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Adoption and impact pathways for Canadian Forest Service genomics research and development initiative projects

Emily Hope
Debby Barsi
Dan McKenney

Natural Resources Canada
Canadian Forest Service

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E. Hope, D. Barsi and D. W. McKenney

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Executive Summary

Government investments in science are under scrutiny to demonstrate impact. The purpose of this report is to provide a preliminary analysis of the potential adoption and impact of eleven Genomics Research and Development Initiative (GRDI) projects at the Canadian Forest Service (CFS). There have been significant investments by the Government of Canada (GoC) in forest genomics-related research and development (R&D). Genome Canada, funded by the GoC, has invested approximately $90 million in forestry related genomics research performed by academic scientists. Federal genomics science is mainly supported by the GRDI, approximately $30 million since its inception in 1999; the projects discussed in this report receive just over $1 million per year. In addition to providing perspectives on expected adoption and impacts on each of the genomics projects, we also provide a summary of some common themes/expectations across all projects, and identify characteristics of projects that appear likely to have very near-term impacts. The analyses completed here are the first steps towards a more quantitative evaluation of the impacts of the investment into the GRDI projects. Indeed this effort aligns with Natural Resources Canada (NRCan) priorities and the GoC's desire to better quantify the impact of research investments.

Our approach draws from methods used by the Australian Center for International Agricultural Research (ACIAR). ACIAR has accumulated some 34 years of experience conducting project evaluations and using assessments to support future research and funding. Our approach made use of two tools: 1) a generic template to establish a narrative on the expected path between research project outputs and final impacts and, 2) a (primarily) closed-ended survey of each project to systematically gather additional details. Importantly, the data from the surveys have been entered into a database that can be used to consistently track research portfolio characteristics over time. In principle, this approach and subsequent data could be used for other (non-genomics) R&D efforts as well.

Results indicate that GRDI projects have a large number of collaborators and users directly involved in the projects. This includes direct user-requests for specific outputs, close collaboration with research and operational institutions, and in-kind contributions from final users. Project outputs are anticipated to generate a variety of impacts that align with the CFS and broader departmental priorities to promote forest sector competitiveness, advance environmental leadership, and optimize forest value. Across all projects, the impacts most commonly identified are economic in nature, supporting the Canadian forest sector through improvements in organizational efficiency in work practices, and reductions in risk to forest product market demand or supply. Environmental impacts, where identified, primarily focused on forest health and were generally longer-term in nature. The social impacts that were identified were related to relationships associated with trade agreements. It is of course particularly difficult to attribute changes in social conditions to particular R&D efforts.

Researchers expressed that the process was useful to them, as it allowed a better understanding of the pathways between intended project outputs and impacts. Evaluations of this nature should help to refine expectations regarding research efforts and provide early assessments of project value. High-level information derived from these evaluations is also of help to quantify/synthesize/summarize research patterns and portfolio investments.

Finally we note that this kind of analysis is not a substitute for cost-benefit analyses that, for example, provide rate of return estimates after projects have been completed and outputs adopted. Such analyses are more typically performed 5-10 years after the research has been completed and require the development of defensible counterfactual narratives depicting the world with and without the research effort.

Glossary

Adoption – The update or use of a project output (i.e. a method, a tool, etc.) by a next or final user.

Bioinformatics – An interdisciplinary field that develops methods and software tools for understanding biological data.

Biosurveillance – A surveillance system in this case using genomic tools to monitor potential threats, insects and diseases, for entry into Canada.

Ecosystem integrity – The quality of a natural unmanaged or managed ecosystem in which the natural ecological processes sustain the function, composition and structure of the system.

GAPP – Genomic Applications Partnership Program; Genome Canada program connecting academic researchers and users with the intent of translating genomics research into applications.

Genetic markers – A portion of the DNA sequence with a known location on a chromosome. Also referred to as molecular markers.

Genotypes – The genetic make-up of an individual, inherited from parents that determines specific characteristics.

Impact – The long- or short-term effect of adopting a project output. Effects may be social, environmental and/or economic.

Market goods – A product or service that is purchased or sold within a market.

Metagenomics – The study of environmental material recovered directly from environmental samples.

MeBr – Methyl Bromide, a pesticide used to treat wood products for pests and pathogens.

Non-market goods – A product or service that is not purchased or sold within a market and hence does not have a market-based value. In the forestry context non-market goods are typically environmental goods or services.

Phenotype – An organism as observed, i.e., as judged by its visually perceptible characters resulting from the interaction of its genotype with the environment.

Phytosanitary concerns – Plant pests and diseases that may impact Canadian trade

Species complex – A group of closely related species that are similar in appearance to the point where differentiation becomes difficult.

Volatile attractant – An airborne substance that attracts specific insects.

Introduction

Government investments in science are under scrutiny to demonstrate impact. Forest and forestry-related research is no exception. Indeed, this pressure has existed for some time in Canada and even internationally (Nature 2016). There is currently a move towards a 'results and delivery approach' for Canadian government programs and policies (Scott Brison, President of the Treasury Board; Agbonlahor, 2016; see also Canadian Geomatics Environmental Scan and Value Study, 2015). However, the long-term, broad-scale and public good nature of many types of research in the forest and forestry-related sector makes it particularly challenging to quantify impacts and welfare changes.

Despite the challenges, this report provides an analysis of the potential adoption and impact of eleven Genomics R&D Initiative (GRDI) projects at the Canadian Forest Service (CFS) (Appendix 1). Our analyses are necessarily *ex ante* (before the fact), given that the projects are relatively new and on-going, and that the research outputs that have been produced have not been in place long enough to generate impacts in the larger societal context.

In addition to providing perspectives on expected adoption and impacts of the genomics projects, we also provide a summary of some common themes across all projects and identify characteristics of projects that appear to have prospects of very near-term impacts. Our intent is to demonstrate what we believe is a useful approach to thinking about research investments in a manner that describes likely adoption and impacts pathways that are attributable to particular projects.

Background

Genomics is the science of DNA sequences and includes the study of the functions of the tens of thousands of genes found in living organisms, and the complexity of their multiple interactions. The practical application of genomics-based tools and knowledge to forest and forestry-related problems is broad in scope.

The GRDI was established in 1999 to support genomics research in federal departments and agencies. Its strategic goal is to contribute solutions to issues that are important to Canadians, such as health, food safety, effective management of natural resources, a sustainable and competitive agricultural sector, and environmental protection. Genomics science at NRCan-CFS intersects many NRCan and GoC goals, including the protection of markets, climate change mitigation and adaptation, and ecosystem integrity.

GRDI at NRCan-CFS Facts

- 1999 GRDI established to build genomics capacity in federal departments and agencies
- 60+ NRCan-CFS projects funded since 1999
- 2011 Shift from capacity building to translation of genomics research into application
- $1.6M Annual GRDI funding to NRCan-CFS for mandate driven projects
- 75+ Phase V project collaborators from universities, the private sector, and government
- 100+ Phase V project publications in reviewed journals
- 6 Number of funding cycles (phases), Phase VI ends in 2018-19
- 11 Number of Phase VI projects
- 50+ Scientific personnel involved in GRDI projects (Phase VI projects)
- 2 Number of Interdepartmental Shared Priority Projects

Specific examples of genomics research in the CFS include the development of tools:

- for forest tree improvement, including advancements in the design of faster breeding programs for traits of interest (e.g. wood properties, growth, pest resistance);
- to help identify invasive species, their origins and forecast potential spread;
- to assess ecosystem health post natural resource development, both in forestry and oil sands mining.

An evaluation of the impacts of the investment into the GRDI projects aligns with NRCan priorities, and with the GoC 's desire to quantify the impact of research investments.

Approach

We have adopted an approach that draws heavily from the experiences and established methodology of ACIAR (http://aciar.gov.au/). ACIAR funds research in agriculture, fisheries, and forestry and has been quantifying the impacts of their research funds since 1982. ACIAR has a long history of using economic principles to help identify and quantify the value of their scientific research investments (see Bartlett, 2016 for a perspective on 3 decades of ACIAR's forest-related investments).

Davis et al. (2008) set out guidelines for ACIAR's three types of assessments that can be completed at different stages of research projects:

1) Desktop Assessment – quick assessments of expected impacts, conducted at any point on the project timeline, the type of analysis undertaken here.
2) Adoption studies – assessments undertaken by the principal scientist(s) involved in the research several years after a project has been completed, with the aim of providing a more detailed assessment of the adoption and use of project outputs, including observed and anticipated impacts.
3) Impact Assessments – detailed quantitative assessments of impacts intended to estimate economic returns to research investments, typically performed anywhere from four to ten years after the project's completion.

Our approach is based on a modified version of the desktop assessment framework described above. We used 1) a generic template to establish a narrative on the expected path between research project outputs and final impacts, and 2) a (primarily) closed-ended survey of each project. The survey allowed us to tease out important details in a more consistent fashion across projects. Completion of the template and survey included reviews of project documents and face-to-face discussions with project leads to develop a deeper understanding of the projects.

The Desktop Assessment one-page template has been modified to better reflect the CFS's context (Figure 1; see Davis et al. 2008 for additional details). There are four key sections of the template, each representing a phase from research outputs to final impacts:

- The first phase identifies the major expected outputs and classifies the outputs into one of four groups: technological outputs, scientific knowledge, capacity built, and policy analysis. All outputs from scientific research can be classified into one of these four categories and they represent primary motivations for government-funded science.
- The second section of the Desktop Assessment template focuses on the adoption phase, where the identified initial (sometimes called "next") users begin to adopt and make use of the project outputs. The processes to impact are identified in four major categories: commercialization, communication efforts, capacity building for users, and policy support. Often the adoption phase is directly influenced by the actions of the research proponents.
- The third section of the template highlights anticipated outcomes and early impacts. These impacts are the quickly felt results of a change in demand, supply, environmental or social pressures (Davis et al. 2008). These impacts affect economic markets (demand and/or supply effects) and non-market goods or services, such as environmental and/or social effects. While these effects are influenced by the nature and success of the previous phases, they are not necessarily influenced by the direct actions of the project team but rather by users of the project outputs.
- Final impacts reflect the idea of wider scale adoption by many or all possible users, and a new 'status quo' within markets, environmental systems, or social networks. These final impacts are the result of broader-scale adjustments to the initial changes in conditions brought about by early users and are classified into three broad categories: economic, environmental, and social (Davis et al. 2008; see also Just et al. 2004 for an in-depth discussion of economic welfare concepts).

The left side of Figure 1 highlights the importance of time by noting project length, expected time to first adoption, first outcomes and final impacts. Within each section of Figure 1 are typical questions asked of project proponents. These questions are intended to help direct conversation and thought towards realistic portrayals of how outputs could progress from research deliverables to larger scale impacts. Some projects may be highly targeted with quickly achievable impacts, while others may be more fundamental and long-term in nature but relevant or useable to a wider constituency.

As noted, the second complementary tool used in our in assessments was a longer survey referred to as CFS-PRIUS (Project Review, Impact, Uptake Summary). This tool was adapted from ACIAR's Project Impact Assessment Survey (Davis et al. 2008), and modified to suit the evaluation of forestry-related studies. The PRIUS provides specific details not captured via the desktop template. Most of the questions are closed-ended, and the respondents must choose answers from a pre-determined set of choices. This helps to maintain consistency in interpretations and allows for more quantitative summaries of responses. PRIUS results are discussed below, with the full survey template available upon request.

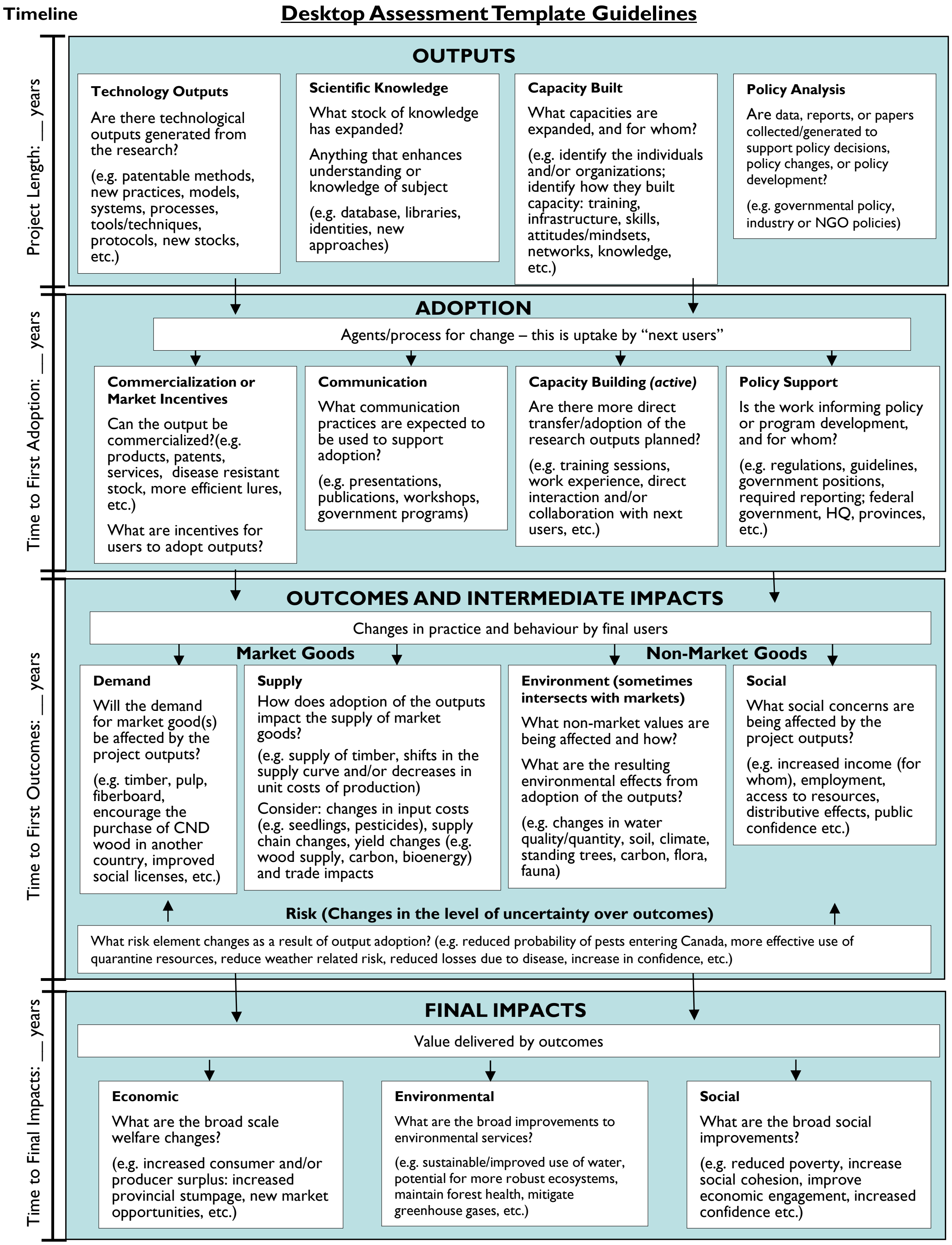

Figure 1. The Desktop Assessment template used to guide interviews with project leads.

We filled out both the one-page template and survey for each project based on our understanding of the project methods and goals. We then reviewed these documents in face-to-face discussions with the lead project members. By filling in the documents, we established initial assumptions about the path between project outputs and impacts. Reviewing them with the project teams allowed for: validation of our understandings; more informed and efficient discussions; consistency in terminology and approach; maintenance of the appropriate economic perspective; minimizing the intrusions on the researcher's time.

Following our interviews with the researchers, we evaluated the results for consistency across projects. To aid in this exercise and provide a visual reference for future use, we created timelines for each technological output, highlighting the years between output completion and expected adoption by next and final users, and the commencement of the anticipated impacts. An example of a project timeline is shown in Figure 2. Completed timelines for each project are shown in Appendix 2.

