently offer proportional improvements, successful application can dramatically enhance sector recovery: for example, triple the recovery for enhanced oil extraction[35, 36], and up to 20-fold more for gold[3]. Despite extensive review of physicochemical enhancers to both mining and energy extraction, application of biotechnological aids has so far been limited to narrow commercial successes (e.g. copper bioleaching, and modest oil recovery efforts).

  Through a better understanding of the microbial activities operating in natural resource environments, omics sciences can improve the effectiveness of biotechnological solutions to raise recovery rates well above current low and diminishing levels;

[33] Definitions: genomics (the study of the complete genome of an organism, i.e. all hereditary information encoded in the DNA); transcriptomics (the study of the transcriptome, the complete set of RNA transcripts produced by the genome at any one time); proteomics (the study of the full or partial set of proteins encoded by a genome); metabolomics (the study of the metabolic products and networks of an organism) ; metagenomics (the identification of all the genetic material present in a sample from a complex environment, e.g. soil, water, gastrointestinal tract, consisting of the genomes of many individual organisms); systems biology (a combination of the above-mentioned technologies to understand the relationship between and function of all components of a biological system); bioinformatics (the science of informatics as applied to biological research).

[34] Voordouw, G. 2011. Production-related petroleum microbiology: progress and prospects. Current Opinion in Biotechnology, 22(3): 401-405.

[35] Rassenfoss, S. 2011. From bacteria to barrels: microbiology having an impact on oil fields. Journal of Petroleum Technology.

[36] Morrison, J. 2012. Dirty work. American Way. http://www.americanwaymag.com/oil-degrading-microbes-terry-hazen. Accessed September 17, 2012.

[37] Ramos-Padrón, E. et al. 2011. Carbon and sulfur cycling by microbial communities in a gypsum-treated oil sands tailings pond. Environmental Science and Technology, 45(2): 439-446.

[38] Lefrançois, E. et al. 2010. Field performance of alder-Frankia symbionts for the reclamation of oil sands sites. Applied Soil Ecology 46(2): 183-191.

scale-up of pilot tests to industrial capacity can address any concerns about consistent or notable improvements. As suppliers resort to extraction from lower-grade accessible ore and waning hydrocarbon reserves, percentage improvements to mature operations can help supply significant market demand[39]. A senior mining biotechnologist with Australia's Commonwealth Scientific and Industrial Research Organization concurs: "Biotechnology has the potential to transform an uneconomic resource into a reserve."[40]

- **Addressing resource-intensive extraction (high water and energy consumption).** Large amounts of water and energy are used for a range of extraction and processing activities in the energy and mining sector, including retrieval of light and heavy crude, and concentrating of metals and minerals. The ratio of hot water used to extract oil sands bitumen averages 3:1[17], straining water and energy resources and generating considerable waste for storage in tailings ponds (even after system recycling). Recovery of metals can similarly consume large volumes of water through irrigation-style bioleaching of heaped ore, or stirred-tank biooxidation of millions of litres of crushed ore, both well-established processes in North America, South America, South Africa, Australia and China.

  The management of water use, recycling and treatment in those industries could be improved through a deeper appreciation of the microbiological processes involved in hydrocarbon extraction and waste consolidation. Increased omics knowledge could additionally help mining industries improve the rate of metal leaching and extent of extraction, or help develop bacteria with optima better suited to leaching environments (withstanding agitation of stirred-tank treatments, higher processing temperatures, acidity, metal toxicity, etc.)[3, 27].

- **Accelerating remediation.** Bioremediation employs biological agents to treat contaminants, such as naphthenic acid from tailings ponds or heavy metals from effluents, to a suitable level for reuse, discharge or disposal. Phytoremediation utilizes the most effective associations of plants with bacteria or fungi to decontaminate polluted sites. Such treatments can benefit the federal government in particular, who oversees more than 20,000 contaminated sites retired from historical mining activities[41]. University of Calgary researchers have already designed a bioreactor for treatment of naphthenic acid, using a cultured biofilm that degrades the contaminant[42]. The CNRC Biotechnology Research Institute is partnering with Suncor to test the efficacy of alder symbionts in soil remediation[43]. Syncrude is working with McMaster University researchers on a reclamation pilot, assessing the sulphur biogeochemistry of composite tailings[44]. A full-scale bioremediation plant operates in the Netherlands to remove heavy metals from mining effluents[45], and both Canada[46] and the US[47] have for decades

[39] Zitha, P. et al. 2011. Increasing hydrocarbon recovery factors. White paper, Society of Petroleum Engineers.

[40] Earls, E. 2012. Mineral-munching microbes: the future of metal mining? Mining-technology.com

[41] Federal contaminated sites – inventory of sites. Government of Canada. http://www.federalcontaminatedsites.gc.ca/sites/inventory-inventaire-eng.aspx. Accessed October 19, 2012.

[42] Turner, R. 2012. Direct biofilm culturing for Alberta oil sands tailings pond water remediation. Presentation, accessed September 17, 2012.

[43] Greer, C. et al. Revegetation of reclaimed oil sands sites using alder-Frankia symbionts: Progress after two growing seasons. National Research Council Canada. Presentation, accessed October 4, 2012.

[44] Warren, L., Stephenson, K. and Penner, T. Sulfur biogeochemistry of oil sands composite tailings. Presentation, accessed October 4, 2012.

successfully utilized microbial degradation to remove cyanide from metal mining effluent. Further study of indigenous organisms at polluted sites will provide important knowledge on microbial diversity in extreme conditions, identify new isolates with contaminant resistance, and make genetic information available to determine the best remedial symbionts. Researchers in Alberta[48] and companies in British Columbia (BioteQ[49]) and Ontario (BacTech[50]) are already undertaking to control contamination processes, and successfully consult internationally.

