Environment and Climate Change Canada | Environnement et Changement climatique Canada

Climate Science 2050:

Advancing Science and Knowledge on Climate Change

Canada

Environment and Climate Change Canada was honoured to lead this national synthesis, which reflects the diverse voices within the Canadian climate change science and knowledge community. We hope this document serves as the basis for an ongoing conversation to advance climate change science and knowledge and, ultimately, action.

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Environment and Climate Change Canada
Public Inquiries Centre
12th Floor, Fontaine Building
200 Sacré-Coeur Boulevard
Gatineau QC K1A 0H3
Telephone: 819-938-3860
Toll Free: 1-800-668-6767 (in Canada only)
Email: ec.enviroinfo.ec@canada.ca

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Executive summary

Science and knowledge are critical in guiding the swift and ambitious action needed to build a resilient, carbon-neutral Canada. The breadth and complexity of the science and knowledge needed to meet this challenge require collaboration across disciplines, sectors, communities, and research bodies. *Climate Science 2050: Advancing Science and Knowledge on Climate Change* (CS2050) is a national synthesis to better understand the breadth of Canadian climate change science and knowledge gaps and guide science and knowledge producers, holders, and funders as they advance the collaborative and interdisciplinary efforts needed to inform climate action. CS2050 encompasses the natural, social, and health sciences, and recognizes the need to mobilize the full spectrum of Indigenous leadership, participation, and knowledge systems. While climate change science has traditionally focused on the natural sciences, CS2050 recognizes the need to elevate the role of social and behavioural sciences, as they have important contributions to make in informing the transformation needed in Canadian society.

Although CS2050 highlights many science and knowledge needs, there is already a strong knowledge base on which to build. The urgency of the climate change challenge means that decision makers should not and cannot wait for all the science to be in before taking action. Climate action must continue in parallel with research activities, drawing on existing knowledge and incorporating new insights as they become available. As such, knowledge synthesis and mobilization—including the dialogue they establish between knowledge producers, holders, and users—are key elements of CS2050. They will ensure decision makers have the best available knowledge and will keep research efforts aligned with user needs. These efforts could include science and risk assessments, knowledge portals, and case studies, and will benefit from increasing climate change science literacy and professional competencies.

Given the scale and urgency of the challenge, and ubiquitous nature of climate change impacts, addressing the science and knowledge needs outlined in CS2050 will require an increasingly integrated approach to advance multiple priorities in parallel. It will also benefit from embracing new and participatory approaches to research and knowledge development (e.g., experimentation, learning by doing, co-production) and from the respectful consideration of Indigenous Knowledge. The science and knowledge needs covered by CS2050 are organized into four outcomes, with a fifth area of work—Earth system climate science—providing a key foundation.

Earth system climate science – Work is needed to reduce uncertainties related to the magnitude, timing, and impacts of future change and the prediction of climate extremes, floods, droughts, and wildfires. This research will enable a better understanding of the influence of climate change on permafrost, glaciers, oceans, ice (sea, river, lake), and freshwater. It is also central to providing more detailed and tailored sector-based information. Research is also needed to evaluate the effectiveness of mitigation efforts (e.g., short-lived climate forcers, climate engineering).

Healthy and resilient Canadians, communities, and built environments – Developing a nuanced understanding of vulnerability, resilience, and empowerment—and how these vary across regions and groups—will help ensure efforts to build health and resilience are effective. Work is also needed to protect and improve the health and well-being of Canadians and increase the resilience of health systems, including a better understanding of climate-related health risks, intersections with action in other sectors (e.g., transportation, urban planning), and innovative and scalable interventions that maximize resilience and empower behavioural change. Building climate-resilient communities and infrastructure will benefit from research into natural infrastructure, community design, the value and co-benefits of resilient infrastructure solutions, and essential infrastructure systems (e.g., energy, water, transportation). There is also a need to understand the climate impacts on governance, trade, global migration patterns, and development and international assistance.

A carbon-neutral society – Accelerating the transformational change needed to meet and exceed Canada's 2030 greenhouse gas (GHG) emissions reduction goal under the Paris Agreement and achieve net-zero emissions by 2050 will require a deeper understanding of the social and behavioural side of decarbonization. Research to understand decarbonization pathways will be valuable, including work related to a just transition and the economic aspects of carbon neutrality. Energy decarbonization is a key research area, as is work to understand the mitigation potential of infrastructure construction and management approaches. In moving toward net-zero emissions, research is needed to help protect and enhance terrestrial and aquatic carbon sinks, from fundamental carbon cycle science to research aimed at developing socio-economic levers and best practices.