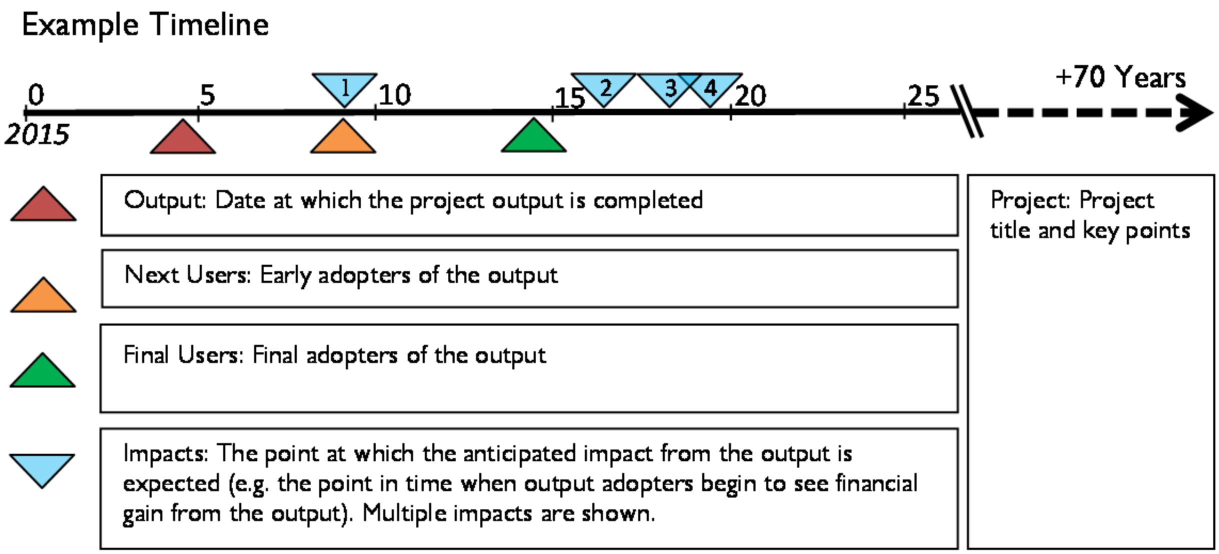

Figure 2. The timeline image constructed for each project to highlight the expected outputs and anticipated impacts.

Results

Desktop Assessments

The one-page summaries and brief narratives about the nature of each project are provided below. These analyses can be used by research managers and analysts to understand and articulate the current genomics research portfolio supported by GRDI funds. They can also serve as a basis for future, more detailed (*ex post* – after the fact) Adoption or Impact Studies. As these analyses were performed during the first year of the research projects, they can only identify anticipated project outputs, the potential pathway to adoption and impact and approximate timelines. These uncertainties limit the conclusions that can be made at this time concerning impact. The projects are not listed in any particular order.

Project 1. Development of metagenomic and bioinformatic tools to facilitate processing of insect trap captures

Trapping and identifying insects is typically a long, expensive process. This is largely a result of the time required to manually sort and identify the insects caught within the trap. In addition, the number of personnel qualified to complete this work is declining. The data generated is critical for forest pest management decisions and related research projects. To address the loss of taxonomic expertise and the high costs associated with processing trap captures, this project aims to develop metagenomic tools to identify captured insects as a cheaper means of obtaining the same results. The project members will compare the metagenomic and traditional taxonomic methods to evaluate identification accuracy and costs, and begin compiling a reference library of beetle DNA for identification of future genomic material.

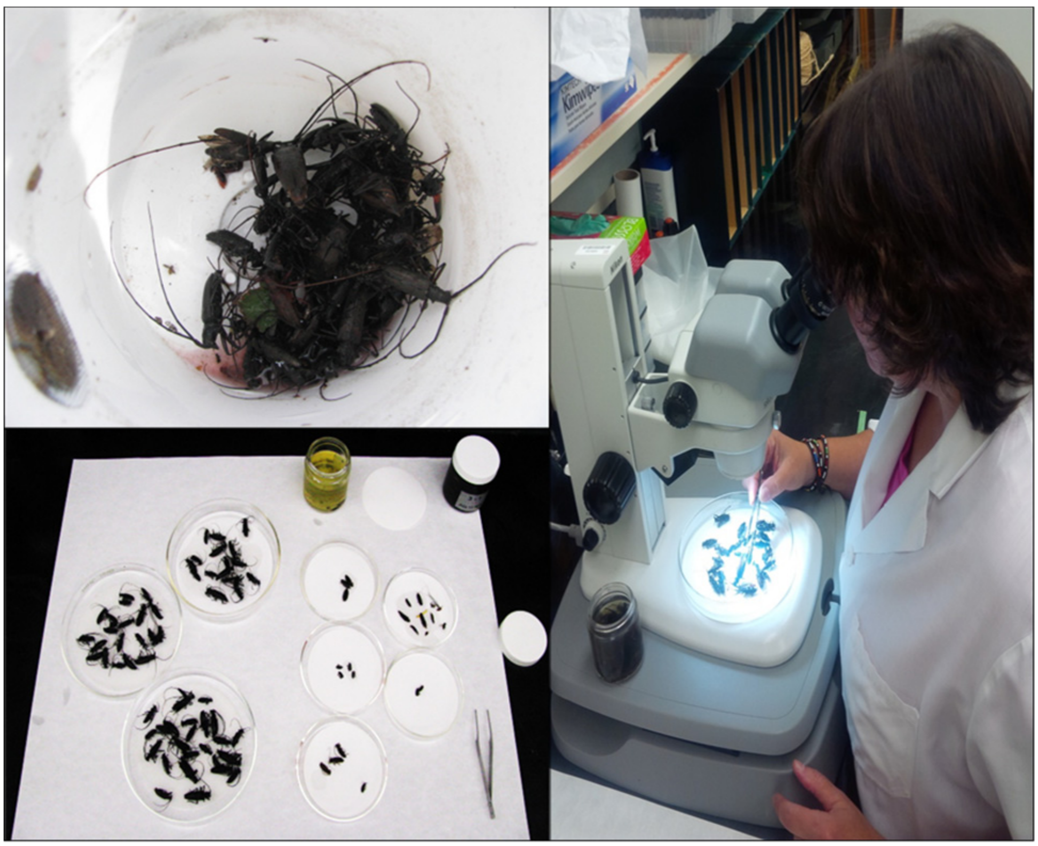

Figure 3. Clockwise from top left: Insect trap capture results; a scientist sorting trap capture results; sorted trap capture results.

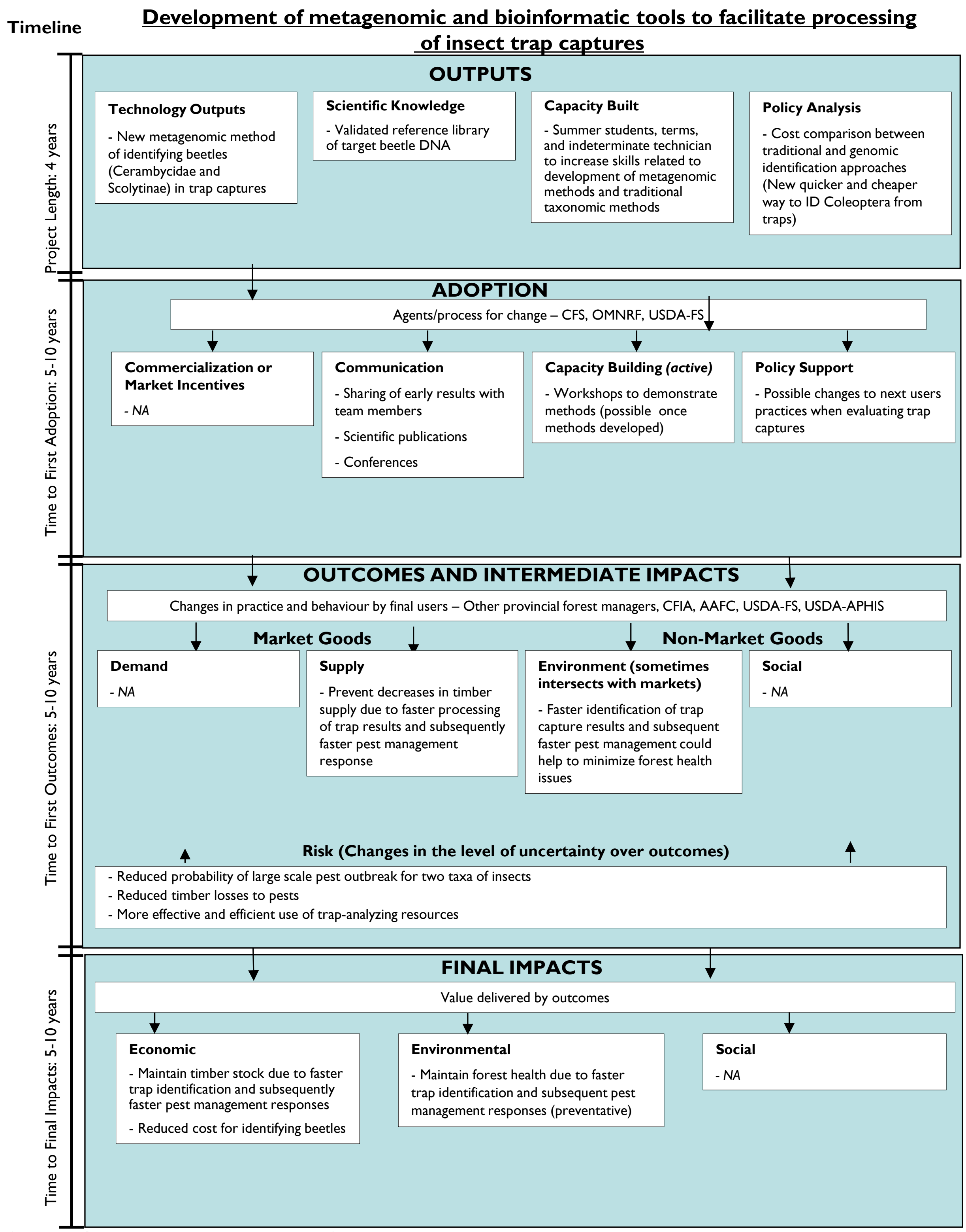

Figure 4. Desktop Assessment for Project 1.

Project 2. Tools for enhanced molecular detection of Asian gypsy moth (AGM) and identification of their geographic origins

Non-native invasive species represent a significant concern to trade, forest product industries and forest health. Of particular interest is the gypsy moth species complex which includes the AGM and its close relative, the European gypsy moth (*Lymantria sp.*), already found in Canada. AGM is endemic to Asia, and has periodically arrived at Canadian borders as an egg mass on ships. The Canadian Food Inspection Agency (CFIA) monitors for AGM at Canadian ports. If eggs are found on a ship, it is the responsibility of the shipping company to eradicate the masses in an effective manner. AGM has the potential to become established in Canadian forests, cause extensive defoliation, and restrict Canadian exports, as other countries also actively work to keep AGM out. By request of the CFIA, this project builds on a previous Genome Canada biosurveillance project, which has developed markers that allow the differentiation of species within the species complex. The project will examine the genome of AGM species to identify location specific markers. The ability to identify the region of origin of the egg masses increases the efficiency of the CFIA's monitoring program and will assist in trade discussions to prevent future invasive species. The project will also create a reference library of AGM genomic markers for future use.

Figure 5. Clockwise from top left: Gypsy moth eggs in North America; container ship potentially transporting infested wood products; adult female gypsy moth.

Timeline

Tools for enhanced molecular detection of Asian Gypsy Moth (AGM) and identification of their geographic origins

Project Length: 4 years

OUTPUTS

Technology Outputs

- Method to identify the origins of AGM from 8 world-wide geographical locations

Scientific Knowledge

- Library of location-specific molecular markers for AGM (for CFIA)

Capacity Built

- Post doc project member to increase skills related to population genomics
- CFS scientists to develop new expertise in assay development and AGM marker development

Policy Analysis

- *NA*

Time to First Adoption: 0-1 years

ADOPTION

Agents/process for change – CFIA

Commercialization or Market Incentives

- *NA*

Communication

- Sharing of early results with team members
- Scientific publications
- Conferences
- Some reporting with CFIA and network collaborators

Capacity Building *(active)*

- Training for CFIA inspectors on the use of the assay

Policy Support

- Enhanced ability for CFIA to apply the current phytosanitary guidelines

Time to First Outcomes: 1-5 years

OUTCOMES AND INTERMEDIATE IMPACTS

Changes in practice and behaviour by final users – CFIA, USDA-APHIS

Market Goods

Demand

- *NA*

Supply

- Supply of all imports (not just wood products) from AGM origin countries would decrease if non-compliant with CND import requirements
- Avoided potential disruption to all CND exports (Worst Case: Canada becomes quarantined and exports must be inspected; costly, multi-year impacts)
- Maintain deciduous timber stock due to avoided entry of AGM
- Avoided costs of removal and replacement of urban trees

Non-Market Goods

Environment (sometimes intersects with markets)

- Avoided entry of AGM will result in maintenance of host tree species on the landscape (prevent defoliation and changes to forest structure)
- Avoided use of pesticides to eradicate AGM populations

Social

- Improved trading relations as a result of tools that will guide phytosanitary discussions between CFIA and trading partners in the context of meeting compliance with Canadian import requirements
- Potential human health allergy effects associated with large scale AGM outbreaks

Risk (Changes in the level of uncertainty over outcomes)

- Reduced losses due to pests
- Improved probability of success of identification so that appropriate regulatory interventions are applied (e.g. diagnostic results available in time for approval for spray programs; spot treatments more likely (dependent on faster diagnostic results))

Time to Final Impacts: 1-5 years

FINAL IMPACTS

Value delivered by outcomes

Economic

- Maintain timber stock due to avoided entry of AGM
- Maintain import and export trade flows for all products that enter and leave via ship

Environmental

- Maintain Canadian forest health

Social

- Maintained economic relations with trading partners (origin identification can lead to bilateral agreements which are more effective)
- Other country adoption of diagnostic technology
- Increased confidence in regulatory processes
- Prevention of health effects (noted above)

Figure 6. Desktop Assessment for Project 2.

Project 3. Ecogenomics of the spruce budworm

The spruce budworm (*Choristoneura fumiferana* Clemens) is a significant defoliator in the Canadian boreal forest, impacting the growth of commercial spruce and fir tree species in eastern North America on a cyclical basis (NRCan, 2016). An outbreak of the budworm is currently occurring in Quebec and is spreading towards Ontario and New Brunswick. In an effort to most efficiently manage the budworm and help minimize impact, the Ontario Ministry of Natural Resources and Forestry (OMNRF) requested the support of this project to help forecast outbreak trajectory. By using molecular markers to characterize genetic structure of spruce budworm populations in Ontario, project scientists can model current and future outbreaks. This information will be provided to the OMNRF, as managers of Ontario forests, to inform spruce budworm management decisions.

Figure 7. Clockwise from top left: Spruce tree; scientist examining foliage for spruce budworm; spruce budworm.