- **Improving assessment, monitoring and compliance.** At each stage of development, energy and mining operations must satisfy evolving provincial and federal regulations, as well as societal critique. Baseline conditions are used to predict and later measure environmental impacts, remediation strategies and regulatory compliance. Since governments began introducing legislation in the 1970s, the sector has worked to identify and resolve environmental impacts in field operations[29]. However, industries often face generic monitoring, remediation or compliance guidelines that may not accurately reflect the inherently complex environments in which they operate. Historically, limited analytical tools for assessing toxicology and potential risk have restricted development of more useful regulations. Development of guidelines that better reflect the environmental diversity of mining and energy sites would require efficient and cost-effective testing of a wider number of endpoints, toxicity data for a broader range of compounds, and a greater understanding of modes of action and species most at risk[51]. Sector industries and management agencies alike would benefit from improved assessment tools to inform a more practicable and effective regulatory framework, and guide risk management decision-making to better address the specific environment in which operations occur.

The omics sciences show great promise for helping to establish baseline data, monitor environmental fluctuations, and assess cumulative impacts through review of microbial, plant and animal samples. Canada has made significant headway in biomonitoring; previous research developed protocols based on next generation sequencing tools for thorough genomic analysis of environmental samples to assess ecosystem health. The US Environmental Protection Agency (USEPA) espouses the benefits of applying genomics tools in risk assessment and compliance monitoring[52, 53]. Improved scoping capabilities would allow better determination of site-specific parameters and prediction of environmental stressors[54]. Existing

[45] Kuyucak, N. 1997. Minerals bioprocessing, biorecovery and bioremediation in mining. Mineral Processing and Extractive Metallurgy Review, 19(1):1-4.

[46] Baldwin, S. 2012. University of British Columbia. Pers. comm. October 1, 2012.

[47] Lawrence, R.W. et al. 1998. The potential of biotechnology in the mining industry. Mineral Processing & Extractions Metallurgy Review, 19:5-23.

[48] Gieg, L. et al. 2011. Microbial activities and communities in oil sands tailings ponds. Presentation, ISMOS-3.

[49] http://bioteq.ca. Accessed December 16, 2012.

[50] http://www.bactechgreen.com. Accessed December 16, 2012.

[51] North, M. and Vulpe, C.D. 2010. Functional toxicogenomics: mechanism-centered toxicology. Int. J. Mol. Sci. 11, 4796-4813.

[52] Potential implications of genomics for regulatory and risk assessment applications at EPA. 2004. USEPA.

[53] Framework for cumulative risk assessment. 2003. USEPA.

[54] Purohit, H.J. et al. 2003. Genomics tools in environmental impact assessment. Environmental Science & Technology, 37(19):356A-363A.

generic guidelines based on parameters from limited case studies[55] could be refined for better industry compliance by site-specific operations.

Updates to federal and provincial regulations have recently focused industry activity on cross-sector collaboration to establish sustainable solutions for meeting the stringent criteria. In support of *Directive 74* from Alberta's Energy Resources Conservation Board, Shell has commissioned a $100M tailings pilot plant, and Syncrude is pioneering expensive technology that it plans to share with the industry for centrifugally thickening tailings[56]. Biosurfactants have also been identified for enhancing tailings treatments. In addition, a University of Calgary team recently received an International Genetically Engineered Machine (iGEM) award from the Oil Sands Leadership Initiative (OSLI) for their naphthenic acid biosensor; bacteria can be a powerful indicator of ecosystem health[57], and incorporation of an electrochemical potential to quantify the response of an organism represents a new level of forensics for assessing environmental change[58]. These tools are poised to fundamentally affect current approaches to biomonitoring, toxicology, risk assessment and, in turn, federal and provincial regulatory frameworks. In time, omics sciences can help re-evaluate regulations and monitoring, for more comprehensive assessment and management of complex environmental impacts. Industries and management agencies will want to incorporate these latest advances into their toolkits.

- **Overcoming aging assets.** Many energy and mining operations draw on easily accessible deposits now in decline. Across the sector, recovery rates vary greatly from 90% down to 10%. Mine site operations lose valuable product to waste fractions during processing, and energy producers typically cannot return more than 50% from original-oil-in-place[13] (and markedly less from non-conventional hydrocarbon resources). Diminishing recovery threatens premature closure of extraction operations across many facilities in the Western Canadian Sedimentary Basin[59] and Canadian Shield[60].

  Since industry infrastructure is already in place, genomics-enhanced biotechnologies that improve recovery or extend the life of existing deposits could provide significant returns through enhanced production processes or control of costly microbial problems such as corrosion or souring. Traditional chemical technologies could either be complemented or replaced by more effective bioflocculants, biosurfactants and biosorbents.

MINING-SPECIFIC CHALLENGES

- **Mitigating acid rock drainage (ARD; or acid mine drainage, AMD).** The dissolution of sulphide-bearing waste rock and tailings may form a deleterious acidic run-off containing dissolved heavy metals. A particular problem for historically active metal mines, ARD in the US affects 10,000 miles of rivers and streams[61]. Remediation typically involves either treatment with a basic compound or, more recently,

[55] A protocol for the derivation of environmental and human health soil quality guidelines. 2006. Canadian Council of Ministers of the Environment.

[56] Harrison, L. 2009. Oilsands tailings ponds creators respond to new rules. New Technology Magazine.

[57] Taubes, C. 2011. Charles Greer talks about the practicality of bioremediation. http://archive.sciencewatch.com/ana/st/oil-spills/11janSToilspGree/. Science Watch, accessed September 22, 2012.

[58] Naphthenic acids in the oil sands. IGEM, Team Calgary. http://2011.igem.org/Team:Calgary/Project. Accessed September 29, 2012.

[59] Fossil fuel infrastructure. 2012. Energy BC. http://www.energybc.ca/map/fossilfuelinfrastructure.html. Accessed October 21, 2012.

[60] Miller, E.W. 1959. Mineral regionalism of the Canadian Shield. The Canadian Geographer, 4: 17-30.

[61] Forum: microbes mediate mining metals. 1998. Environmental Health Perspectives, 106(11):A531.

manipulating the activity of microbial populations through the addition of chemical agents or nutrients.