Resilient terrestrial and aquatic ecosystems – To ensure Canada's ecosystems remain healthy and resilient, research is needed to improve our foundational understanding of the impacts of climate change on the processes that underpin healthy ecosystems, the sensitivity, resilience, and adaptive capacity of species and ecosystems, and the effects of changing stressors and their cumulative impact on biodiversity and ecosystems. Work will also be needed to anticipate and minimize the threats to vulnerable species and ecosystems, as well as efforts to develop and test adaptation measures. Nature can also be a powerful ally in addressing climate change, and work is needed to address knowledge gaps related to identifying and deploying nature-based solutions, such as research into potential negative effects, socio-economic and cultural valuations and trade-offs, and the impact of extreme events on these solutions when implemented.

Sustainable natural resources – Helping the agricultural, forestry, fisheries, water management, mining, and energy sectors—and the traditional lifestyles connected to these industries—remain resilient and productive in the face of climate change requires a better understanding of the risks climate change poses (e.g., extreme events, water availability, pests, disease, invasive species). Meanwhile, as some resource-based communities navigate a just transition, social science research can help to understand the social, cultural, and economic impacts of this transformation. Furthermore, an integrated understanding of natural resource and land/water goals and opportunities will help maximize co-benefits (e.g., advancing carbon sequestration, health, energy, and food security simultaneously). Canada's natural resource sectors will also benefit from research to inform climate-smart, sustainable practices.

Three key areas of foundational capacity are essential in supporting work across all science and knowledge needs identified in CS2050. Whether carried out on the ground or via satellites, monitoring and surveillance efforts continue to be key in providing situational awareness, assessing change, informing action, and measuring progress. The magnitude and diversity of climate change data and knowledge will require advances in digital infrastructure (e.g., data storage and management, high-performance computing), including tools for data management, extraction, manipulation, visualization, standardization, and interoperability. Finally, ensuring climate change science is open and accessible will increase transparency, maximize investments, and accelerate progress.

CS2050 represents an opportunity to make deliberate decisions about climate change science and knowledge activities and funding in Canada, which will be essential in guiding the way to a resilient, carbon-neutral society.

SCIENCE & KNOWLEDGE NEEDS

Earth System Climate Science

Biogeochemical and hydrological processes
Permafrost, glaciers, sea/lake/river ice, oceans, freshwater
Mitigation effectiveness
Climate extremes
Downscaling strategies

Healthy & Resilient Canadians, Communities, & Built Environments

Place-based, intersectional understanding
Healthy Canadians and resilient health systems
Climate resilient communities and infrastructure
Trade, migrations, development, governance

Carbon-neutral Society

Social and behavioural change
Pathways to decarbonization
Carbon sinks
Economics of carbon neutrality

Resilient Terrestrial & Aquatic Ecosystems

Climate impacts on biodiversity
Species and ecosystem adaptation
Nature-based climate solutions

Sustainable Natural Resources

Risks to natural resource sectors
Integrated understanding and valuation
Climate action

FOUNDATIONAL CAPACITY

Monitoring & Observation

Expanded networks
Innovative approaches
Standardized protocols
Integrated datasets

Digital Infrastructure

Data storage and management
High-performance computing
Data integration
Tools for manipulation, visualization, etc.

Open Science

Fair data
Indigenous data sovereignty
Open publications

Introduction

Climate change is real; we are seeing evidence for it across Canada, and some additional warming and further changes in climate are unavoidable.[1]

The magnitude and urgency of the climate change challenge cannot be understated. Canada's economy, infrastructure, environment, health, and social and cultural well-being are already feeling its consequences, though these impacts are not experienced to the same degree by all Canadians. In response, Canada's House of Commons declared a national climate emergency in June 2019. Many of these impacts will continue even if the temperature goal set out in the Paris Agreement[2] is achieved, and current emission reduction commitments under the agreement have been collectively assessed as being insufficient to meet this goal. This emphasizes not only the need for a concerted effort to adapt to these impacts, reduce risks and vulnerabilities, and build resilience, but also the need for Canada and other countries to increase their level of ambition in achieving net-zero emissions and stabilizing temperature to avoid further harm.

As we increase the speed and ambition of our climate action, science and knowledge will play an essential role in helping us navigate the complex intersections, synergies, and trade-offs inherent in building a thriving, climate-resilient, carbon-neutral Canada that is just and equitable. The scientific consensus around anthropogenic climate change does not signal the end of the need for climate change science. Far from it. Sustained, synthesized, and inclusive science and knowledge will allow us to understand what is in store for Canada and the world, assess the risks, take informed and ambitious action, and track our progress against set milestones. This includes a deeper understanding of both the climate system and the social systems underpinning action. It also includes the science and innovation needed to continue developing the approaches that will be pivotal in addressing climate change—from clean technology to nature-based climate solutions to resilient, low-carbon infrastructure—and to ensure they are applied, monitored, and evaluated in the most effective way.