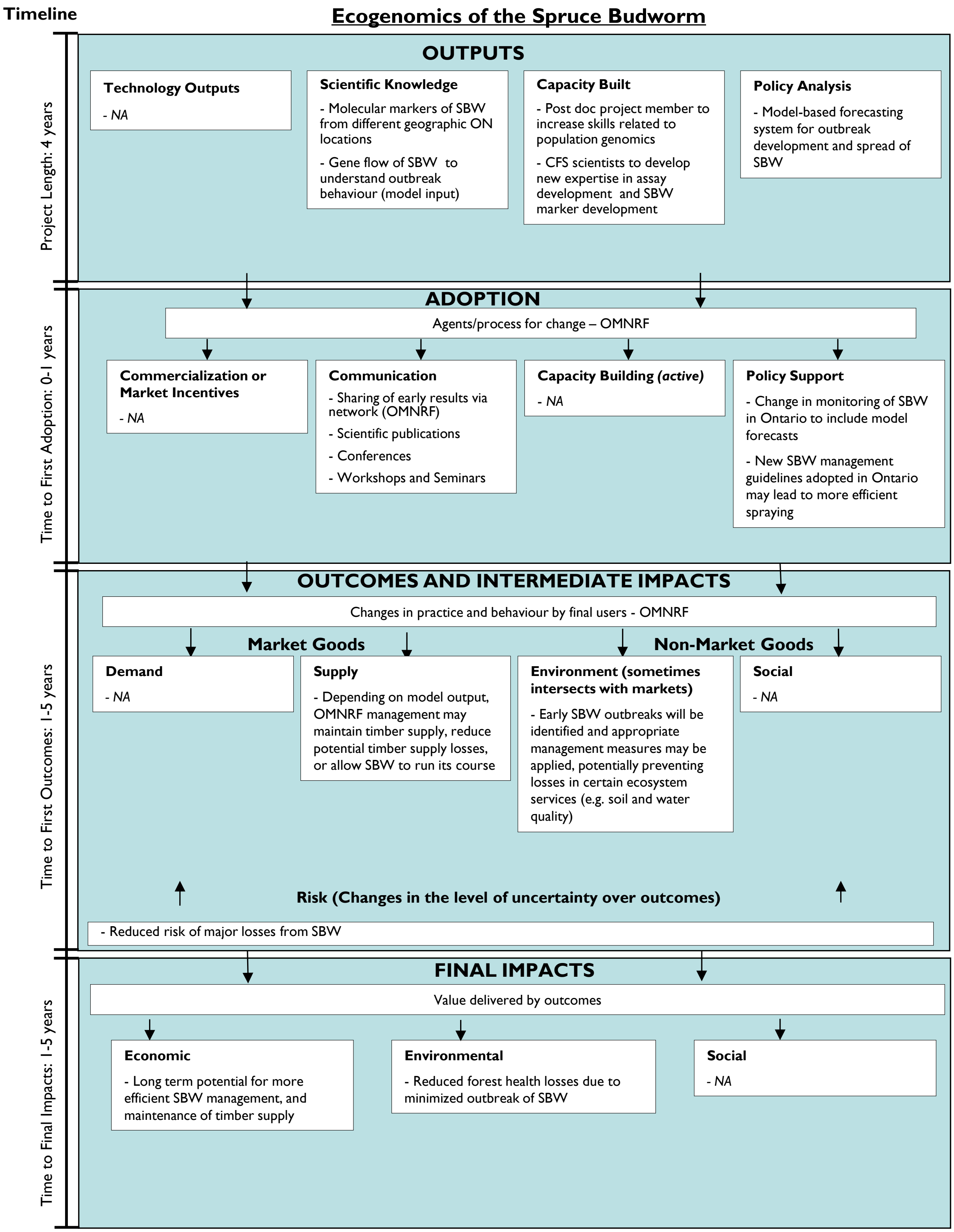

Figure 8. Desktop Assessment for Project 3.

Project 4. Accelerating the discovery of insect volatile attractant molecules with genomics

Trapping insects is generally a reliable means of obtaining information on the presence or absence of an insect and its population levels. In order to be most attractive, the traps use pheromone lures specific to the target insect. Unfortunately, the identification of the insects' pheromone and the compounds within it is a time intensive process dependant on many variables including insect biology. This is a significant hindrance when addressing rapidly evolving insect outbreaks. This project will create a proof of concept method to identify the active compounds that the target insect responds to. This method will make use of genomic tools to examine ten beetle species' molecular sensory receptors, and match the appropriate attractant compound(s). In addition to the proof of concept method, project members will also create a reference library of the target beetles' sensory receptors for future research and use.

Figure 9. Electroantennogram; device to measure antennal response to volatile stimuli.

Timeline

Accelerating the discovery of insect volatile attractant molecules with genomics

Project Length: 4 years

OUTPUTS

Technology Outputs

- New and quicker method of identifying active molecules for lure development for select beetles (~10 species)

Scientific Knowledge

-The identity of the most active attractive molecules for each species of beetle

- **Long term goal**: development of a library of sequenced receptors

Capacity Built

- GLFC staff and (possibly) students (M.Sc. and PhD) project members to build skills related to reverse chemical ecology and genomics

Policy Analysis

- *NA*

Time to First Adoption: 1-5 years

ADOPTION

Agents/process for change – CFS, scientific community, lure development companies

Commercialization or Market Incentives

- Potential for knowledge of active compounds for use in lure traps to be patented but not currently planned

Communication

- Sharing of early results with team members

- Scientific publications

- Conferences and webinars

Capacity Building *(active)*

- *NA*

Policy Support

- Changes to monitoring and trapping practices and guidelines

Time to First Outcomes: 1-5 years

OUTCOMES AND INTERMEDIATE IMPACTS

Changes in practice and behaviour by final users - provincial forest managers, CFIA

Market Goods

Demand

- *NA*

Supply

- Prevent decreases in timber supply due to faster lure development and subsequent pest management response

Non-Market Goods

Environment (sometimes intersects with markets)

- Faster identification of lure compounds for unwanted beetles, faster placement of traps and subsequent pest management responses which results in maintenance of forest species

Social

- *NA*

Risk (Changes in the level of uncertainty over outcomes)

- Reduced probability of currently undetectable invasive beetles entering Canada
- Reduced timber losses to pests
- Potential to reduce pest management costs

Time to Final Impacts: 1-5 years

FINAL IMPACTS

Value delivered by outcomes

Economic

- Maintain timber stock due to time advantage as a result of faster identification of active compounds for use in lure, and subsequently faster management response

Environmental

- Maintain forest health due to faster identification of active compounds and lure production, and subsequently faster forest management response (preventative)

Social

- *NA*

Figure 10. Desktop Assessment for Project 4.

Project 5. Developing the next generation bio-surveillance tools for tracking and preventing forest pest invasions

Monitoring for potential pests (native or exotic) can be a difficult and expensive task. This project arose from a request by the CFIA for more information on a particular group of problem species to support their monitoring efforts. Making use of next generation genomic sequencing tools, the project scientists will generate a reference database of outbreak maps, DNA barcodes and genomic data to support the CFIA. In addition, project members will be developing a proof of concept portable detection system for *Phytophthora ramorum*, the pathogen that causes sudden oak death (SOD). A portable detection system may eliminate the need for costly laboratory detection.

Figure 11. Top photo: healthy forest; Bottom photo: forest damaged by an insect infestation.

Developing the next generation biosurveillance tools for tracking and preventing forest pest invasions

Timeline

OUTPUTS

Project Length: 4 years

Technology Outputs
- New method to detect and monitor select pests using next generation sequencing (pests include AGM, EAB and DED)
- Portable detection system for forest pests (proof of concept)

Scientific Knowledge
- Enhanced reference collections (digital records, Maps of disease outbreak routes, DNA, Barcodes, genomic profiles, metadata) for target species

Capacity Built
- Project members (post docs) to increase capacity related to next generation sequencing for diagnostics and monitoring

Policy Analysis
- *NA*

ADOPTION

Time to First Adoption: 1-5 years

Agents/process for change: CFIA, provincial governments, NPPOs (USDA-APHIS)

Commercialization or Market Incentives
- Potential for portable detection system to be patented

Communication
- Sharing of early results with team members
- Scientific publications
- Conferences
- Workshops
- Raise awareness of project results with FP Innovations, and FAO IPPC through A. Uzunovic)

Capacity Building *(active)*
- Training of CFIA and National Plant Protection Organizations (NPPOs)

Policy Support
- Changes CFIA practices and guidelines regarding phytosanitary approaches

OUTCOMES AND INTERMEDIATE IMPACTS

Time to First Outcomes: 1-5 years

Changes in practice and behaviour by final users: CFIA, provincial governments, industry (JDI)

Market Goods

Demand
- *NA*

Supply
- Maintain timber supply by preventing entry and/or establishment of target organisms
- Maintain export levels of wood products due to prevention of organism establishment

Non-Market Goods

Environment (sometimes intersects with markets)
- Maintained existing forest ecosystem services through prevention of entry of AGM and *Phytophthora*
- Limit impact on forest ecosystem services by minimizing spread of EAB, DED, WPBR, and other root rot diseases (*Annosus*)

Social
- Increased trust in regulatory response to target organism
- Improved bilateral trading relationships through the application of tools to reduce phytosanitary risks

Risk (Changes in the level of uncertainty over outcomes)
- Risk of targeted exotic organisms becoming established in Canada is reduced
- Risk of targeted organisms spreading in Canada is reduced

FINAL IMPACTS

Time to Final Impacts: 1-5 years

Value delivered by outcomes

Economic
- Prevented losses in timber supply by preventing organism outbreak

Environmental
- Maintain forest health through improved detection and monitoring of target organisms

Social
- *NA*

Figure 12. Desktop Assessment for Project 5.

Project 6. Applied genomics for tree breeding (Genomics Applied Partnership Program - GAPP) and new applications

Traditional tree breeding approaches of ensuring high quality tree stock are time consuming, requiring sufficient seedling growth (approximately15 years) prior to testing. This project uses unique genomic methods to test seedlings as young as one year for key traits in white spruce (e.g. height, wood density, etc.) thus reducing the time required to identify the key genotypes. The genomic methods are targeted to the needs of some specific forest product producers, and a strategy to encourage additional forest product producers to participate will be developed. This project will also produce a library of genetic traits that correspond to other desired characteristics (i.e. drought and pest resistance). The final phase of this project will assess the CFS's capacity to perform genomic "fingerprinting" to identify and differentiate Canadian spruce species. This "fingerprinting" technique can be used in the future to detect mislabeled tree species and address imports of illegally logged timber products.

Figure 13. Clockwise from top left: Spruce seedlings; mature spruce tree; spruce cones.

Timeline

Applied genomics for tree breeding (GAPP) and new applications

Project Length: 4 years

OUTPUTS

Technology Outputs

- Unique models to identify optimal tree stock based on genomic profiles for individual users (Québec and New Brunswick provincial governments, JDI)

Scientific Knowledge

- Catalogue of phenotypes for drought and insect resistance trees for use in genomic selection

Capacity Built

- Post Doc. and undergrad students will increase their tree genomics skills
- Inventory of capacity to identify species level "DNA fingerprints" of native spruce species

Policy Analysis

- Through GAPP project, development of "User Marketing Strategy" which includes economic and market analyses for various implementation scenarios, also the development of user uptake models

Time to First Adoption: 1-5 years

ADOPTION

Agents/process for change: provincial governments, industry

Commercialization or Market Incentives

- *NA*

Communication

- Sharing of early results with team members
- Scientific publications
- Conferences

Capacity Building *(active)*

- Transfer of genomic profiles/prediction models to end-users (GAPP) Meetings (Jan 2016) with "Extended User Group" to share approach and results for future uptake by non-participating provinces (AB, BC)

Policy Support

- *NA*

Time to First Outcomes: 5-10 years

OUTCOMES AND INTERMEDIATE IMPACTS

Changes in practice and behaviour by final users: provincial governments, industry, CBSA

Market Goods

Demand

- *NA*

Supply

- Increased supply in high quality spruce seedlings
- Increased supply of drought resistant and pest resistant spruce seedlings

Non-Market Goods

Environment (sometimes intersects with markets)

- Offset tree mortality from pests and climate change drought effects from planting resistant trees

Social

- *NA*

Risk (Changes in the level of uncertainty over outcomes)

- Reduced risk of trade disputes on origin of Canadian spruce exports
- Reduced risk of losses of white spruce due to drought or insects

Time to Final Impacts: 10 + years

FINAL IMPACTS

Value delivered by outcomes

Economic

- Cost savings for breeders by having their select trees sooner than via traditional breeding techniques

Environmental

- Maintain forest health due to avoided losses to drought and insects
- Increased forest resilience due to inclusion of 'select' spruce trees

Social

- Avoid trade disputes with export countries regarding wood identification or origin of Canadian wood products (for native spruce species)
- Increased confidence in proving origin of Canadian spruce exports

Figure 14. Desktop Assessment for Project 6.

Project 7. Development of a molecular method to detect living *Phytophthora* spp. of phytosanitary concern in wood

The import of harmful pests into Canada is of major concern to the forest products industry, and Canadian trade in general. *Phytophthora spp.* (plant damaging organisms) is currently not in Canada but is present in the United States. Should *Phytophthora* become established in Canada, it is likely that Canadian exports of wood products would be subject to trade barriers. The aim of this project is to develop a method of detecting whether the pathogen is alive or dead in samples that have tested positive. Furthermore, novel phytosanitary treatments to replace methyl bromide, the standard product currently used and a known ozone depleter, are under development. The effectiveness of these novel treatments is unknown. The ability to test whether a pathogen, such as *P. ramorum*, is living or dead will provide crucial information on the efficacy of these novel treatments.

Figure 15. Clockwise from top left: Processed lumber; raw logs; ship docked at port.

Development of a molecular method to detect living *Phytophthora* spp. of phytosanitary concern in wood

Timeline

Project Length: 3 years

OUTPUTS

Technology Outputs

- New molecular method (RT-qPCR) to identify the state (living vs dead) of four species of *Phytophthora* of phytosanitary concern

Scientific Knowledge

- Library of markers from nuclear genes for four *Phytophthora spp* (*P. ramorum, P. cinnamomi, P. lateralis, P. alni*)

-Effectiveness of novel wood commodity (sawnwood, chips, logs, etc.) treatments (by applying new method) for eradication of *Phytophthora* spp.

Capacity Built

- Student (a co-op and a M.Sc. student) project members increase skills related to marker development for *Phytophthora* spp. and other pathogen species of concern

- Network collaborators (CFIA to validate molecular method)

Policy Analysis

- *NA*

Time to First Adoption: 1-5 years

ADOPTION

Agents/process for change: CFIA, FPInnovations (treatment development)

Commercialization or Market Incentives

- *NA*

Communication

- Sharing of early results with team members
- Scientific publications
- Conferences
- Webinars, Presentations
- Raise awareness of new method with CFIA through Chair of International Forestry Quarantine Research Group (Eric Allen)
- Raise awareness of project results with FPInnovations and FAP, IPCC, through A. Uzunovic

Capacity Building (*active*)

- Training for CFIA lab specialists

Policy Support

- Change in International Plant Protection Convention (IPPC) protocol for *Phytophthora spp.*

-Pitch changes in protocols to NAPPO collaboration

Time to First Outcomes: 1-5 years

OUTCOMES AND INTERMEDIATE IMPACTS

Changes in practice and behaviour by final users: CFIA, industry, potential for other NPPOS

Market Goods

Demand

- *NA*

Supply

- Maintain imports of ornamental product supply (Products that test positive for *Phytophthora*, but is shown to be dead, can be imported)

Non-Market Goods

Environment (sometimes intersects with markets)

- Reduce ozone depletion by eliminating the use of methyl bromide for *Phytophthora* treatments

Social

- Improved trading relations as a result of tools that will guide phytosanitary discussions between CFIA and trading partners in the context of meeting compliance with Canadian import/export requirements

Risk (Changes in the level of uncertainty over outcomes)

- Reduced risk of destruction of ornamental plants identified as positive for *Phytophthora*, but contain dead *Phytophthora*

Time to Final Impacts: 1-5 years

FINAL IMPACTS

Value delivered by outcomes

Economic

- Knowledge of wood treatment effectiveness allows for continued exports

- Maintenance of ornamental trade flows

Environmental

- Maintain forest health (avoided *Phytophthora* spp. presence)

Social

- Confidence in regulatory system for phytosanitary issues

- Increased trust in the safety of Canadian wood product exports (related to novel wood treatment approaches)

Figure 16. Desktop Assessment for Project 7.