Biochemical manipulation of ARD can substantially reduce the need for expensive neutralizer treatments; in this way, Japan saved 70% on the remediation of a copper smelter. Ontario developers first established pilot tests for an ARUM (Acid Reduction Using Microbiology) Process that effectively reduced metal contaminants in polishing ponds, but even that technology has been superseded.[47] Combinations of neutralizing chemicals and laboratory cultured microbes have now been patented for application in the US and Canada. Studies at the University of Wisconsin further reveal that two naturally occurring bacteria catalyze ARD to varying degrees, creating new opportunity for development of predictive tools based on natural levels of microbial consortia at a site. Researchers at the University of California, Berkeley continue to explore the key organisms of ARD, but a deeper understanding of the effect of chemical inhibitors on the microbial constituents is required to determine any tool's true predictive capabilities for managing mine site conditions.

- **Advancing bioleaching/biooxidation.** Particularly effective bacteria, such as *A. ferrooxidans*[27], are used to leach valuable metals into solution for electroplate recovery (bioleaching), or concentrate valuable solids through the leaching of low value impurities (biooxidation). These biohydrometallurgy processes become increasingly important for extracting metals and minerals from low-grade ore as high-grade reserves are depleted.

  Bioleaching currently produces almost a quarter of the world's copper, and biooxidation enables 20-fold concentration of gold prior to extraction[3]. In the interest of advancing this field, thermophilic bacteria with optimal performance at 65–85°C have been isolated and enriched for commercial applications. Substantial leaching by other extremophilic bacteria at temperatures around 4°C has also been observed, relevant to emerging opportunities in the reserves of Canada's Arctic. In addition to bacteria, the microbial diversity of bioleaching sites includes fungi and algae, and warrants closer metagenomic analysis to determine optimal community structure for best industry performance, especially since the mechanisms of the renowned microbial components are not well understood, and global warming introduces evolving variables that are yet to be baselined.[62, 63] The annual international Biohydromet conference organizer in 2012 remarked that "rapid advances in our understanding of the science of microorganisms has in effect awoken biohydrometallurgy from its long slumber, and it now looks as though it might start to realize its true potential and provide real benefits".[30]

ENERGY-SPECIFIC CHALLENGES

- **Ameliorating pipeline corrosion.** It is now well established that sulfate-reducing bacteria contribute to the corrosion of water transport pipelines[64] and that injection of nitrate into pipeline water can cause nitrate-reducing bacteria to outcompete more damaging sulfate-reducing bacteria, lowering the incidence of corrosion. Recent metagenomic studies have revealed that other organisms, such as methanogenic archaea, can also contribute to corrosion. Further genomics research to identify the key microbial components and environmental factors involved in corrosion will allow operators to predict and manage the problem more effectively.

[62] Brandl, H. 2001. Microbial Leaching of Metals. Biology Set (2nd Ed): Chapter 8. Wiley. DOI: 10.1002/9783527620999.ch8k.

[63] Chandrapralla, M. and Natarajan, K.A. 2010. Microbially induced mineral beneficiation. Mineral Processing & Extractions Metallurgy Review, 31:1-39.

[64] Park, HS. 2011. Effect of sodium bisulfite injection on the microbial community composition in a brackish-water-transporting pipeline. Applied Environmental Microbiology, 77(19):6908-6917.

- **Treating well souring.** Although sour gas production (H_2S) poses a challenge for all extraction and processing facilities, it is particularly problematic where water injection is used to extend the production life of reservoirs. As with sulfate-reducing bacteria causing pipeline corrosion, operators attempt to control souring through competition from nitrate-reducing bacteria induced with added nutrients, or by non-specific biological suppression with biocides. A better understanding of the complex microbial communities present in the well being treated will allow operators to determine optimal dosage and timing for treatment, decreasing the cost and improving the effectiveness of souring control.
- **Mitigation of greenhouse gases.** Microbial activity is responsible for vast quantities of methane emitted from residual hydrocarbon in tailings ponds and storage tanks. Twenty times more potent than CO_2 as a greenhouse gas, emission is due to the activity of methanogenic archaea[34]. Despite its significance, one of the principal biological mechanisms controlling emissions (methane oxidation) is not yet well characterized[65]. However, a consortium of scientists from Canada, the US and China have sequenced one of the world's hardiest methanotrophs from a New Zealand geothermal field (temperature optima 90°C)[66], and have since studied methanotrophs from permanently cold ocean sediments (temperatures to -1°C)[67]. Anaerobic methanotrophs that utilize nitrate or sulfate for methane oxidation have also been isolated. It has been estimated that methanotrophs active in the surface layers of oil sands tailings ponds remove up to 50% of the methane emitted by the ponds' microbial constituents, but more needs to be known about the factors limiting their activity.
- **Addressing oil/hydrocarbon spills.** Indigenous hydrocarbon-degrading microorganisms commonly clean up natural hydrocarbon releases with remarkable efficiency. However, remediation rates vary considerably for leaks in soil, the ocean, or the Arctic. Remediation of contaminated soils can often be accelerated through addition of a fertilizer to stimulate the activity of natural aerobic bacteria. Oceanic microbes react proximally to an oil seep, with populations responding markedly to hydrocarbon supplies. Organisms capable of degrading light crude oil in the Gulf of Mexico responded with dramatic population increase in the plume from BP's Deepwater Horizon rig explosion, and degraded the dispersed hydrocarbon in a matter of days; however, the Exxon Valdez heavy crude spill in Alaska had no such native degraders to respond to that disaster[36]. On-site remediation in Canada's high Arctic also faces other limiting factors, such as temperature, essential nutrients and available water[68]. More needs to be done to understand the microorganisms and functional genes involved in the highest biodegradation rates to optimize design of the most effective remediation strategies at each locale.

[65] Hallam, S.J. 2004. Reverse methanogenesis: testing the hypothesis with environmental genomics. Science, 305(5689):1457-1462.

[66] Hellish hot springs yield greenhouse gas-eating bug. TerraDaily. http://www.terradaily.com/reports/Hellish_Hot_Springs_Yield_Greenhouse_Gas_Eating_Bug_999.html. Accessed September 17, 2012.