No single discipline, sector, order of government, community, or research body can undertake the breadth or complexity of the science and knowledge required to meet the climate change challenge. The skills, knowledge, experience, and resources needed are substantial and diverse. Broad interdisciplinary collaboration is crucial, especially in advancing the science and knowledge to inform integrated and coordinated mitigation and adaptation efforts. Further, the inclusion of First Nations, Métis, and Inuit leadership and knowledge, while respecting their sovereignty over and ownership of their knowledge and data, will be a crucial part of a more resilient and adaptive response to a warming climate.

Climate Science 2050: Advancing Science and Knowledge on Climate Change (CS2050) is designed to support and inform these collaborative and interdisciplinary efforts. It encompasses the natural, social (including economics), and health sciences. There is already an extensive foundation of scientific work to build on, as demonstrated in *Canada's Changing Climate Report*, the Canadian Council of the Academies' report on *Canada's Top Climate Change Risks*, and the work of the Intergovernmental Panel on Climate Change (IPCC), to name just a few. (For an overview of the state of climate change science in Canada, see Annex 1.) CS2050 is a forwardlooking endeavour, building on this knowledge and aligning with ongoing mitigation and adaptation efforts and priorities. While CS2050 highlights a wide array of science and knowledge needs to be addressed, climate action can and must proceed in parallel, drawing on the existing body of knowledge and incorporating new insights as they emerge.

[1] Bush, E. and Lemmen, D.S., editors (2019): *Canada's Changing Climate Report*; Government of Canada, Ottawa, ON.

[2] Holding the increase in average global temperature to well below 2˚C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5˚C.

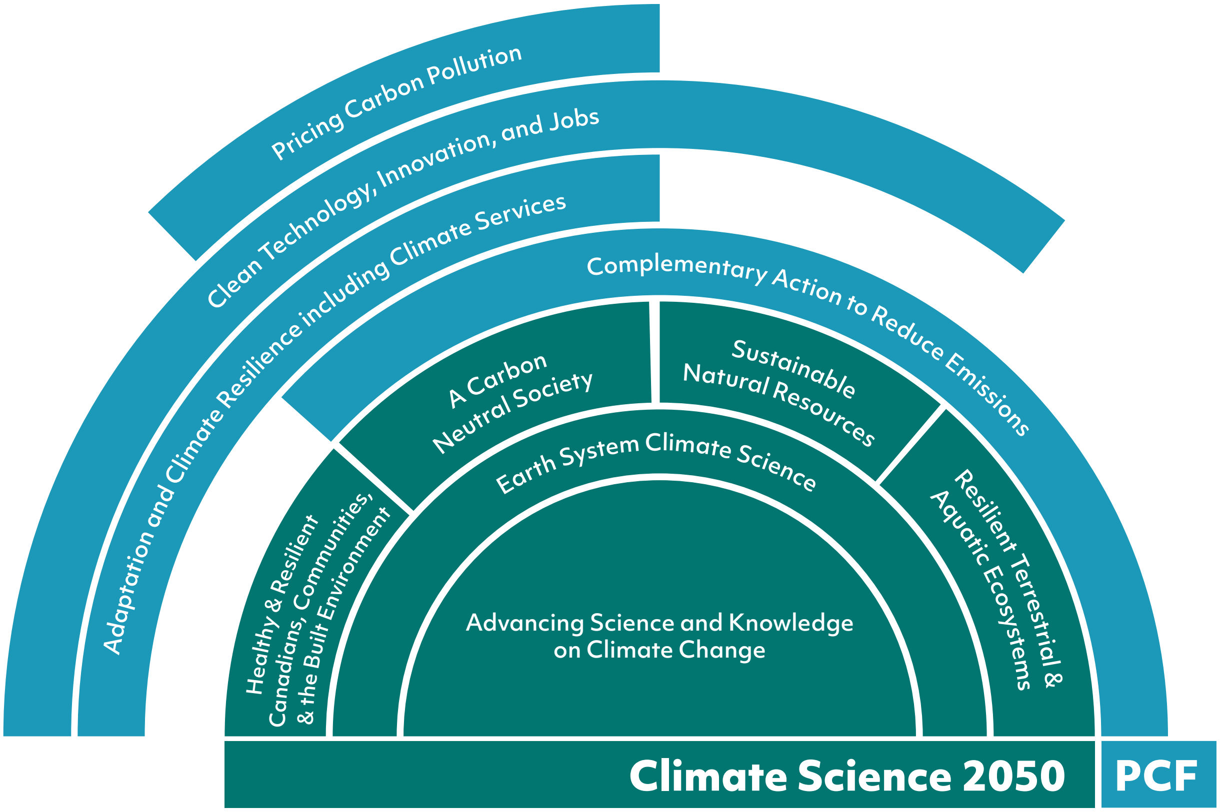
As a national synthesis of the breadth of Canadian climate change science and knowledge needs and gaps, CS2050's overarching objective is to inform planning, investment, and implementation across the full range of Canadian climate change science and knowledge producers, holders, and funders. This includes governments of all levels, Indigenous Nations, communities, and organizations, a wide range of academic disciplines, the private sector, non-governmental organizations, and civil society. An additional objective is to facilitate the mainstreaming of climate change science and knowledge so that these considerations are integrated by default into decision making in all sectors and communities, as well as into research planning. Knowledge synthesis and mobilization will facilitate this mainstreaming, making these efforts just as important as knowledge generation. While decision making and action (e.g., decision-support systems, services, policies, regulations) are crucial and are informed by the knowledge generated under CS2050, they fall outside its scope.