Project 8. Genomics-assisted tree breeding for improving remediation of disturbed forest ecosystems

White pine blister rust (WPBR - *Cronartium ribicola*) has plagued five needle pine species in Canada for approximately 100 years, causing mortality and a decline in commercial five needle pine species such as eastern and western white pine (*Pinus strobus* and *Pinus monticola*). Although WPBR is somewhat manageable through silvicultural practices, forest managers, governments and conservation agencies have been seeking WPBR resistant pines with the intent of restoring five needle pine species on the landscape. The purpose of this project is to use genomics to identify and understand WPBR resistance mechanisms in four five needle pine species (western white pine, limber pine, whitebark pine, and eastern white pine). Genomics will allow for the identification of individuals that are fully resistant or partially resistant to WPBR, enabling more informed breeding and planting decisions. The project will additionally be producing a library of genomic markers for resistance in the species.

Figure 17. Clockwise from top left: White pine seedlings; mature white pine over-story; white pine blister rust infecting a pine tree.

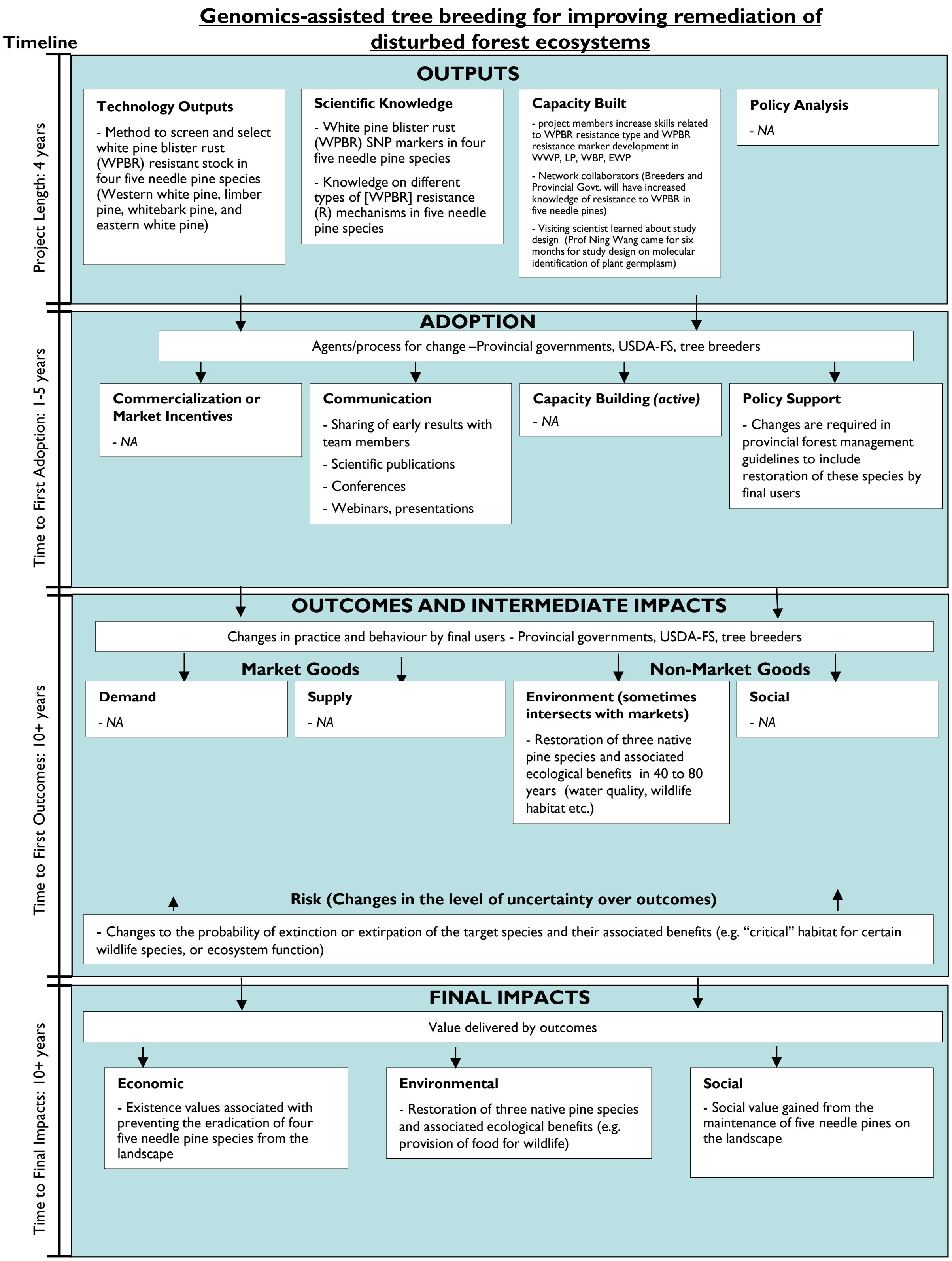

Figure 18. Desktop Assessment for Project 8.

Project 9. An early detection tool for emerald ash borer (EAB) and ash resource protection

EAB (*Agrilus planipennis* Fairmaire) is an invasive non-native insect species, inadvertently introduced into Canada in 2002. EAB larvae have ultimately killed millions of infested ash trees, resulting in devastating losses of ash trees across eastern North America. It is likely to continue its spread across the continent. The loss of ash trees across southern Ontario and Quebec has been highly visible, and garnered much public attention. Unfortunately few options are available for EAB treatment in Canada. This project seeks to develop knowledge that can be used to help slow the spread of EAB. A primary output will be a genomic based diagnostic method to identify different species of ash trees. The majority of municipalities are not able to distinguish between ash species, and so have no means to identify possible resistance. In an effort to improve future EAB detection, the project will identify genomic signatures indicating the presence of EAB prior to any physical symptoms. The project will also examine compounds produced by EAB that trigger a defensive response in ash trees. Finally, the project will produce a library of markers within the ash tree genome that could lead to the detection of a gene for resistance.

Figure 19. Clockwise from top left: Damaged ash trees; emerald ash borer; emerald ash borer trap in an ash tree.

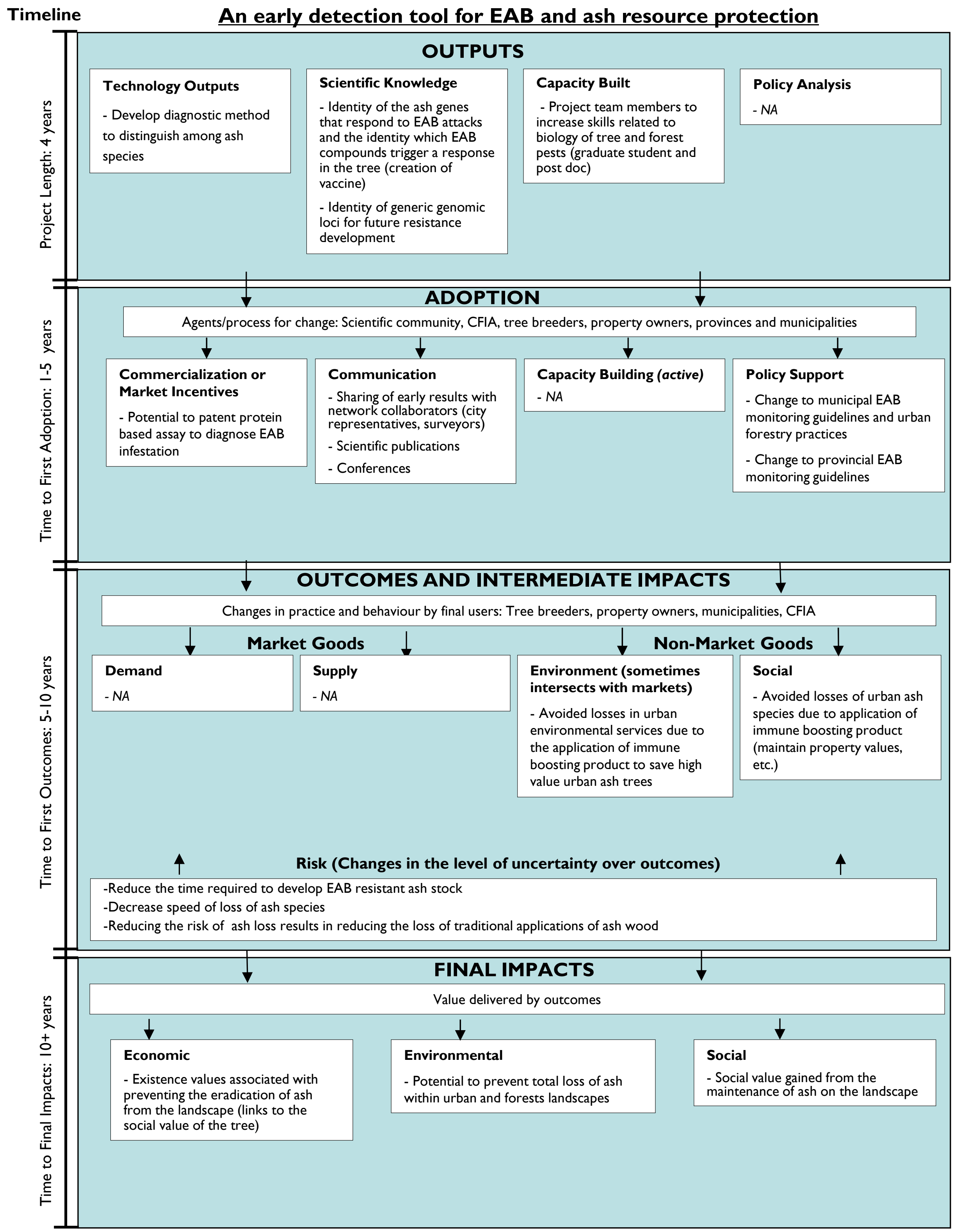

Figure 20. Desktop Assessment for Project 9.

Project 10. Innovative land reclamation approaches following oil sands mining: a phytoremediation approach based on tree-soil microbiome interactions

Oil sands companies in Alberta have committed to restoring land to a functioning ecosystem after oil extraction is complete. Restoration is an expensive process, and will likely influence social acceptance of oil sands operations. The goal of this project is to improve the remediation process for oil sand soils, focusing on the relationship between soil microbes and different varieties of aspen trees planted on three sites: oil sands, disturbed forest and natural forest. This project will develop a method to monitor tree-microbe interactions, and will evaluate the aspen varieties based on the associated microbes best suited for sustainable tree growth. This project will also evaluate the potential for inoculating tree seedlings with soil microbes for accelerated remediation.

Figure 21. Top Photo: Landscape to be reclaimed; Bottom Photo: Scientist collecting soil samples from oil mined landscape.

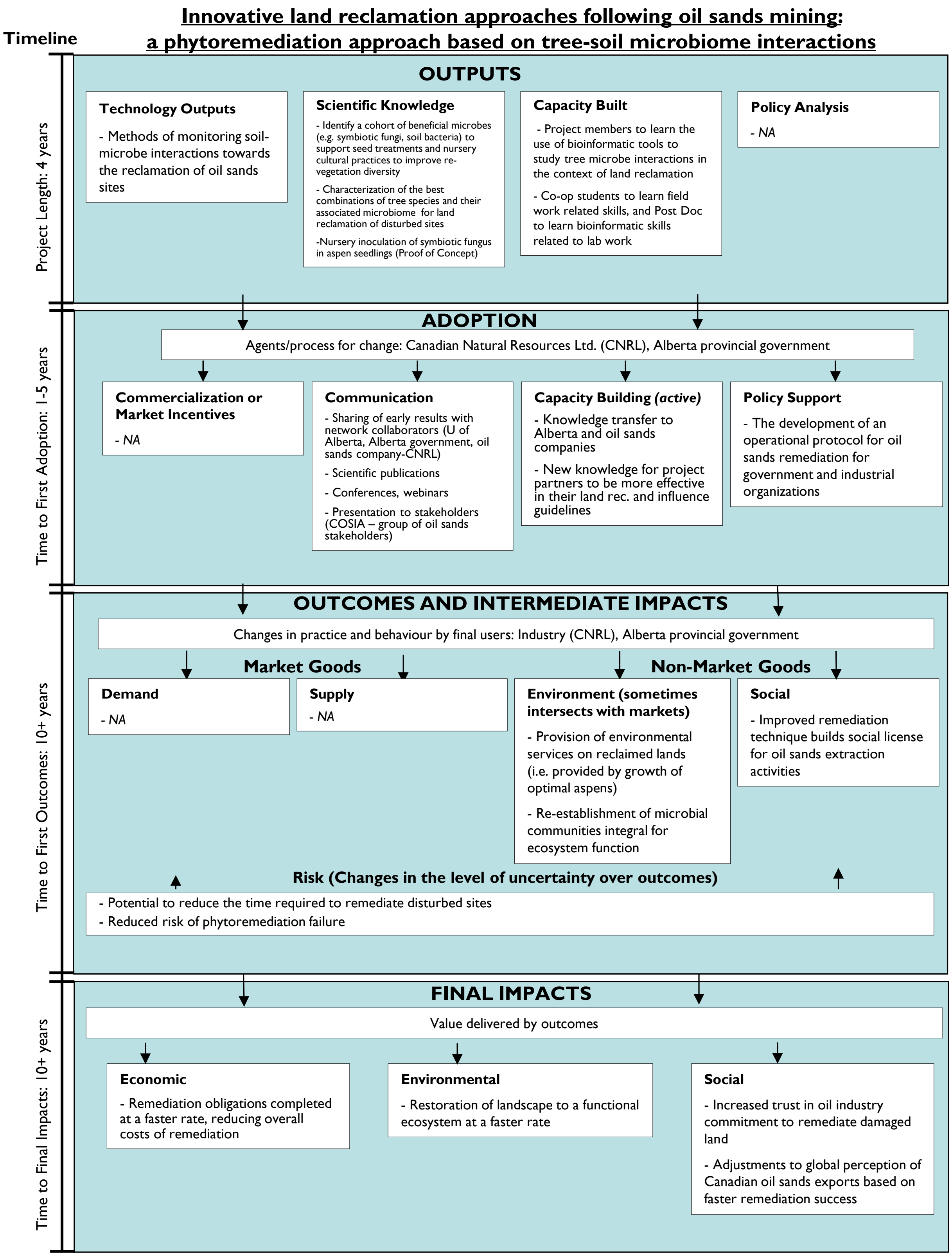

Figure 22. Desktop Assessment for Project 10.

Project 11. Developing molecular and environmental genomic approaches for microbial and invertebrate communities to assess ecosystem integrity in forest management.

Forest product producers are facing increasing pressure to demonstrate the sustainability of their harvesting practices, and many producers make use of forest certification processes to validate their management practices. This project, motivated in part by a request from a forest product producer, seeks to develop a genomics-based method to assess the effect of various silvicultural practices on key soil microbes and invertebrates. The developed method is intended to be used by forest managers to identify sustainable practices that support forest certification. Additionally, the project will identify profiles of aquatic and terrestrial microbes and invertebrates under various forest management practices to gauge the impact of different harvesting processes.

Figure 23. Aquatic and terrestrial ecosystems.