[67] Dunfield, P. 2009. Methanotrophy in extreme environments. Open access, DOI: 10.1002/9780470015902.a0021897.

[68] Yergeau, E. et al. 2012. Metagenomic analysis of bioremediation of diesel-contaminated Canadian high Arctic soils. PloS One, 7(1).

8. SUCCESS OF PAST CANADIAN INVESTMENTS IN SECTOR GENOMICS

Canada has a vibrant world-class scientific community, with more than 20 large-scale genomics projects funded to perform research in the energy and mining sector. As scientists scour the environment to identify and make sense of biological processes, modern tools become ever more efficient and affordable at capturing and processing omics data. Tremendous amounts of raw information have been catalogued, analyzed and interpreted with the goal of translating discoveries to benefit the sector directly. The following examples are recent Canadian undertakings that have the potential to substantially impact energy and mining industries.

METAGENOMICS FOR GREENER PRODUCTION AND EXTRACTION OF HYDROCARBON ENERGY

In order to provide a platform from which to explore further biotechnological enhancements, this Genome Alberta/Genome BC/Genome Canada project received $11.6M to build a metagenomics database for the sector, determining "who is there, what are they doing, and how can we steer their actions to our advantage"[69]. The database of microorganisms, genes and biological processes was a necessary first step for future development of biotechnology applications. Recent early accomplishments include:

- **Reducing biocorrosion.** It was discovered that unnecessary addition of bisulphite to pipelines fuels bacteria that generate corrosive products. This led a major energy company to look at phasing out excess use of bisulphite in a critical water system feeding a steam-assisted gravity drainage oil sands operation.
- **Controlling oil field souring.** Metagenomic analysis revealed that successful control of souring with nitrate injection is determined by the makeup and dynamics of the indigenous microbial communities. Models can be developed from metagenomic analysis to optimize nitrate injection dosage and timing for most effective reduction of souring. Findings from this work have already been applied to offshore operations by Suncor, and onshore operations by Enerplus, two Alberta-based oil companies.
- **Safe tailings pond closure.** Metagenomic analysis of tailings ponds helped determine the microorganisms driving densification, toxicity and greenhouse gas emissions. Manipulation of the indigenous constituents opened the door to accelerate water recycling, detoxification of remaining tailings/water, and reduced greenhouse gas effects. Suncor will use this information to ensure that tailings ponds are safely closed.
- **Waste remediation.** Tailings ponds contain many toxic compounds, such as naphthenic acids and residual bitumen, which must be remediated before ponds can be reclaimed. Review of microbial communities derived from tailings ponds revealed microorganisms capable of identifying and degrading contaminants. These are now being isolated and developed for their sensory and treatment capabilities.

GENOREM: IMPROVING BIOREMEDIATION OF POLLUTED SOILS THROUGH ENVIRONMENTAL GENOMICS

The GenoRem project was awarded $7.8M from Génome Québec/Genome Canada to improve and develop environmentally friendly technologies for treating polluted soils. The project proposes an innovative phytoremediation approach to decontaminating various polluted sites. Employing recently developed omics technologies and integrating them with traditional field and molecular biology experiments, GenoRem will generate guidelines for policy-makers

[69] Metagenomics for greener production and extraction of hydrocarbon energy. http://www.hydrocarbonmetagenomics.com/. Accessed September 17, 2012.

and industry on environmentally respectful phytoremediation procedures. Scientifically determining the most effective plant, fungal and bacterial symbiotic associations, willow became the plant of choice. Living in intimate symbiosis with numerous soil microbes, it is a 'pioneer' species that grows rapidly in harsh climates and on poor, even polluted, soils. The soil decontamination protocols being developed will be more effective than traditional phytoremediation on account of optimized microbes identified to interact with the plants.[70]

GENOMICS TOOLS FOR MONITORING AND IMPROVING TREATMENT OF MINE DRAINAGE

Funding from Genome BC, NSERC and industry in the amount of $1.5M was used to improve the design and operation of passive treatment systems for metal- and sulphate-contaminated seepage at mine and mineral processing sites. Next generation sequencing was used to compare the microbes of successful treatments with those from problematic systems, leading to implementation of new strategies for improving treatment operations. Functional metagenomics was used to identify and characterize new enzymes involved in the degradation of organic matter and transformation of arsenic. These enzymes, or the microbes expressing them, can be incorporated into new technologies to enhance performance of the treatment systems.[46]

ALDER-*FRANKIA* SYMBIONTS FOR IMPROVED REVEGETATION AND REMEDIATION OF OIL SANDS TAILINGS

National Research Council Canada's Biotechnology Research Institute is supporting development of alder symbionts for field remediation of tailings sand. Alders fix atmospheric nitrogen in a symbiotic association with bacteria, and can also form mycorrhizal associations. In the greenhouse, inoculation with *Frankia* species significantly increased seedling biomass, root nodules, and plant nitrogen content. After only one year in the field at a Suncor remediation site, the inoculated alders demonstrated increased microbial activity, and an ability to improve soil characteristics[43]. Phytoremediation shows promise as a treatment for accelerating reclamation of retired mine sites.

BIOPRODUCTS AND ENZYMES FROM ENVIRONMENTAL METAGENOMES (BEEM)

In order to better understand the biological processes involved in breakdown of pollutants at contaminated sites, the Ontario Genomics Institute, Genome Canada and partners invested $10.9M in an international project. The team of chemical engineers, biologists and consultants are working with industry to apply their knowledge of gene sequencing and computer modeling to identify, screen and analyze communities of microbes capable of restoring contaminated land and water. Understanding the natural function of such indigenous recyclers to break down contaminants, the team has developed and commercialized a microbial consortia (called KB-1®) that is already being used for groundwater clean-up at sites across the world. In this project, the team plans to contribute to the sustainability of future biorefineries by applying basic research knowledge and skills to develop other microbial-based processes for the transformation, reuse, recycling and remediation of contaminants and byproducts from common industrial processes.