Overall, the science and knowledge needs highlighted in CS2050 are organized according to four broad outcomes that they support, all of which are enabled by advances in a fifth area of work: Earth system climate science. These outcomes are:

- healthy and resilient Canadians, communities, and built environments;
- a carbon-neutral society;
- resilient terrestrial and aquatic ecosystems; and
- sustainable natural resources.

Several of the science and knowledge needs identified across these outcome areas demonstrate the necessity of interdisciplinarity in advancing work on multiple fronts simultaneously and, in doing so, helping address the intersecting knowledge gaps decision makers must navigate. In addition to emphasizing interdisciplinarity, bringing the social and behavioural sciences into the climate change science dialogue more fully will be essential in advancing work across all outcome areas and empowering action.

The outcomes that provide the organizing structure for CS2050 are consistent with the goals of many of the foundational climate change strategies and plans that form the policy backdrop of CS2050. Federally, this includes the *Pan-Canadian Framework on Clean Growth and Climate Change* (PCF), and CS2050 can be positioned as a complementary science pillar for the PCF. However, the policy landscape is much broader. CS2050 is intended to support the objectives of other government, Indigenous, and sector-based climate change plans and strategies, informing the ongoing implementation of existing plans and serving as a building block for future climate plans and action from the near term to mid-century and beyond. It also supports Canada's obligations—for instance, under the *Canadian Environmental Protection Act, 1999* and the United Nations Framework Convention on Climate Change—to undertake climate change research, monitoring, and reporting.



While CS2050 lays the groundwork for setting priorities that will help focus collective efforts in Canada, it is important to recognize that climate change is a global phenomenon that will require collaboration and activity beyond Canada's borders. The work CS2050 advances will enable continued Canadian leadership and participation in international climate change science efforts. This will allow us to leverage international science to enhance Canadian research capacity and to contribute to advancing science and knowledge in a way that reflects the global nature of climate change.

BOX 1. GOVERNMENT OF CANADA PARTICIPATION AND LEADERSHIP IN INTERNATIONAL CLIMATE CHANGE SCIENCE

Government of Canada climate change science is embedded in, and contributes to, a wide range of international efforts. Canadian scientists make significant contributions to IPCC reports, as well as other international syntheses, such as those of the Arctic Council. Canadian climate modelling and data analysis research undertaken as part of the multi-national World Climate Research Programme and the World Meteorological Organization's climate program allows Canada to contribute to and access the leading-edge understanding of our climate system.

Canadian scientists play leadership roles in international research efforts to monitor and model a wide variety of aspects of the global climate system, such as Arctic sea ice and freshwater fluxes, snow cover, and short-lived climate pollutants. Canada is a member of the international Group on Earth Observations (GEO) network, which has a mandate to collect Earth Observations (EO) and provide open EO data in support of the United Nations (UN) Sustainable Development Goals, the Sendai Framework for Disaster Risk Reduction, the UN System of Environmental and Economic Accounts, and the UN Framework Convention on Climate Change (UNFCCC). Observations collected and curated from Canadian networks feed into international databases, such as the global snow dataset of the European Space Agency climate change initiative and the Global Runoff Data Centre for river flows. Canada also runs one of only three global intercomparison monitoring sites to ensure consistent monitoring of GHGs worldwide.

The path to CS2050

In developing CS2050, Environment and Climate Change Canada convened discussions with a range of partners and stakeholders to ensure that the climate change knowledge synthesis, mobilization, and research needs identified here reflect the diversity of perspectives represented by Canadian climate change science and knowledge producers, holders, funders, and users. Engagement efforts included a scoping survey (November 2018) sent to approximately 200 science and knowledge producers and users to identify short- and medium-term gaps, and a national workshop (February 2019) that brought together more than 100 experts from a range of sectors and disciplines to discuss science and knowledge priorities and opportunities for collaboration and knowledge mobilization. In addition, two targeted expert workshops informed this work, which were focused on permafrost and on carbon cycle science and policy (both June 2019). These efforts were complemented by a series of bilateral discussions with key partners and stakeholders.