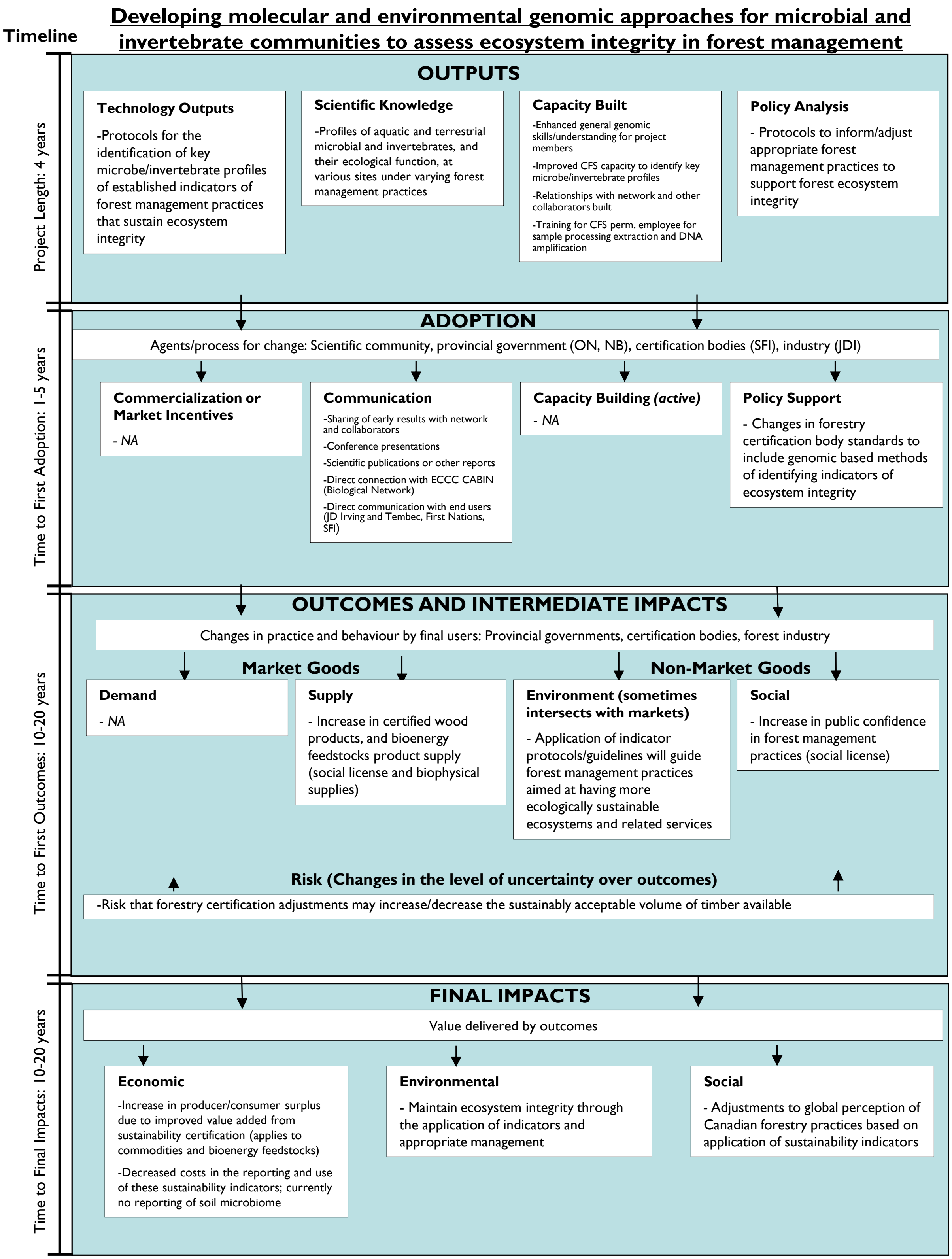

Figure 24. Desktop Assessment for Project 11.

Survey Results

While the Desktop Assessments provide high level summaries of the projects and potential adoption and impacts, the PRIUS surveys provide a greater level of detail, and allow a more thorough examination of the outputs expected from each project.

The survey starts by obtaining information about the project in general, identifying targeted geographic and ecological regions, expected impacts, forest management-related motivational factors and what, if any, type of sustainability objectives are involved. The second phase of the survey seeks detailed information about the project outputs that show the most potential for impact. For brevity (and to a larger extent, realism), we have limited the survey to examine at most three major outputs. Questions for each output are intended to gather information on next and final users of the output, positive and negative factors that may influence adoption, anticipated social, environmental and economic impacts, and current and anticipated levels of adoption.

These survey results provide useful information for comparing and contrasting the GRDI projects, and a starting point for a database of research project outputs and impacts. In the longer run this kind of database could also be used to identify important issues such as dominating research areas and gaps, evaluate the nature of the most common types of outputs produced from different projects, and estimate anticipated adoption rates, etc.

Summary Observations

Project Funding: The eleven projects will receive approximately $4 million from the GRDI over four years, with roughly $1 million in funding scheduled each year. These totals do not include any in-kind contributions made by research partners or externally sourced funding. Approximate breakdowns by project are contained in Appendix 1.

Target Areas and Motivating Factors: At the project level, eight of the eleven GRDI projects (~70%) focus on delivering tools and methods that can be used to minimize or prevent forest pest disturbances. Many of these projects have the potential to impact large portions of the country as they examine issues affecting entire species and pest host ranges, and may have international trade implications. Although these project outputs may have broad implications across the country, to add validity and precision, we have identified impacted regions as those in which the disturbance is primarily expected to occur. As such, the forested regions in Canada specifically targeted by these projects include the Great Lakes-St. Lawrence forest region (6 projects), the Boreal forest region (5 projects), followed by the Coastal (4 projects), Montane (3 projects), Subalpine (3 projects), and Columbian regions (3 projects); note that each project may select more than one forested region as the area of focus. Not surprisingly, the key motivating drivers identified for these research projects fit within the context of forest disturbances, one of NRCan's Environmental Stewardship corporate objectives.

The remaining three projects examine aspects of innovation in the forestry sector, forest product markets, and forest ecosystems. These projects take place in select provinces and the outputs are generally geared more towards local/regional issues, but in principle could have broader applicability. The forested regions likely to be impacted by these projects include the Coastal (1 project), Montane

(1 project) and Subalpine (1 project) forests, the Acadian forest (1 project), and all forested regions (1 project). The Forest/Forestry-related motivating drivers behind these projects appropriately focus on Forest Productivity and Trade, and Forest Regeneration and Silviculture. Table 1 illustrates a breakdown of these motivating drivers across all projects (in some cases more than one motivating driver was identified for each project).

Table 1: The motivating drivers behind each project, as identified by project leads

Motivating Drivers	***Number of Projects***
Forest Regeneration and Silviculture	3
Harvest Systems and Techniques	1
Forest Inventory	1
Forest Planning	0
Forest Policy and Management	2
Forest Monitoring	4
Forest Productivity and Trade	4
Fire Management	0
Forest Road and Transportation	0
Communications and Technology Transfer	0
Forest Biodiversity: Plants	1
Forest Biodiversity: Wildlife	1
Forest Health: Insects	3
Forest Health: Diseases	1
Forest Health: Other	0
Forest Health: Invasive Species	3
Forest Ecosystem Functioning	2
Forest New Product Development	0
Forest Based Bioenergy	0

Output Types: Examining the individual outputs produced by each project has yielded useful summary information regarding the type of outputs, and the impacts expected from these outputs. In keeping with the underlying structure of the desktop assessment, outputs are classified into one of four categories: Technology, Capacity Building, Policy Analysis and Scientific Knowledge. Of the 31 outputs identified, 15 are categorized as scientific knowledge, and eleven are considered technological outputs. The remaining outputs are divided between policy analysis (4 outputs) and capacity building (1 output).

Users: The identified users of these outputs are broken into two groups; next users are, more often than not, project collaborators and are likely to adopt the output sooner while final users are those who are likely to adopt the output once it has been successfully demonstrated. The most commonly identified next user groups include Government Organizations (19 outputs), Other Scientific Researchers (11 outputs) and the Forestry Industry (8 outputs). Over half of the outputs are intended for final use by some level of government, be it federal, provincial or municipal. Within the Federal GoC , the CFIA (6 outputs) and the CFS (6 outputs) are the most common users of GRDI project outputs. There are also a number of project outputs intended for use by Forestry Industry. This highlights the collaborations that are occurring between GRDI projects, and industry representatives. Figure 25 illustrates the proportion of final users identified for all of the project outputs.

It should be noted that we have only allowed the identification of the CFS itself as a next/final user in very specific circumstances. For this to be the case, outputs must be used for a purpose other than the continuation of the original research project. For example, if a new method of identifying trapped insects was developed, the CFS could be considered an output user.

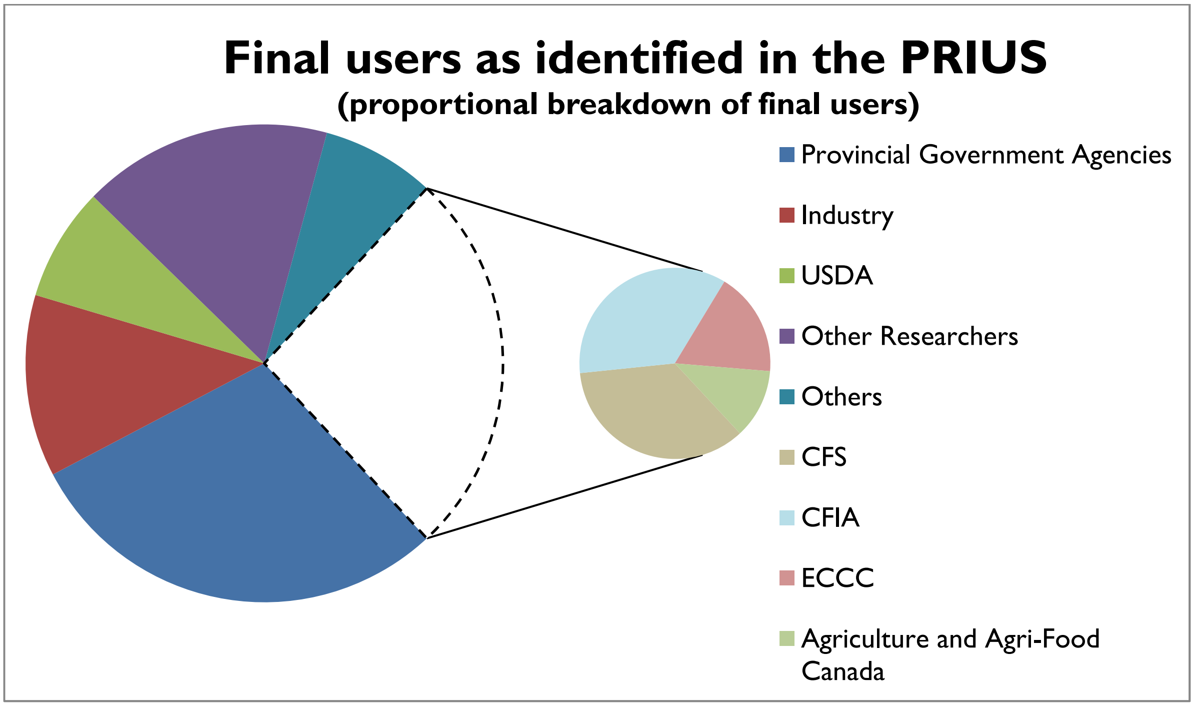

Figure 25. The proportional breakdown final users for each output, divided into six categories, with an additional 4 sub-categories identified for federal government agencies - USDA (United States Department of Agriculture), CFIA (Canadian Food Inspection Agency), and ECCC (Environment and Climate Change Canada).

<u>Influential Factors:</u> Identified users typically have strong incentives to adopt the project output. These users are generally involved in the project as participants or collaborators, or have approached the research team with a stated need. Often there are clear financial gains from adoption of outputs. For example, adoption of technology outputs may produce financial gains through increases in organizational efficiency. Direct answers to users' policy needs may not have immediately obvious financial gains but are targeted at improved decision-making for issues of pressing concern. Adoption of scientific knowledge outputs is often encouraged through exposure of the work via journal articles, workshops, seminars and conferences. Figure 26 identifies the positive factors influencing output adoption that have been identified by the project leads.

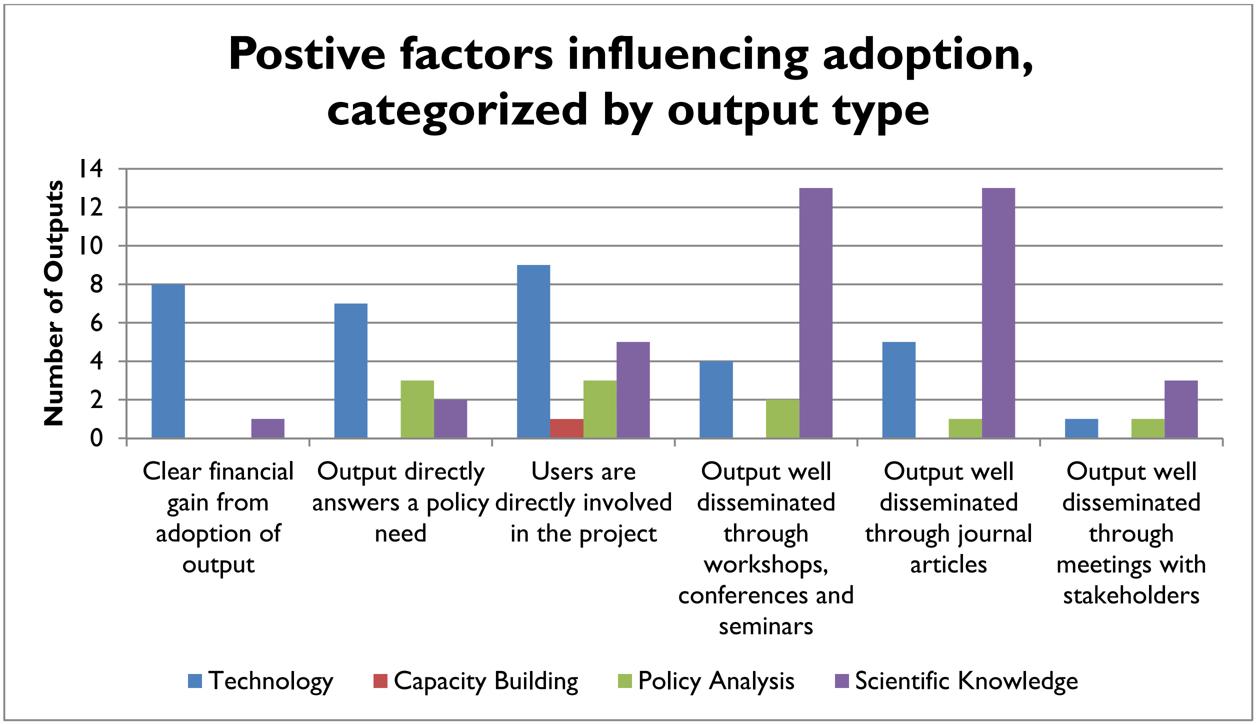

Figure 26. The number of outputs, categorized by output type, identifying select positive factors influencing adoption, as identified by project leads.

In addition to positive influential factors, negative influential factors have also been identified. The most commonly cited negative influence on adoption noted by project leads was the possibility of a lack of confidence (e.g. uncertainty) or complexity associated with the output. Additionally identified negative factors included the potential lack of demonstration in the claimed results, and a limited ability to satisfy the high skills capacity an output requires. Figure 27 shows the proportions of potential negative factors influencing adoption, as nominated by project leads.

Anticipated Impact Pathways: The paths between project output and impact are somewhat more easily traced for technology, capacity building and policy analysis type outputs than changes in the stock of scientific knowledge. In the latter case impacts are generally more uncertain and difficult to attribute to a single project. Hence, for the purposes of this analysis, we have not identified impacts for scientific knowledge in the majority of cases. Projects impacts were categorized as: 11 – social-related, 23 – environment-related, and 33 – economic-related.

Expected Impacts: The eleven GRDI projects are all intended to protect forest services in some way. Accordingly, a social impact stemming from each project could perhaps be argued to include the intergenerational transfer of improved forest health and subsequent community well-being. This could be the case if the projects are successful and similar projects would not have been undertaken or achieved parallel goals. These potential impacts, while important, are again not easily attributable to any one project, and are therefore not captured by our survey in a detailed manner. It could be argued that research projects *per se* are not the most efficient or effective way to achieve these types of social goals.