BIOMONITORING 2.0: HIGH-THROUGHPUT GENOMICS FOR COMPREHENSIVE BIOLOGICAL ASSESSMENT

Biomonitoring seeks to describe and understand biological diversity at multiple ecological levels, both as a means to learn the characteristic species diversity of different habitats, and to establish baseline data for

[70] Burger, G. et al. 2012. GenoRem: Improving bioremediation of polluted soils through environmental genomics. Environmental Engineering and Management Journal, 11(3).

early detection of environmental stresses before they reach critical thresholds. This project looks to overcome the limitations of current practices, where sampling frequency and intensity is constrained by laborious procedures, and methodologies focus on a narrow subset of species at a given location. 'Biomonitoring 2.0' is a new system for simultaneously reducing sample costs while dramatically increasing information available from biological samples. Based on cutting-edge DNA-sequencing technologies and state-of-the-art computational analyses, new genomics tools and technologies will be integrated into a well-established Canadian biomonitoring framework. Coordinating closely between industry, government, Aboriginal and non-government stakeholders, the project will greatly increase Canada's ability to manage its natural resources, and maintain its strength in biomonitoring.

EXPLORING ECO-TOXICOGENOMICS

Toxicogenomics studies the way in which an organism responds at a genetic level to toxic substances in its environment. Scientists at Environment Canada are exploring the use of toxicogenomics as applied to wild species (eco-toxicogenomics), researching the effects of a variety of contaminants on soils, sediments, birds and aquatic life. They are also investigating the potential application of eco-toxicogenomics for monitoring ecosystem health to develop possible 'early warning systems'. For example, Environment Canada scientists and colleagues at McMaster University are comparing genetic mutations in certain species living in either urban settings, rurally or near active steel mills. Ongoing studies are attempting to determine the effects of exposure to polycyclic aromatic hydrocarbons (PAHs) and other environmental contaminants. The cataloguing, analyses and interpretation of data from eco-toxicogenomics research can provide a clearer picture of biological responses and susceptibility to contaminants, enabling development of customized tests and risk assessment methodologies[71]. As *Environmental Science & Technology* once published, "the successful incorporation of toxicogenomics into regulatory frameworks may someday be regarded as the most important intellectual and practical contribution from this generation of eco-toxicologists"[72].

[71] Exploring eco-toxicogenomics. 2008. Environment Canada. EnviroZine 79(2).

[72] Ankley, G.T. et al. 2006. Toxicogenomics in regulatory ecotoxicology. Environ. Sci. Technol. 40(13):4055–4065.

9. THE SOCIOECONOMIC IMPACT OF SUCCESSFUL GENOMICS-ENABLED SOLUTIONS

In the same way that engineering solutions have slowly but profoundly impacted industry, so too can the latest omics advances. It took decades for Canada's 1969 invention of steam-assisted gravity drainage to revolutionize the energy industry, but eventually oil sands operators were able to double accessible volumes of oil[14, 73]. Sequencing of the human genome over a decade ago facilitated countless breakthroughs in the biomedical field[74], as will well-researched, industry-enabled genomics solutions strategically applied to the energy and mining sector. Extraction processes have already been improved by using bacteria to optimize performance conditions, either in suspension (such as in bioleaching[3]) or as part of a biofilm apparatus (as proposed for remediation of toxic naphthenic acid[42]). To affect the activity of microbes in enhanced oil recovery, scientists have added high-performance bacteria *in vivo* or provided nutrients to stimulate native microbial growth[34]. However, earlier investigations have not always been profitable, as researchers have taken time to better understand microbial environments. Now, large-scale stirring tanks employ bacteria to concentrate precious metals up to 20-fold[3], and microbially enhanced oil recovery (MEOR) is gaining credibility as a cost-effective means for 5–10% increases in hydrocarbon output[35, 36]. This is the opportune time for integrating genomics advances with engineering infrastructure to create indispensable biogeochemical tools for reservoir and mining engineers.

Indisputable socioeconomic benefits are to be gained from the application of omics technologies to improve Canada's valuable energy and mining sector operations: industry leadership, growth of exports, more trained personnel, reduced environmental impacts, and steady supplies of high-demand products. Experts acknowledge that microbial techniques show promise, if feasibility can be established through field tests, and economic viability is supported by regulatory requirements[29]. Both are expected of the sector in the near term, as omics advances inform industry operations, and legislators increasingly implement constructive regulations. Canada's expansive hydrocarbon, metal and mineral endowments provide ample opportunity for reaping rewards from genomic refinement to challenges in exploration, extraction, processing and remediation. In an industry with capital accumulation of $620B over 62,000 miles of pipeline, maintenance costs are estimated to consume 1% of annual operating expenses[10]. Substantial economic benefit could come from improvements to infrastructure maintenance as a result of omics analyses of pipeline contents, which could additionally provide information on a whole suite of indigenous microorganisms suited to a range of unique operational environments. As Canada's untapped Arctic resources become more accessible, recently-discovered extremophilic bacteria can be utilized to explore new economic opportunities. Nunavut continues to champion mineral exploration and development in the remote north. More than 11M hectares are under lease to gold, diamond, uranium, iron and base metal interests, generating almost $500M in local investments annually[75]. Exploration initiatives in these regions increasingly partner with Aboriginal peoples in employment and business development. In Alberta, the Athabasca Tribal Council was instrumental in working with oil sands developers to ensure partnership around long-term benefits, environment, human and physical infrastructure, and employment/training[76]. The application of research to industry attracts new talent and trains Canadians in fields as diverse as microbiology, chemical engineering and geoscience[35]. Contributing 11% of GDP, even a 1% improvement in yield would provide $1.5B and employment for tens of thousands of Canadians.

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[73] Lowey, M. 2004. Father of innovation – Roger Butler's SAGD process opened up the oilsands. University of Calgary News.

[74] Lander, E.S. 2011. Initial impact of the sequencing of the human genome. Nature, 470(7333):187-197.