CS2050's publication does not signal the end of these conversations. As a synthesis it lays the groundwork for identifying key priorities that can be used to focus the collective expertise of the Canadian climate change science and knowledge community. It also serves as a springboard to an ongoing conversation around climate change science, which will evolve with advances in our understanding of our warming world and as new questions, challenges, and opportunities emerge. Taken together, these efforts will contribute to shaping future research directions.

Guiding principles

Several principles will guide CS2050's implementation, given that it will be an ongoing process involving of a range of actors and disciplines. While CS2050 provides guidance on what should be addressed, the principles below offer guidance on how knowledge synthesis, mobilization, and research efforts can build on existing knowledge and understanding in a respectful, inclusive, and interdisciplinary way that benefits all Canadians.

- Ensure **equity of diverse knowledge systems**, making space for Indigenous leadership and innovation, and recognizing that Indigenous Knowledge is a distinct network of knowledge systems that cannot be integrated into western science but that there are spaces where the two can co-exist and co-create knowledge.
- Further **Indigenous self-determination in research** to support an approach to climate change research that is holistic, place-based, and responsive, and that respects Indigenous sovereignty and ownership of data and Indigenous Knowledge.
- Embrace **interdisciplinarity** to produce science and knowledge that reflect the complexity and interconnections inherent in climate change and that encompass different kinship systems and relationships with the land.
- Emphasize **collaboration** across generations, disciplines, sectors, orders of government, organizations, and regions to bring together a range of experiences, perspectives, and areas of expertise.
- Adopt a **flexible, adaptive approach** in science and knowledge activities to be responsive to emerging priorities, challenges, and opportunities.
- Apply an **intersectional** lens that considers how climate change intersects with various identity factors (e.g., race, class, gender) to develop solutions that tackle both climate change and inequity, removing systemic barriers and promoting well-being.

- Respond to **local and regional** contexts, needs, priorities, protocols, cultures, and ways of knowing, involving communities affected by the research to produce tailored and effective adaptation and mitigation efforts.
- Consider climate change **mitigation, adaptation, and sustainable development** in an integrated way to maximize co-benefits and avoid maladaptive actions.

BOX 2. SYNERGIES BETWEEN CLIMATE CHANGE AND SUSTAINABLE DEVELOPMENT

Climate change poses a significant threat to sustainable development. In 2015, the United Nations adopted three multilateral frameworks that, together, reflect the important linkages between climate change and other environmental, social, and economic issues:

- the 2030 Agenda for Sustainable Development, which outlines 17 Sustainable Development Goals (SDGs);
- the Sendai Framework for Disaster Risk Reduction, which developed seven targets to better deal with disasters (including "building back better"); and
- the Paris Agreement, which aims to strengthen the global response to climate change, taking into consideration equity and sustainable development.

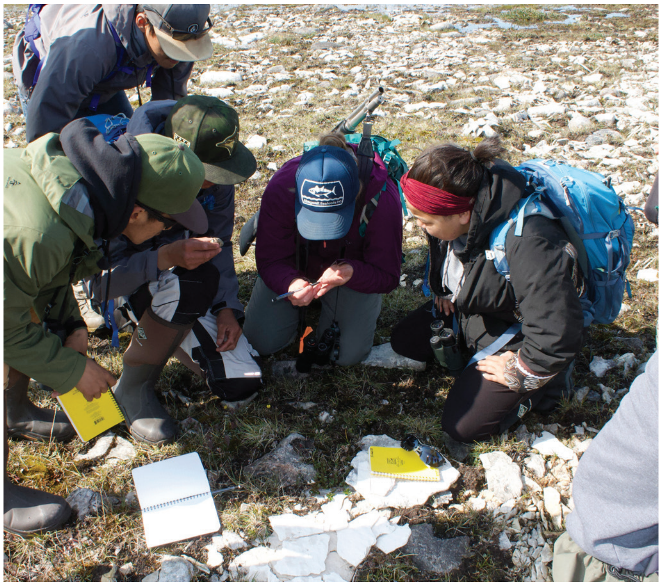
The Intergovernmental Panel on Climate Change Special Report on 1.5°C notes that mitigation and adaptation pathways consistent with limiting warming to 1.5°C are associated with multiple synergies and trade-offs across the SDGs. The net response, however, is determined by the pace and magnitude of the changes, the choice of climate action pathway, and how societies manage the transition. Currently, the most robust synergies on a global scale are associated with SDGs for health, clean energy, cities and communities, economic growth, and infrastructure. Conversely, the likely trade-offs of climate action have implications with SDGs for poverty, hunger, clean water, and life on land and life below water. Research is needed to understand the net impact of climate action on SDGs and develop strategies to promote synergies and mitigate trade-offs.