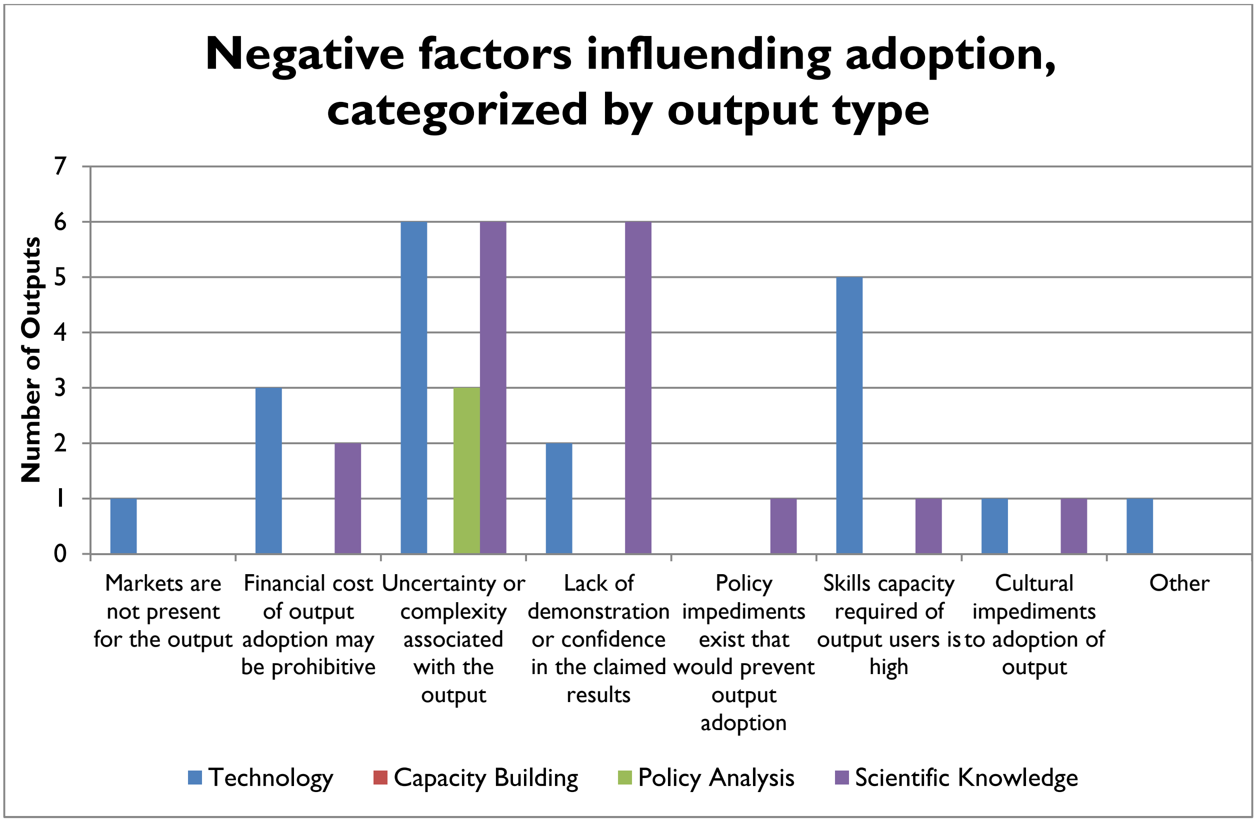

Figure 27. The number of outputs, categorized by output type, identifying select negative factors influencing adoption as identified by project leads.

Expected impacts, are broken down into general sub-categories within the social, environmental and economic types of impacts and shown in Figures 28-30. Within the social category, the majority of possible impacts were classified "other", which included such things as increased public confidence in forest management practices and regulations, and maintenance of trade relationships. Human health impacts were also identified as possible outcome of some projects. In terms of environmental impacts, most identified effects were associated with forest health (e.g. forests not being subjected to new alien species). Economic impacts were primarily expected to include increased organizational efficiency (e.g. cheaper or more effective pest surveys), and reductions in risk associated with the supply and/or demand of forest products. Over time, further sub-categories may be added to the survey template to provide additional elaborations.

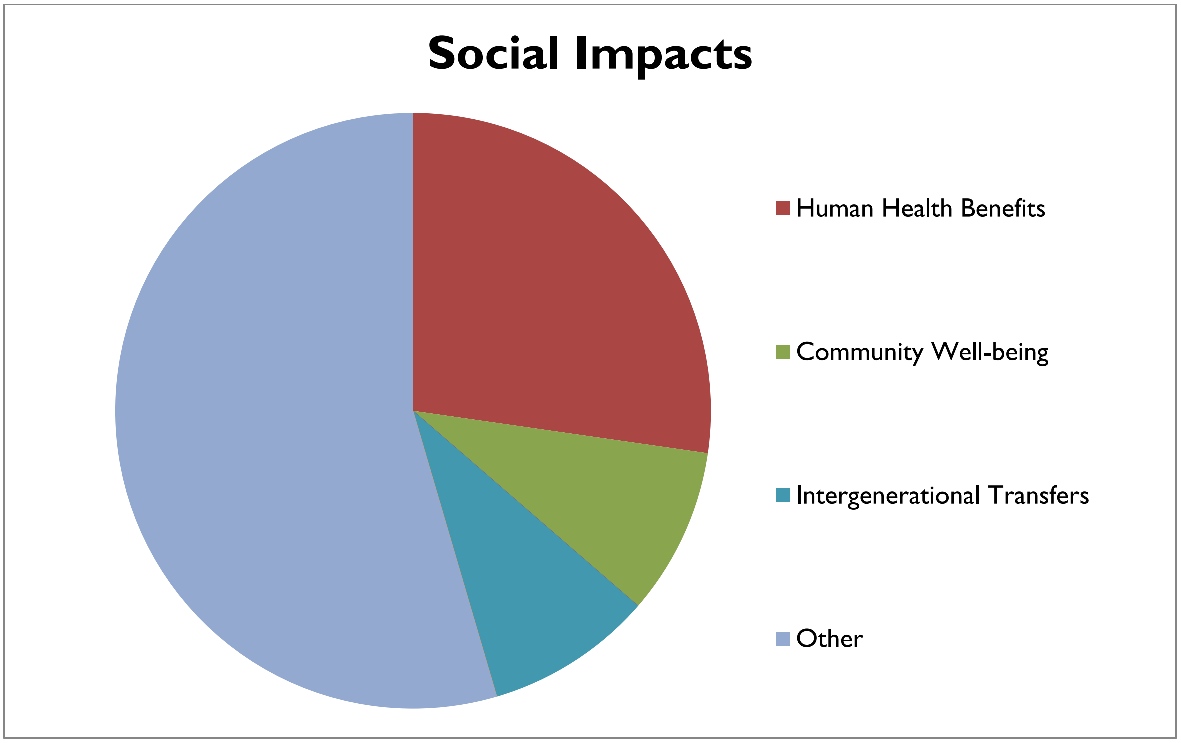

Figure 28. A proportional breakdown of the social impacts identified for each output into four categories, as identified by the project leads.

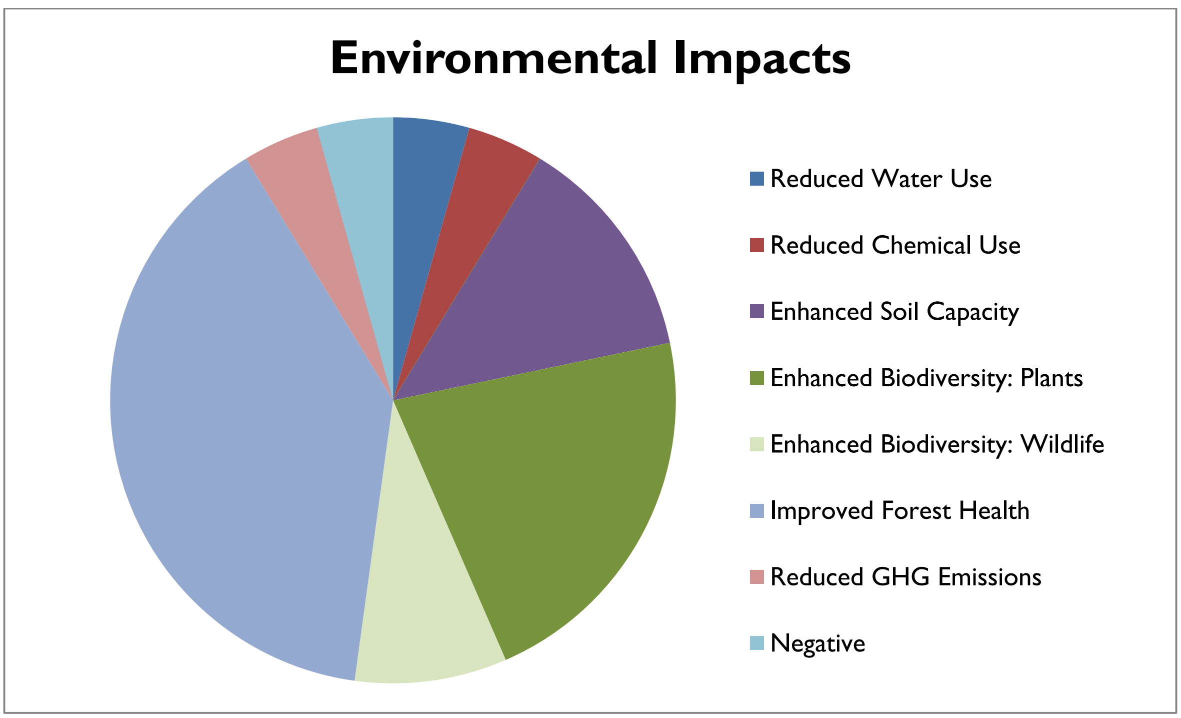

Figure 29. A proportional breakdown of the environmental impacts identified for each output into eight categories, as identified by the project leads.

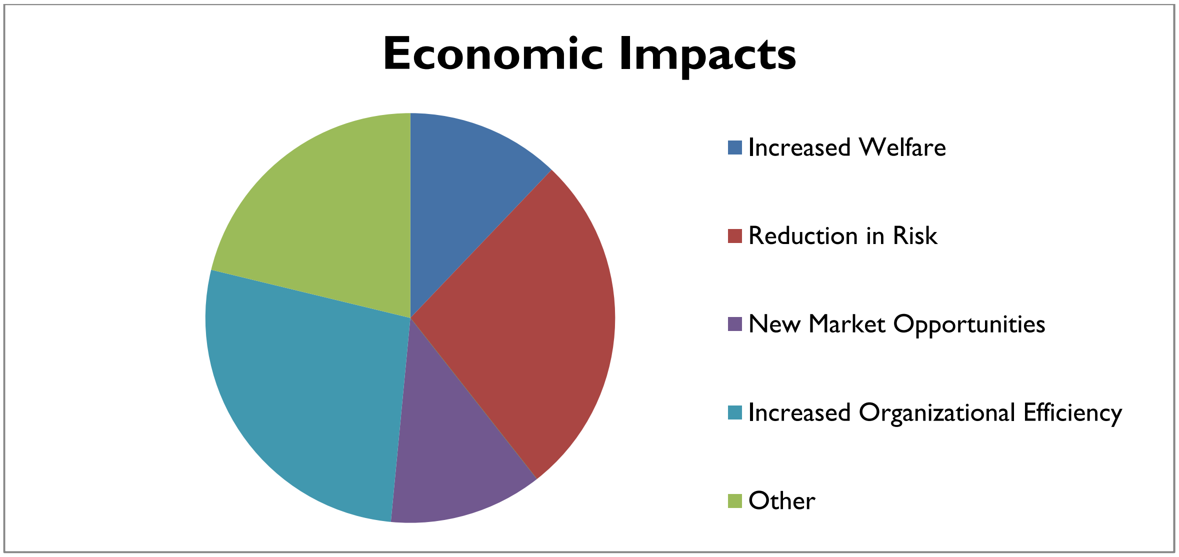

Figure 30. A proportional breakdown of the economic impacts identified for each output into five categories, as identified by the project leads.

<u>Impact Lag Time:</u> The final section of the PRIUS survey gathered expectations on adoption, including anticipated lags between output completion and observed impacts. These data are intended to provide a consistent articulation of expected adoption rates. Most proponents anticipated a very high rate of adoption of project outputs, with over 70% of the identified final users adopting the outputs (20 outputs) (see Figure 31). This may be reasonable given the targeted nature of many projects and the close collaborations with users.

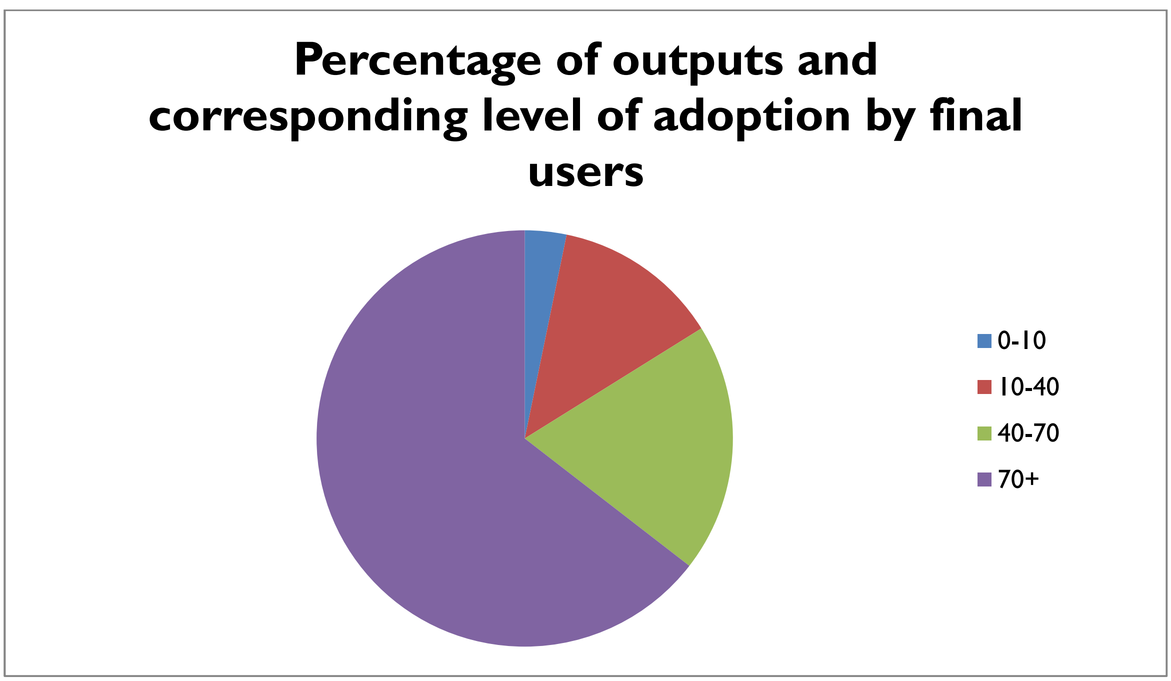

Figure 31. Proportional breakdown of the percentage of final users likely to adopt the output, as identified by the project leads.

Figure 32 illustrates the breakdown of output types and the associated time between output adoption and anticipated impact. The majority of technological and scientific knowledge-type outputs are expected to have impacts within five years of adoption. Note that we have defined scientific knowledge impact as members of the scientific community accessing published journal articles, reports and presentations, etc. and having this work influence their own research efforts. Recall a major challenge is attribution of broader-scale societal impacts from changes in the stock of scientific knowledge.