Technological advances offer governments the opportunity to better inform regulatory standards with comprehensive field data more reflective of the complex environments in which industries operate, and provide confidence that companies can develop the tools needed to respond effectively (although scale-up of technology to industrial levels currently presents a delay to implementation). The omics sciences provide one avenue for exploring alternative microbial procedures that are typically more environmentally friendly than existing physicochemical processes[56, 77]. Escalating public pressure would seem to support the Canadian development of such novel approaches, for the health of the economy, stewardship of the environment, and well-being of Canadians.

The Genome Alberta/Genome Canada-funded research consortium is currently cataloguing genetic information for the microbes, biological processes and enzymes responsible for methanogenic hydrocarbon conversion[69]. The resulting metagenomic database will enable detailed review of the genetic potential of the natural environment to reduce greenhouse gas emissions from tailings ponds. Recent government regulations have accelerated initial industry movement in this direction; for example, Alberta's *Directive 74* sets aggressive targets for handling and disposal of tailings waste. Energy companies there have had to provide almost $1B[78] in financial guarantees to ensure sufficient funds for decommissioning sites, spearheading a thorough review of potential reclamation technologies, such as metabolic modeling of reverse-methanogenesis. Suncor was the first to fulfill its reclamation obligations in reverting a 40 year-old pond to public land, however less than 1% of the land disturbed by oil sands mining yet complies with the new requirements[56, 77]. The federal government holds responsibility for an additional 20,000 mine sites contaminated by historical operations[59].

Industry promotes scientific collaboration through the coordination of pilot tests and sharing of knowledge[56]. Both internationally and in Canada, public private partnerships are becoming common for exchanging technology and expertise. In a research partnership with the Norwegian oil industry, the US company Glori Oil utilized Silicon Valley funding to implement microbial technology developed in India. In Canada, Alberta-based Dycor Technologies Ltd. utilizes funding from Western Economic Diversification and the Saskatchewan Government to validate and advance a proprietary proof of concept to field testing; successive MEOR projects have resulted in industry-funded analysis and enhancement of down-hole well site microbial activity for increased recovery. The private partners are working with the regional Genome Centre to make extensive metagenomic and bioinformatics data publicly available[79]. Such an enterprise perfectly meets the definition of public private partnerships: joining expertise to address public need through

[75] Nunavut: uncovering the potential. 2012. AANDC Nunavut Regional Office, Mineral Resources. Mining North.

[76] Aboriginal-mining industry round table report. 2004. Mining Association of Canada/Canadian Aboriginal Minerals Association.

[77] Valentine, T.E. and Litton, K-L.G. 2011. Alberta's oilsands: the changing landscape of reclamation obligations. Energy Bridge.

[78] Mine financial security program. Alberta Environment. http://environment.alberta.ca/03388.html. Accessed September 29, 2012.

[79] Keller, W. 2011. Deductive Microbial Enhanced Oil Recovery (MEOR) – phase 1A final report. Dycor technologies Ltd. Pers. comm. June 24, 2011.

[80] Definitions. The Canadian Council for Public-Private Partnerships. http://www.pppcouncil.ca/resources/about-ppp/definitions.html. Accessed September 23, 2012.

sharing of resources, risks and rewards[80]. Omics technology implemented in Canada and abroad will enable industry and governments to uphold their fiduciary responsibility by maximizing resource output from available deposits, increasing access to reserves, and helping to manage environmental impacts from larger-scale operations required to serve the world's growing population. Coordination with international partners around funding, expertise and access to data and commercialized innovations will increase Canada's capacity for economic, social and environmental prosperity, and ensure that our sector participation remains world-class.

10. CANADA'S LEADERSHIP AND STRENGTHS

Along with plentiful natural resources, Canada has substantial processing and infrastructure capabilities in energy and mining. Its strength as an export nation has created a network of reliable international markets. A stable economy has capably weathered recent global uncertainties, and forms the backdrop for government efforts to streamline project approval processes and establish policies for enhanced resource exploration. An assembly of provincial governments operates under the oversight of a federal government amenable to development and focused on scientific research and technological advancement. Substantial investment in omics infrastructure and research activities provides the foundation for Canada to lead in developing the energy and mining sector. Through cofunding of successive research competitions over the last 10 years, $150M has been invested in almost 20 related research projects across Canada. From microbial genomics to metagenomics, from biomonitoring to industrial applications, scientists from coast to coast have been coordinating with industry on relevant advances. Recent successes already include outputs from research on biomonitoring, environmental remediation, and microbially enhanced energy extraction.

Canada's energy resources were valued at $880B in 2011, and mineral assets totaled $370B[81]. Drawing on this natural wealth, mining activities are distributed evenly across towns and urban centres from east to west[11], whereas onshore hydrocarbon extraction is focused in the four provinces of Quebec, Ontario, Alberta and BC[82]. An extensive pipeline, rail and seaway system creates versatile access to markets. In addition to the principal US export partner, other top export markets include representatives from the strong expanding BRIC economies (such as Brazil, India and China), along with nations undergoing more modest growth (such as Australia, Japan and South Korea)[19]. Substantial incentives for investing in exploration are offered in the form of generous tax reductions and exemptions; a treaty with China offers dividend tax rates as low as 10%, with the first $500,000 tax free[9]. Once established, new ventures can supply goods across the highly networked North American grid.

Strong support for scientific research is provided by a national tri-council, who coordinates generous federal funding for the fields of natural sciences and engineering, social sciences and humanities, and health. The three research councils (NSERC, SSHRC and CIHR, respectively) contribute to personnel and operating costs, and the Canada Foundation for Innovation (CFI) provides funding for state-of-the-art equipment infrastructure. Over the last decade, Genome Canada has also invested and leveraged more than $2B in omics activities through its six regional Genome Centres, who work together to determine research priorities of provincial and national concern. Through the long-term support of scientific innovation, Canada boasts an impressive track record in science and technology; with only 0.5% of global population, Canada generates nearly 5% of the world's most frequently cited publications[83]. Although the National Research Council of Canada offers its international EUREKA! network for connecting industrial R&D with more than 40 other nations, it has been noted recently that scientific discoveries could be better translated into applications. This is particularly true in the area of natural resources

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[81] Canada's natural resource wealth. 2011. Statistics Canada, The Daily, September 6, 2012; http://www.statcan.gc.ca/daily-quotidien/120906/dq120906a-eng.htm. Accessed October 4, 2012.