Importantly, there is a lack of recognition of how climate action impacts the poor and most vulnerable populations. A key commitment of sustainable development is the concept of Leaving No One Behind, which extends across several SDGs. Climate action must consider its impacts on all people and adhere to the principles of equity, fairness, and just transition.

Overall, climate change action and sustainable development are intrinsically linked: action on one can help advance achievement of the other, and inaction on one can jeopardize achievement of the other. There is strong alignment between climate change research priorities and the SDGs. Situating climate change research in the broader socio-economic context of sustainable development can advance both agendas and help facilitate the mainstreaming of climate change science and knowledge.

Indigenous-led climate change science and knowledge

The importance of Indigenous spaces in climate change science



There is a need to ensure that there are both physical and conceptual spaces in climate change research and knowledge generation that support the inclusion and leadership of Indigenous Peoples, researchers, and Elders and Indigenous Knowledge systems. Since time immemorial, Indigenous Peoples have led as stewards of the lands, waters, and ice. Indigenous Knowledge systems, built upon generations of relating to, observing, understanding, and living off of the land, are not static, and they continue to evolve and be developed. These knowledge systems are critical for identifying and adapting to changing environmental conditions. While First Nations, Métis, and Inuit are disproportionately affected by the impacts of climate change, they are leading crucial contributions to climate change science and knowledge.

Despite their long-standing relationships to the land, water, and ice, Indigenous Peoples have experienced ongoing marginalization by western scientific research practices and colonial policies. First Nations, Métis, and Inuit have unique relationships with lands, waters, and ice, distinct from other Canadians. The recognition and affirmation of Aboriginal and treaty rights in Section 35 of the *Constitution Act, 1982*, reflects this. As such, it is critical that their voices, worldviews, and knowledge are given space to lead in climate change science and knowledge decisions. While Indigenous Peoples in Canada have certain shared experiences and values, recognizing the distinctions between these groups is essential in understanding and respecting their diversity. Respectfully acknowledging their distinct governance structures and knowledge is fundamental in ensuring an appropriate approach to climate change science and research.

Mobilizing Indigenous Knowledge systems in climate change research and decision making allows Canada to better respond to climate change and contributes to the maintenance and revitalization of culture, food and water security, resource co-management, healthy lands and waters, economic development, community infrastructure, and health and well-being. Indigenous-led research generates crucial and relevant data and evidence for decision making at various scales. This is an important step to reconciliation, Indigenous sovereignty, self-determination, and implementing the United Nations Declaration on the Rights of Indigenous Peoples in Canada.

The equal and respectful co-development of climate change research and knowledge involving multiple knowledge systems can also serve as a mechanism through which long-term, meaningful partnerships can be fostered between researchers and Indigenous partners. This enables Canadian research to better respond to the unique and distinct research needs and interests of First Nations, Métis, and Inuit communities. Enhancing the inclusion of Indigenous Knowledge—while respecting Indigenous Peoples' ownership and control over their knowledge, data, and information—and innovation through these partnerships can support the inherent rights and interests of Indigenous Peoples.

BOX 3. CREATING SPACE: PROMOTING THE PARTICIPATION, KNOWLEDGE, AND RIGHTS OF INDIGENOUS PEOPLES IN INTERNATIONAL CLIMATE DISCUSSIONS

Taking direction from Indigenous leaders, Canada worked in full partnership to advance rights-based language in the text of the Paris Agreement. Due to this shared advocacy, a direct reference to the "rights of Indigenous Peoples" can be found in the preamble of the Agreement, creating the foundation for further decisions on amplifying the rights, voices, and knowledge of Indigenous Peoples in the UNFCCC. Over the last several years, Canada, in partnership with leaders from the National Indigenous Organizations, championed the creation of the Local Communities and Indigenous Peoples Platform, and the creation of the Facilitative Working Group (FWG)—the first Constituted Body with equal representation between Indigenous Peoples and State representatives. The platform is an important space for the direct and meaningful participation of Indigenous Peoples in the UNFCCC process, and enables international collaboration of Indigenous networks. Its purpose is to strengthen the knowledge, technologies, practices, and efforts of Indigenous Peoples related to addressing and responding to climate change and enhancing their engagement in the UNFCCC process. The first Work Plan—co-created by the FWG—was adopted in 2019 at the 25th Conference of the Parties in Madrid.

Canadian delegations to the UNFCCC and the IPCC also include representatives from National Indigenous Organizations, ensuring that Indigenous Peoples can provide input into Canada's positions, that Government officials can benefit from their perspectives and knowledge, and that the important role Indigenous Knowledge plays in understanding climate change is recognized. References to the value and importance of Indigenous Knowledge were most recently included in the IPCC Special Report on Oceans and Cryosphere in a Changing Climate, which recognized that Indigenous Knowledge underpins successful adaptation efforts and enables public awareness and social learning.