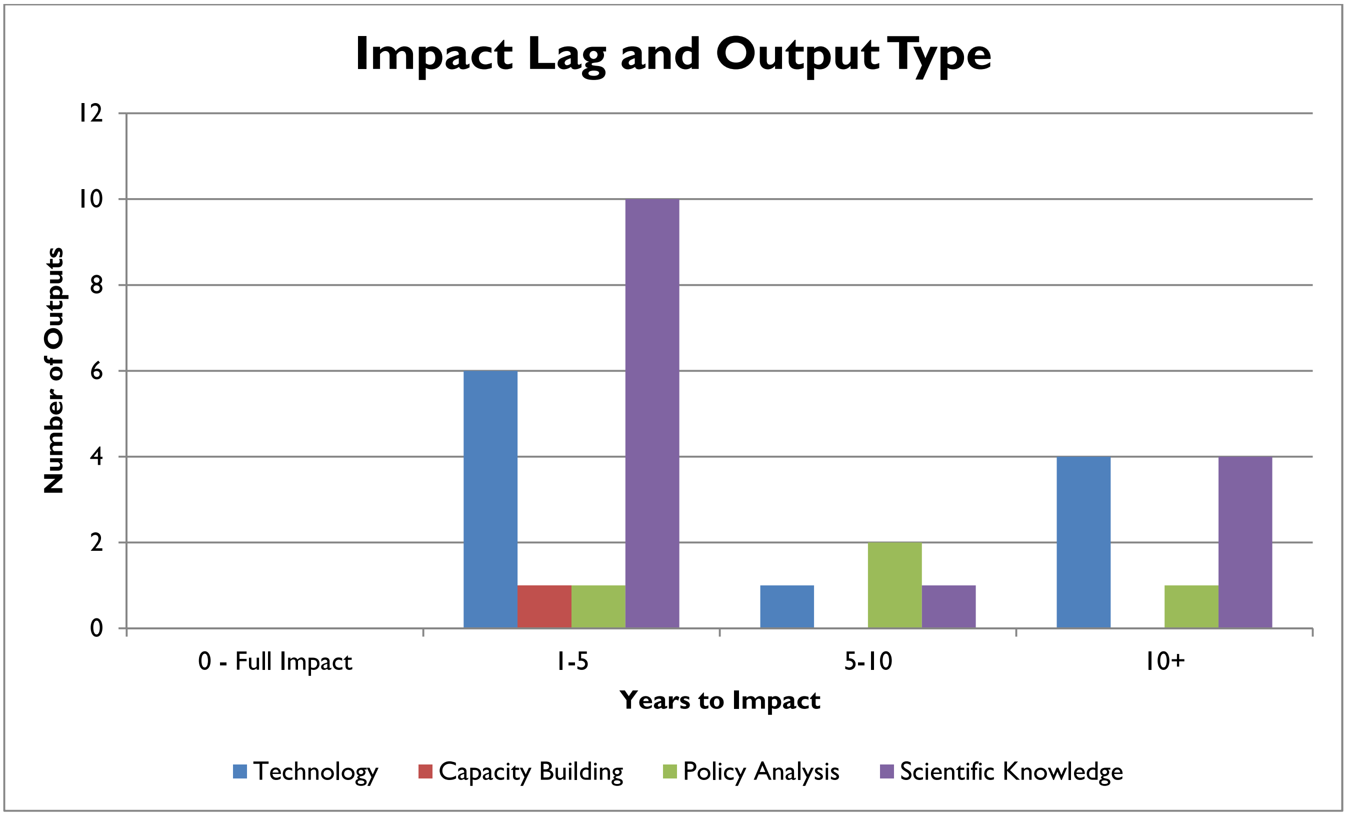

Figure 32. The number of project outputs categorized by output type that have been identified to have an impact lag of 1-5 years, 5-10 years, or 10+, as identified by project leads.

Concluding Comments

The need to assess the potential impacts of government-based scientific research is not a new phenomenon, but is increasingly considered a necessity to justify such investments. Here we have applied a consistent and tested approach to analyze and evaluate a set of ongoing GRDI projects. This approach includes 1) the use of a descriptive one-page summary (i.e. Desktop Assessment), which helps lay out the pathway between project outputs and the anticipated social, environmental and economic impacts and 2) a more intensive, detailed survey to gather specific project output information, including data on expected output users, rate of uptake, timelines to adoption, and impacts. This helped create consistent thinking about the relationships between research projects and impacts.

Specific conclusions include:

- A large number of collaborators and users are directly involved in many projects. These are often arising from direct requests of users, and involve tight linkages with partner institutions/organizations.
- Most users are associated with some level of government (Federal organizations such as the CFIA or CBSA, provincial ministries like the Ontario Ministry of Natural Resources and Forestry, and municipal governments looking to improve their forest management). This is an implicit demonstration of the public good nature of many of the projects. However several projects also involve industrial partners hence could also be expected to generate benefits for the private sector.
- Of the eleven projects, six can be considered exploratory and have proof of concept outputs. Uncertainty associated with these projects was occasionally listed as a negative factor influencing the potential adoption of the output. We note that fundamental and high risk projects may have large impacts even though attribution can be difficult. There is a strong economic rationale for government funding of this type of science because there is little market-based incentive for the private sector to undertake such research.
- Project outputs are anticipated to generate a variety of impacts that align with NRCan/CFS priorities to promote forest sector competitiveness, advance environmental leadership, and optimize forest value. Across all projects, the impacts most commonly identified are economic (49%) and support the Canadian forest sector through improvements in organizational and industry efficiency in work practices, and reductions in risk to product market demand or supply. The environmental impacts identified, although fewer in number (34%) often focus on forest health. The few social impacts (16%) that were identified are generally related to relationships associated with trade agreements. Taken together, this set of projects provides what would appear to be a reasonable mixed portfolio of primarily economic and environmental impacts.

GRDI projects support innovation for the forestry sector, forest product markets, and forest ecosystems. Although these projects often focus on specific areas of the country, given the nature of the problems being addressed they should also have national impacts once completed. It is anticipated that other government organizations will make the most use of the outputs, followed by other scientific researchers and the forestry industry. These users are likely to adopt project outputs based on potential financial gains, and the potential to use outputs to address a policy requirement. For scientific stock of knowledge outputs, adoption is encouraged through publication in scientific journals and appearance at relevant conferences and workshops. Negative factors that may inhibit the adoption of some GRDI project outputs include uncertainty in outputs and complexity.

In the long term, GRDI projects can be expected to generate a variety of environmental and economic benefits; the majority of the benefits are likely economic in nature (i.e. increased organizational efficiency and reductions in risk, etc.), although a number of positive environmental impacts were also identified (a particular focus on forest health). Project leads typically anticipate that more than 70% of the individuals (e.g. persons, groups or organizations) identified as next or final users will make use of the output. This belief is strongly supported by the high number of collaborations occurring between GRDI project leads and next/final users. Many of the identified impacts are likely to begin to occur within 5 years of output adoption.

Acknowledgements

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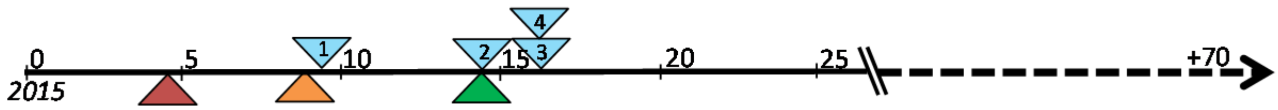
Appendix 1: Phase VI Projects

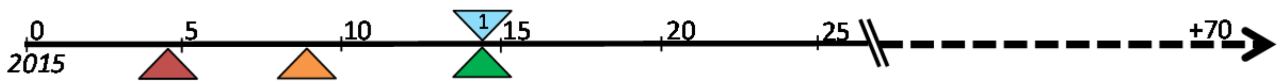
Project Title	Project Leads	Project Location	Total Project Funds
Development of metagenomic and bioinformatic tools to facilitate processing of insect trap captures	J. Allison	Great Lakes Forestry Centre, Ontario	$215,000
Tools for enhanced molecular detection of Asian Gypsy Moth (AGM) and identification of their geographic origins	M. Cusson	Laurentian Forestry Centre, Quebec	$315,000
Ecogenomics of the spruce budworm	M. Cusson	Laurentian Forestry Centre, Quebec	$285,000
Accelerating the discovery of insect volatile attractant molecules with genomics	D. Doucet	Great Lakes Forestry Centre, Ontario	$235,000
Developing the next generation biosurveillance tools for tracking and preventing forest pest invasions	P. Tanguay	Laurentian Forestry Centre, Quebec	$630,000
Applied genomics for tree breeding (GAPP) and new applications	N. Isabel	Laurentian Forestry Centre, Quebec	$585,000
Development of a molecular method to detect living *Phytophthora* spp. of phytosanitary concern in wood	I. Leal	Pacific Forestry Centre, British Columbia	$130,000
Genomics-assisted tree breeding for improving remediation of disturbed forest ecosystems	J.J. Liu	Pacific Forestry Centre, British Columbia	$300,000
An early detection tool for emerald ash borer (EAB) and ash resource protection	A. Séguin	Laurentian Forestry Centre, Quebec	$320,000
Innovative land reclamation approaches following oil sands mining: a phytoremediation approach based on tree-soil microbiome interactions	A. Séguin	Laurentian Forestry Centre, Quebec	$520,000
Developing molecular and environmental genomic approaches for microbial and invertebrate communities to assess ecosystem integrity in forest management	L. Venier	Great Lakes Forestry Centre, Ontario	$390,000

Appendix 2: Project timelines

Project 1. Development of metagenomic and bioinformatic tools to facilitate processing of insect trap captures.

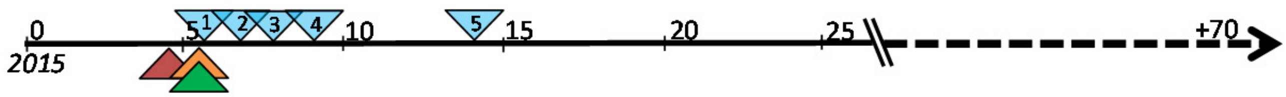


Output: Proof of Concept metagenomic method of identifying beetles	Project: Development of metagenomic and bioinformatic tools to facilitate processing of insect trap captures
Next Users: CFS, OMNRF, USDA; uptake 5-10 years	
Final Users: Next Users, other federal government agencies, other provincial government agencies; uptake 5-10 years	
Impacts: 1. More efficient processing of insect trap captures, 2. Improved efficiency and effectiveness of insect monitoring, 3. Earlier management decisions with potential to improve forest health, 4. Possibility for more cost effective response to incursions of non-native insect species	



Output: Cost comparison between traditional and genomic approaches	Project: Development of metagenomic and bioinformatic tools to facilitate processing of insect trap captures
Next Users: CFS, OMNRF, USDA; uptake 5-10 years	
Final Users: Next Users, other federal government agencies, other provincial government agencies; uptake 5-10 years	
Impacts: 1. Increased uptake of new genomics-based methods of identifying trap captures	

Project 2. Tools for enhanced molecular detection of Asian Gypsy Moth (AGM) and identification of their geographic origins.



Output: Method to identify the origins of AGM

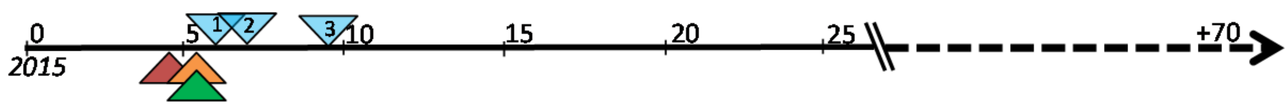
Next Users: CFIA; uptake in 0-1 years

Final Users: CFIA; uptake in 0-1 years

Impacts: 1. Reduced risk of import and export barriers, 2. Maintained relations with trading partners, 3. Maintain forest health due to avoided AGM establishment in Canada, 4. Reduced possibility of human health allergy effects associated with large scale AGM outbreaks, 5. Increased confidence in regulatory processes and decisions made

Project: Tools for enhanced molecular detection of Asian Gypsy Moth (AGM) and identification of their geographic origins

Project 3. Ecogenomics of the spruce budworm.



Output: Forecast model for SB outbreak and spread in Ontario

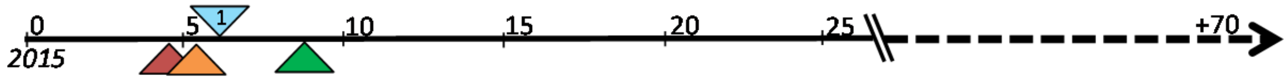
Next Users: OMNRF; uptake 0-1 years

Final Users: OMNRF; uptake 0-1 years

Impacts: 1. Improved forest management decisions on monitoring and spray treatments, 2. Potential for improved targeting of Bt spraying programs (reduced impact on non-SB lepidoptera), 3. Reduced risk of forest loss from SB outbreak

Project: Ecogenomics of the spruce budworm (SB)

Project 4. Accelerating the discovery of insect volatile attractant molecules with genomics.



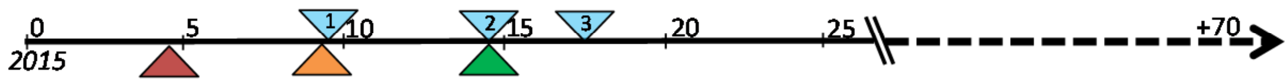
Output: Improved method to identify compounds for insect lures

Next Users: CFS and scientists; uptake 1-5 years

Final Users: CFS and scientists; uptake 1- 5 years

Impacts: 1. Potential application of method to other species of concern, reducing the time required to develop a lure for an insect

Project: Accelerating the discovery of insect volatile attractant molecules with genomics



Output: Identity of most active pheromone compounds for beetles

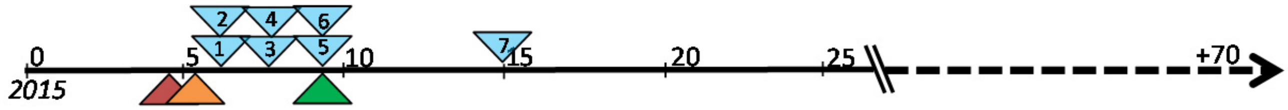
Next Users: Federal government agencies, provincial forest managers; uptake 5-10

Final Users: Federal government agencies, provincial forest managers, industry; uptake 5-10 years

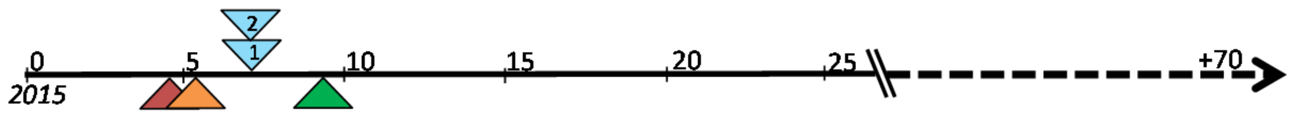
Impacts: 1. Improved trapping and monitoring efficiency (if not created by lure development company), 2. Commercialization potential for industry (lure development) to manufacture and sell pheromones for identified species, 3. Reduced risk of forest losses

Project: Accelerating the discovery of insect volatile attractant molecules with genomics

Project 5. Developing the next generation biosurveillance tools for tracking and preventing forest pest invasions.