[82] Lemphers, N. and Woynillowicz, D. 2012. In the shadow of the boom: How oilsands development is reshaping Canada's economy. The Pembina Institute.

[83] Executive summary, the state of science and technology in Canada. 2012. Council of Canadian Academies.

and the environment, where science and technology output has been in decline since 2005. Already, industry has been working collectively to address technological shortcomings in their own sectors. The Mining Association of Canada launched a pioneering initiative around sustainability and governance, *Towards Sustainable Mining*. The Canadian Association of Petroleum Producers recently spawned a progressive group, Canada's Oil Sands Innovation Alliance. Alberta's *Directive 74* has prompted coordination of research strategies around tailings pond remediation. Industry is poised to build further on early success to improve the sector.

Industry-research partnerships are supported by the Government of Canada through 42 endowed Industrial Research Chairs, and 155 Canada Research Chairs across a range of sectors. Expansive scientific and commercial platforms make Canada attractive to researchers and investors alike. From decades-old sector inventions like kerosene, natural gas-powered transit, and steam-assisted gravity drainage to an established genomics research and funding infrastructure[17, 73, 84], Canada moves into a future primed for public private partnerships and streamlined field operations. Agencies such as The Pembina Institute and Canada's Public Policy Forum support scientific research with rigorous policy review, expanding the breadth of Canada's leadership in the sector. The full complement of resources, skillsets and networks sets the stage for coordinated collaboration in Canada and internationally, to lead the world in omics-based innovation for an energy- and resource-intensive future. Implementation of a robust genomics strategy for the sector will aid Canada and the world in achieving a more sustainable future.

[84] Petrochemical industry. The Canadian Encyclopedia. http://www.thecanadianencyclopedia.com/PrinterFriendly.cfm?params=A1ARTA0006251. Accessed September 16, 2012.

11. SECTOR CHALLENGES AND OPPORTUNITIES FOR THE STRATEGY TO ADDRESS

COMMUNICATION, EDUCATION AND TRAINING

Despite significant advances in comparable sectors, genomics is still broadly viewed as an emerging science for energy and mining. Decision-makers in hydrocarbon resource extraction have principally relied on engineering solutions, then chemical solutions, and only more recently turned to the potential utility of omics. Whereas mining has employed biotechnology successfully for decades, but progress and interest in new advances has since stalled. Existing early-stage collaborations have resulted in provision of substantial samples from industry for metagenomic assessment. Further work moves in the direction of not only identifying organisms present at commercial sites, but defining their function and operating thresholds. Much work remains to be done, but sector industries operate at such a scale that even incremental improvements in extraction, processing or waste treatment remain huge opportunities if a sound business case can be made. The opportunity to advance understanding between sector participants, and enhance the technical capacity of research to improve industry operations, provides Canada with the potential to have a profound scientific and commercial impact internationally in this emerging field.

Enable interdisciplinary capabilities

Currently, foundational research generates great swaths of useful data that requires expert opinion to review. Therefore, an important aspect of future development needs to include training of industry staff, and then involvement of scientific expertise in decision-making. Researchers must be informed of industry needs and opportunities, and foundational data must be interpreted correctly for industry use. Then the potential for scale-up from bench research to field applications can be properly explored. Cross-sectoral teams of researchers and industry representatives should collaborate transparently to move new technologies into applications, working to demystify the public's perception of genomics applications and assuage environmental concerns. Additionally, regulators need to further assess the larger-scale potential of new technologies for the purposes of monitoring and compliance.

Identify a sector champion

An important proposition arising from the stakeholder workshop was that of an ‘ambassador agency’ to oversee communications, education and articulation of industry challenges for the benefit of research proponents. Representatives from both energy and mining recommended an interdisciplinary industry association to champion ongoing dialogue, drawing either from an existing association, or devising a committee with members of various associations and expertise. Joining forces across industry would enable prioritizing of common issues for research pursuit, and development of a roadmap for moving solutions forward, including management of IP. In addition, such an umbrella association could provide industry advisors for project review, help determine relative industry contributions for ongoing collaborative research, and assist with pre-market validation of any project outcomes. Industry consortia have an important role to play in helping academic partners assess how ROI is measured, and guiding research partnerships toward greater industry utility. Interdisciplinary workshop participants identified distinct short- and long-term sector priorities for the association to consider, belying a different readiness for commercial uptake in the respective fields of mining and energy. Across the sector, each industry can gain from the other in dialogue and in practice, and an overarching organization to coordinate and streamline these interactions is a natural step forward for any effective strategy. Already, the Petroleum Technology Alliance of Canada (PTAC) has engaged with the Genome Centre proponents in consideration of a champion role.

LEVERAGE SUCCESSFUL SYNERGIES

To accelerate implementation of the strategy, workshop participants also encouraged emulation of successful collaborative models at work in other sectors. These include several Canadian and US examples:

Consortium for Research and Innovation in Aerospace in Québec (CRIAQ)

Established as a non-profit consortium of industry and academia, CRIAQ promotes and conducts collaborative pre-competitive industry research primarily at universities and with support from the Quebec government and NSERC. The principal objectives are to increase the competitiveness of the aerospace industry and enhance the collective aerospace knowledge base through improved education and training of students.

Green Chemistry Canada

Funded by the governments of Ontario and Canada, Green Chemistry Canada uses "smart" chemistry to design safer, waste-reducing or less resource-intensive products and processes. Innovations originating from academia and industry are transformed into breakthrough green products, services and industries to enhance quality of life and preserve the environment. Researchers and entrepreneurs are offered the expertise and resources they need to advance their technologies to market: industry collaborations; product, application and business development expertise; IP management; and scale-up manufacturing.