Mobilizing Indigenous leadership and participation in climate change science and knowledge

Supporting capacity building within Indigenous communities, organizations, and governments is essential for sustainable, self-determined knowledge generation. Research by and with Indigenous Peoples must consider how projects can increase research capacity and leadership in communities beyond the lifespan of the project. This includes supporting Indigenous researchers as Principal Investigators, training community members to undertake research themselves, providing employment opportunities, contributing to community research infrastructure, and supporting the research needs and priorities of the community.

Research by and with Indigenous Peoples should also respect their protocols, policies, governance structures, and Aboriginal or treaty rights.[3] In many cases, Indigenous Peoples of Canada have protocols and policies guiding consultation, research, or the inclusion of Indigenous Knowledge. Further, when Indigenous communities partner with external researchers, results should be communicated in culturally appropriate and accessible ways, linking to existing information resources where possible.

The capacity to enable the full spectrum of involvement in research—from participation to co-development to support for Indigenous-led initiatives—needs to be incorporated within non-Indigenous governments and research institutions. Critically, non-Indigenous individuals involved in science and knowledge production should be trained on the diverse contexts of Indigenous Peoples. Other essential actions include consensual data management practices (e.g., the First Nations principles of OCAP®: ownership, control, access, and possession of knowledge and data originating in Indigenous communities[4]), Indigenous leadership in

[3] The *Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans* provides a framework for the ethical conduct of research involving Indigenous Peoples.

[4] OCAP® is a registered trademark of the First Nations Information Governance Centre (FNIGC) www.FNIGC.ca/OCAP.

research governance, the recruitment and retention of Indigenous researchers, community members, and youth, adequate funding for projects led and co-led by Indigenous Peoples, and equity participation in research, development, and demonstration (RD&D).

There is a spectrum of ways to improve the meaningful involvement of Indigenous Peoples in climate research and knowledge synthesis, mobilization, and generation. Indigenous participation and leadership in climate change science will differ greatly on a case-by-case basis, as community contexts, research priorities, and capacities vary. Actions towards the advancement of Indigenous-led climate change science and knowledge in Canada can include, but are not limited to:

- elevating opportunities for Indigenous leadership and participation in community-based monitoring;
- aligning resources with research and climate change strategies and priorities of First Nations, Métis, and Inuit organizations, governments, and communities, for example, the *National Inuit Climate Change Strategy* (2019) and future plans as they are developed;
- co-developing projects in which Indigenous Peoples are involved at all stages of RD&D, that respond to Indigenous priorities, and that respect a distinctions-based approach;
- seeking review and approval from the appropriate Indigenous leadership bodies prior to conducting research on Indigenous lands, waters, and ice; and
- formalizing partnerships with research agreements.

It is important that Indigenous Knowledge and worldviews lead decision making related to climate change science and knowledge. Fostering productive and respectful spaces for Indigenous leadership and representation ensures that Canada's approach to climate change is more holistic and responsive.

SCIENCE IN ACTION: APPLYING INDIGENOUS KNOWLEDGE SYSTEMS IN CLIMATE MONITORING AND RESEARCH

The Indigenous Community-Based Climate Monitoring Program at Crown-Indigenous Relations and Northern Affairs Canada supports projects that weave together multiple ways of knowing. Indigenous communities across the country leading these projects co-apply Indigenous Knowledge Systems and science to answer climate questions relevant to their context, as they self-determine. Indigenous Knowledge Systems often inform which climate indicators are monitored, where, and how often, and may be used to create monitoring methodologies consistent with cultural protocols. Interviews with Elders and knowledge holders are used to gather information on historical trends and changes over time and inform broader climate change strategies. Elders and knowledge holders are often integral to training youth and on-the-land monitoring activities, facilitating intergenerational knowledge transfer. As an example, as part of their Climate Monitoring Program, Dene Tha' First Nation has formed an Elders and Youth Advisory Group to advise the project team and incorporate Dene Tha' value systems and traditional practices into monitoring protocols, data collection methodologies, and study area maps. Through their program, this project team aims to maintain strong cultural identity and language, traditional ways of living, and spiritual relationships with the land.

A new lens: Weaving Indigenous Knowledge into CS2050's implementation

Other sections in this document contain references to some of the climate change science and knowledge priorities of Indigenous Peoples. For example, infrastructure, extreme weather events, food and water security, and human health are all influenced by climate change and are currently of research interest to many Indigenous communities in Canada. However, references to Indigenous research priorities in CS2050 are by no means exhaustive, and it is important for researchers to identify national, regional, and local climate science and knowledge priorities. Besides learning of priorities directly from individuals, these can be found in Indigenous research and climate strategies, and explored through early engagement and co-development with Indigenous partners. Directing research and funding towards the distinct climate change science and knowledge priorities of First Nations, Métis, and Inuit, will contribute to resilient communities and ecosystems in Canada for generations to come.