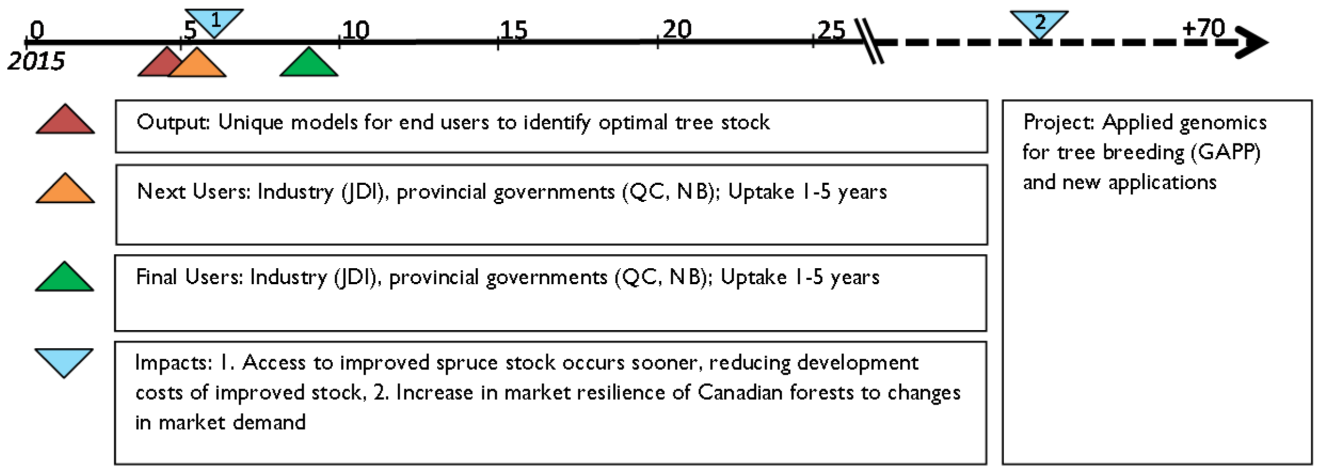


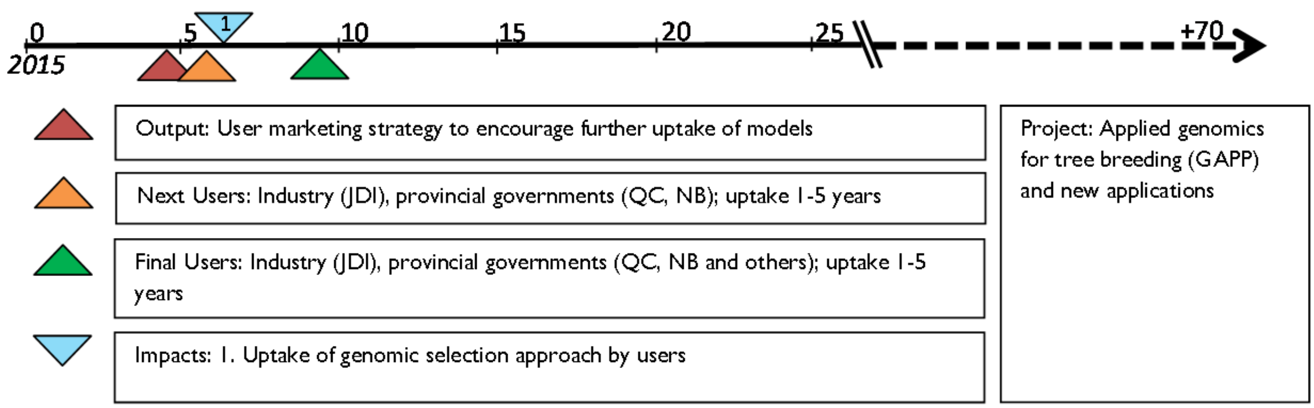
Output: Method to detect and monitor pests using genomics	Project: Developing the next generation biosurveillance tools for tracking and preventing forest pest invasions
Next Users: CFIA, provincial governments (ON, QC); uptake 1-5 years	
Final Users: CFIA, NPPOs, provincial governments, industry (FPInnovations); uptake 1-5 years	
Impacts: 1. Reduced risk of import and export barriers, 2. Maintained relations with trading partners, 3. Maintain forest health due to avoided pest establishment /outbreak in Canada, 4. Reduced possibility of human health effects associated with large scale AGM outbreaks, 5. Reduced loss of urban/valuable species, 6. Reduced loss of socially valuable species, 7. Increased trust in the regulatory response to target organisms interceptions	



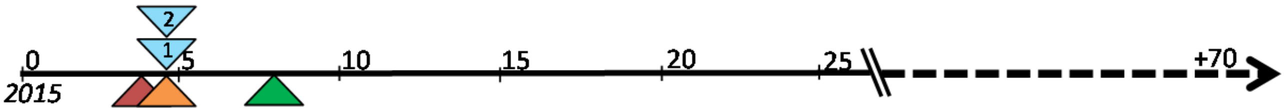
Output: Proof of concept portable detection system for *P. ramorum*	Project: Developing the next generation biosurveillance tools for tracking and preventing forest pest invasions
Next Users: CFIA; uptake 1-5 years	
Final Users: CFIA, provincial governments; uptake 1-5 years	
Impacts: 1. Cheaper, faster and more portable method of detecting *P. ramorum*, 2. Maintain forest health due to avoided SOD establishment in Canada	

Project 6. Applied genomics for tree breeding (GAPP) and new applications.





Project 7. Development of a molecular method to detect living *Phytophthora spp.* of phytosanitary concern in wood.



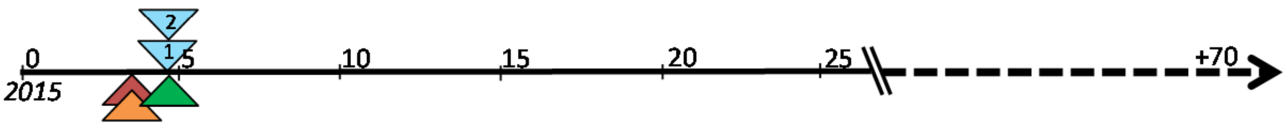
Output: Method of evaluating living vs. dead *Phytophthora*

Next Users: CFIA, industry; uptake 1-5 years

Final Users: CFIA, industry; uptake 1-5 years

Impacts: 1. Reduced risk to industry due to avoided *Phytophthora* related trade restrictions, 2. Maintain forest health by preventing pathogen establishment in Canada

Project: Development of a molecular method to detect living *Phytophthora* spp. of phytosanitary concern in wood



Output: Application of genomic tool to test efficacy of phytosanitation treatments

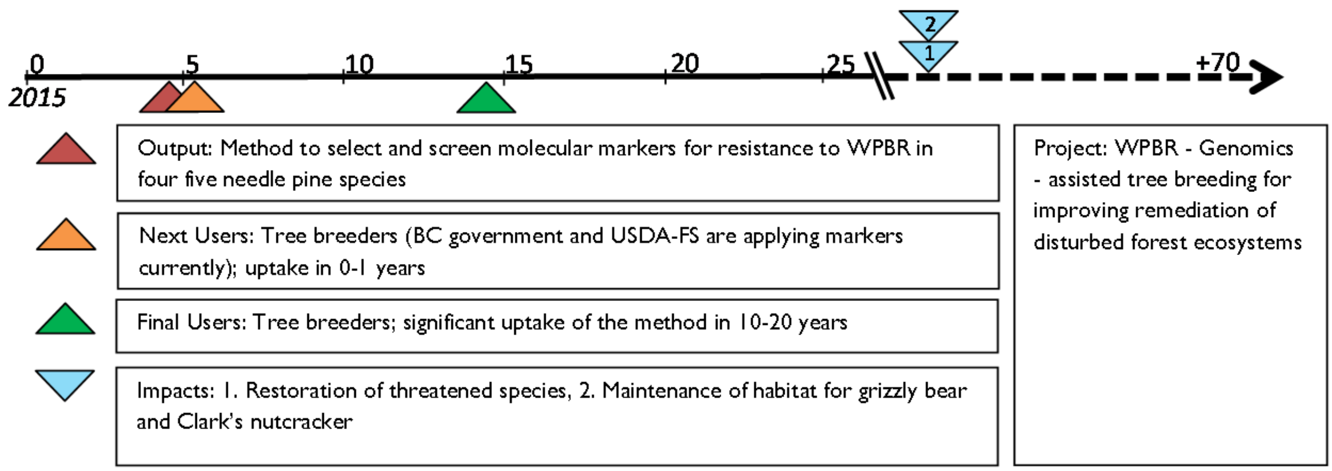
Next Users: CFIA, treatment developers; uptake 0-1 years

Final Users: CFIA, industry; uptake 0-1 years

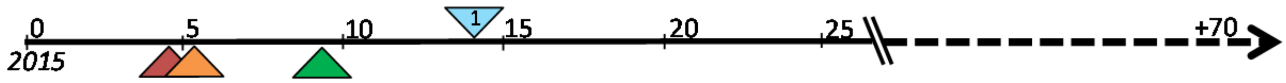
Impacts: 1. Reduced environmental damage from increased use of validated environmentally benign phytosanitary treatments, 2. Reduction in harmful chemicals entering the environment from elimination of harmful treatment practices

Project: Development of a molecular method to detect living *Phytophthora* spp. of phytosanitary concern in wood

Project 8. Genomics-assisted tree breeding for improving remediation of disturbed forest ecosystems.



Project 9. An early detection tool for emerald ash borer (EAB) and ash resource protection.\



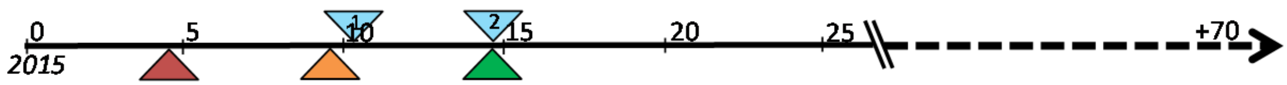
Output: Diagnostic method to distinguish between ash species

Next Users: Researchers and scientists; uptake 1-5 years

Final Users: Researchers and scientists, breeders and municipalities; uptake 1-5 years

Impacts: 1. Potential for breeders to identify and breed punitive resistant ash

Project: An early detection tool for emerald ash borer (EAB) and ash resource protection



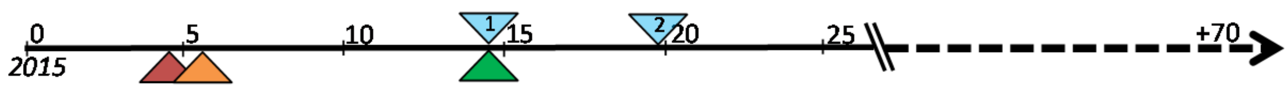
Output: Ash genes that respond to EAB attacks

Next Users: Researchers and scientists; uptake 5-10 years

Final Users: Researchers and scientists, breeders, municipalities and property Owners; uptake 5-10 years

Impacts: 1. Potential to save high value trees, 2. Potential to patent protein based assay to diagnose EAB infestation (10+ from project completion)

Project: An early detection tool for emerald ash borer (EAB) and ash resource protection



Output: EAB compounds that trigger a response in ash

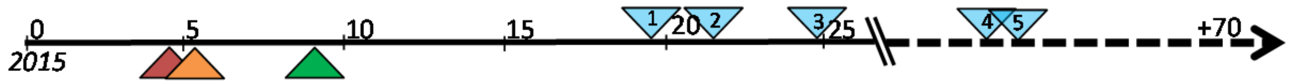
Next Users: Researchers and scientists; uptake 1-5 years

Final Users: Researchers and scientists, breeders, municipalities and property owners; uptake 10-20 years

Impacts: 1. Immune boosting compound has potential to boost urban and natural forest ash trees ability to withstand EAB attack, 2. Social benefit of maintaining ash species on the landscape (urban)

Project: An early detection tool for emerald ash borer (EAB) and ash resource protection

Project 10. Innovative land reclamation approaches following oil sands mining: a phytoremediation approach based on tree-soil microbiome interactions.



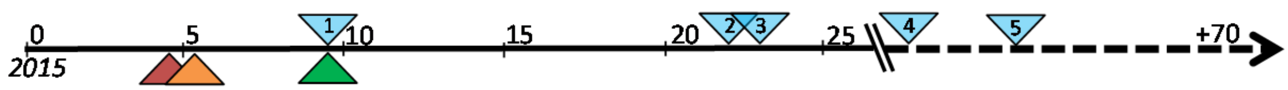
Output: Methods of monitoring tree-soil microbe interactions towards the reclamation of oil sands sites

Next Users: Industry (CNRL), Alberta provincial government; uptake 1-5 years

Final Users: Industry (CNRL), Alberta provincial government, oil sands stakeholders; uptake 1-5 years

Impacts: 1. Adoption of biomarkers may reduce the risk of remediation failure, 2. Potential for reduced costs of remediation if biomarkers can identify more effective reclamation processes, 3. Improved soil capacity of reclaimed sites towards ecosystem establishment , 4. Improved remediation processes may increase likelihood of future approval for oil sands developments (Positive economic, potential negative environmental effects), 5. Improved public opinion of oil sands developments if remediation successful

Project: Innovative land reclamation approaches following oil sands mining: a phytoremediation approach based on tree-soil microbiome interactions



Output: Characterization of ideal *populus* species for land reclamation of disturbed sites

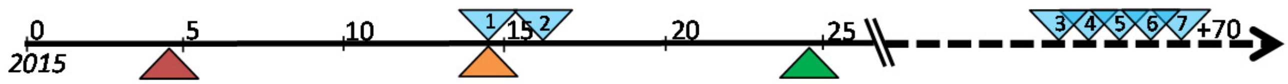
Next Users: Industry (CNRL), Alberta provincial government, scientific community; uptake 1-5 years

Final Users: Industry (CNRL), Alberta provincial government, oil sands stakeholders; uptake 1-5 years

Impacts: 1. Use of aspen species will improve soil microbe capacity of the reclaimed sites, 2. Potential for reduced costs of remediation if ideal aspen varieties are used, 3. Use of ideal aspen varieties may reduce the risk of remediation failure, 4. Establish novel ecosystems, 5. Improved public opinion of oil sands developments if remediation successful

Project: Innovative land reclamation approaches following oil sands mining: a phytoremediation approach based on tree-soil microbiome interactions

Project 11. Developing molecular and environmental genomic approaches for microbial and invertebrate communities to assess ecosystem integrity in forest management.



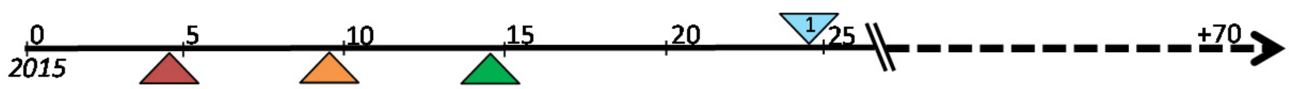
Output: Methods for identifying microbe profiles to assess sustainability

Next Users: Industry (JDI), Provincial forest managers, scientific community; uptake 10-20 years

Final Users: Forest certification organizations, federal government agencies, provincial governments, industry; uptake 10-20 years

Impacts: 1. New protocols are less costly, 2. Knowledge of sustainability could increase or decrease industry risk, 3. Increased certified wood product supply, 4. Maintenance of clean water supplies and aquatic habitats, 5. Maintenance of ecosystem integrity and related ecological services, 6. Protect forests for next generations, 7. Increase in public confidence in forest management practices

Project: Developing molecular and environmental genomic approaches for microbial and invertebrate communities to assess ecosystem integrity in forest management



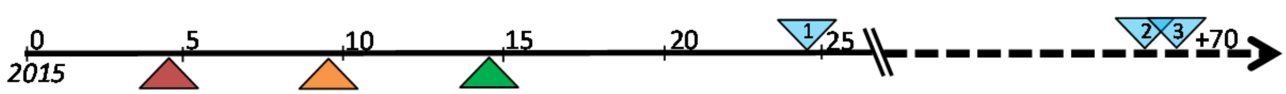
Output: Profiles of microbial and invertebrates at various sites

Next Users: Researchers and scientists; uptake 5-10 years

Final Users: Researchers and scientists, provincial regulators; uptake 5-10 years

Impacts: 1. Data set the benchmark against which ecological sustainability will be measured by regulators

Project: Developing molecular and environmental genomic approaches for microbial and invertebrate communities to assess ecosystem integrity in forest management



Output: Report on protocols to inform forest management practises

Next Users: Provincial governments, industry, federal government agencies; uptake 5-10 years

Final Users: Forest certification organizations, federal government agencies, provincial governments; uptake 5-10 years

Impacts: 1. Maintain market through adoption of report recommendations, 2. Possible improvements in ecological sustainability if report recommendations adopted,
3. Potential to improve (maintain) forest health into the future

Project: Developing molecular and environmental genomic approaches for microbial and invertebrate communities to assess ecosystem integrity in forest management