Strategic Environmental Research and Development Program (SERDP)/Environmental Security Technology Certification Program (ESTCP)

In the US, SERDP and ESTCP act as the environmental research programs for the Department of Defense. The latest scientific and technological breakthroughs are used to enhance environmental performance, reduce costs and sustain capabilities. The programs respond to common environmental technology requirements, promoting partnerships and collaboration among academia, industry, military services and other federal agencies. Although independent programs, they are managed from a joint office to ensure full coordination of efforts, from basic and applied research to field demonstration and validation.

DEVELOP PILOTS AND DEMONSTRATION PROJECTS

In the short-term, genomics can help identify environmental diversity, establish baseline data and develop indicators for monitoring industry operations and remediation. Integrating omics technologies with existing geochemical operations will further empower future applications. As with the health sector, results from the laboratory need to be translated into pilot tests, whose outcomes can be scaled up to field testing; the homogeneous environments of the laboratory need to be trialed against the heterogeneous operational environment. Industry players might consider collectively sharing the risks (and costs) of pilot studies, such that proof-of-concept demonstrations can be effectively translated into the field without delay.

Essential ingredients

Critical advice was provided on the design of pilots and demonstration projects during the workshop consultation:

- Develop capacity in interdisciplinary research infrastructure and data analysis;
- Design projects to achieve measurable outcomes within two years, with a focus on economic returns;
- Extend outreach and communication efforts to broaden understanding and collaboration between managers in industry and bench researchers; and
- As research develops and applications progress, different levels of industry input are perhaps warranted.

Different levels of application

Industry at the workshop recommended that omics advances could assist directly at three different levels of application: early-stage, near-term, and late-stage applications:

- Early-stage applications. Omics technologies are already used in some early-stage applications to generate baseline data, and monitor any positive effects of remediation or negative effects of industry activities. Other early-stage efforts should address the ongoing need for fundamental knowledge, which can be woven into existing physico-chemical operations to offer biogeochemical solutions. Once preliminary data has helped identify and characterize the biological activity at mining and hydrocarbon energy sites, a clear demonstration of the potential for omics applications can be made (such as those featured below). Thereafter, small-scale pilots can be developed. The recent workshop recommended that foundational research would be best supported by public funding, with industry providing samples; biomonitoring applications could already be tested alongside traditional monitoring methodologies. Genome Canada's recently launched Genomic Applications Partnership Program (GAPP) is intended to stimulate such public private partnership. To increase collaboration between scientists and research 'end-users', Genome Canada is committing $30M to the program to leverage additional funding from industry, government, non-profit or other organizations to create a $90M R&D investment.
- Near-term applications. After development of pilots, near-term omics applications could act to advance monitoring, biosensing, recovery efforts (such as non-sulphide bioleaching), reclamation or treatment (such as waste transformation, bioreactor optimization, and improved water treatment and use). Regulators should be involved in the identification and development of near-term solutions, since they have a vested interest in these technologies gaining traction in the field; mining and energy companies have not characteristically been early adopters of new technology, unless a good business case exists. The pursuit of omics applications in industry will require sound fiscal reasoning, along with cross-sectoral communication to overcome knowledge gaps and pre-conceptions. Both researchers and industry will need to focus on profitable outcomes for interdisciplinary interactions to be worthwhile; each will have to step closer to the other to achieve a common understanding of the potential for omics to improve the sector.
- Late-stage applications. Full-scale application of omics technologies can advance existing operations, renew previously discarded prospects, or result in entirely new commercial processes. In each case, any biological constraints will need to have been addressed for successful on-site application, e.g. pH, temperature, toxicity of the environment, metal tolerance, resistance to abrasion, control and containment. Joint Industry Projects can be used to further incubate the translational potential for maximum ROI, offering a way for partners to distribute the costs of developing a solution to a shared challenge or prospect.

12. IN SUMMARY

Canada's energy and mining industries have an ideal opportunity to enhance their operational efficiencies and environmental performance by actively pursuing new omics applications. Unthinkable more than a decade ago, it is now possible to cost-effectively generate a complete profile of the biological communities at work in industrial environments, enabling insights into "who is there, what are they doing, and how can we steer their actions to our advantage".

Canada has led the way with a comprehensive stakeholder consultation process that included representation from industry, researchers, government, regulators and Aboriginal peoples assessing the vital role for omics to enhance operations in both energy and mining. The importance of this sector nationally and internationally, and the magnitude of operational and environmental challenges faced, makes this an urgent economic opportunity. This Sector Strategy Paper demonstrates that omics applications have already yielded important results and industry is poised to explore further timely outcomes. Enhanced cross-sectoral collaboration will be key to realizing the full potential of omics applications. The strategy is an important starting point for identifying champions to sustain interdisciplinary dialogue and determine best practices for leveraging synergy into sector impacts. Effectively implemented, this strategy will help the sector fully appreciate the benefits available from omics technologies for addressing the most pressing common challenges and seizing unique opportunities.

APPENDIX:
STAKEHOLDER WORKSHOP PARTICIPANTS

LAST NAME	FIRST NAME	JOB TITLE	COMPANY
Adamson	Richard	Managing Director	Carbon Management Canada
Alvarado	Oscar	Project Research Analyst	BacTech Environmental
Atlas	Ron	Professor	University of Louisville
Bailey	David	President and CEO	Genome Alberta
Baird	Donald	Research Scientist	Environment Canada
Baldwin	Sue	Associate Professor	University of British Columbia
Bell	Cindy	Executive VP, Corporate Development	Genome Canada
Bolton	Alexander	Board Member	Energy Resources Conservation Board
Budwill	Karen	Research Scientist	Alberta Innovates – Technology Futures
Burns	Kyeema	Consultant	AGE Consulting
Caffrey	Sean	Project Manager	Genome Alberta
Chapman	Peter	Principal/Senior Environmental Scientist	Golder Associates Ltd
Cheel	Daphne	Executive Director	Government of Alberta
Clarke	Teresa	Director, Research Programs	OGI – Notetaker
Cook	Eric	CEO/Executive Director	Research and Productivity Council
Cunningham	Lesley	Senior Policy Advisor	Ministry of Economic Development and Innovation
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