BOX 4. EXCERPT FROM THE INUIT TAPIRIIT KANATAMI'S NATIONAL INUIT CLIMATE CHANGE STRATEGY[5]

PRIORITY AREA 1: Advance Inuit capacity and knowledge in climate decision making

Inuit have largely been excluded from participation in federal, provincial, and territorial climate decision making. In order to ensure that Inuit can meaningfully contribute to climate decisions, and to improve local Inuit access to the best available climate data and services, we must have the opportunity and capacity to become fully engaged. Increased capacity, coordination and information sharing are necessary to benefit climate decision making both within and beyond Inuit Nunangat by improving climate research and educational goals, and enabling more effective use of Inuit knowledge.

Objectives

1.1 Strengthen Inuit self-determination in climate change decisions, policy making and assessment processes

1.2 Facilitate and support regional Inuit climate change strategies

1.3 Promote Inuit-driven climate change research and monitoring

Actions

1.1.1 Influence policy and practice to ensure Inuit knowledge is equitably used in climate change decision making

1.2.1 Ensure regional climate strategies are in place and linked to the adoption of the national Inuit climate change strategy

1.3.1 Ensure climate information is available to all Inuit to inform evidence-based decision making

1.3.2 Establish two-way climate change information sharing best practices among Inuit from the local to the international level

1.3.3 Build Inuit regional and circumpolar climate change exchange opportunities

1.3.4 Develop a mechanism for effective in-house sharing of emerging Inuit climate change initiatives and corresponding data among Inuit representational organizations

1.3.5 Promote Inuit-led and co-produced climate change research and monitoring

Long-term outcomes

- Inuit have meaningful roles at climate change decision-making tables
- Culturally appropriate, Inuktut educational initiatives linked to on-the-land Inuit knowledge transfer are sustainably and widely available across Inuit Nunangat, and internationally across Inuit Nunaat to Inuit in other circumpolar countries
- Best available knowledge, both Indigenous and scientific, is accessible and used in climate decision making across Inuit Nunangat and Inuit Nunaat

[5] Inuit Tapiriit Kanatami (2019): National Inuit Climate Change Strategy, Ottawa, ON. www.itk.ca/national-inuit-climate-change-strategy/resources/ (Excerpt from page 21, used with permission.)

Knowledge synthesis and mobilization

Integrating and contextualizing findings from individual studies (knowledge synthesis) and translating research outcomes into useful knowledge for practitioners (knowledge mobilization) are key activities in mainstreaming climate change science and knowledge into planning and decision making. While a great deal of knowledge has been developed, only a portion reaches decision makers in a timely or accessible fashion, and a lack of capacity among decision makers can also hamper their ability to use the information. Placing importance on knowledge synthesis and mobilization, in addition to knowledge generation, will allow Canada to reap the full benefit of its investments in climate change science and knowledge. Knowledge synthesis and mobilization also serve to establish a dialogue between knowledge producers and users, keeping research aligned with user needs and maximizing its utility and relevance. Opportunities for knowledge synthesis and mobilization for a range of topics (e.g., infrastructure, ecosystems, Arctic and North) are identified in Annex 2.

Broad national assessments, such as the reports produced under the Canada in a Changing Climate process (e.g., *Canada's Changing Climate Report, Canada's Marine Coasts in a Changing Climate*, and *Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation*) and expert panel reports, such as the Canadian Council of Academies' *Canada's Top Climate Change Risks and the Final Report of the Expert Panel on Sustainable Finance*, have helped raise general awareness and guide Canada's response to climate change. Beyond national-level reports, it is also important to produce knowledge syntheses tailored to the specific priority needs of various target users.

Increasingly, government departments, the private sector, Indigenous groups, and academic networks are preparing targeted climate science information (e.g., local-level assessment studies), drawing together results from surveillance, observation, and monitoring programs, model outputs, interdisciplinary analyses, and **science and risk assessments**. However, there are limitations to how accessible and understandable these targeted science and risk assessments are for individuals, communities, businesses, governments, and other organizations developing climate action plans. Knowledge mobilization efforts can increase the accessibility and use of these reports, as well as datasets and other scientific findings, in advancing resilience and decarbonization efforts. This includes improved Indigenous outreach, translation, and access to science and risk assessments. Further, creating targeted **knowledge portals** for communities, regions, or key sectors (e.g., energy, infrastructure, health, agriculture, fisheries, tourism)—and building on and promoting those that already exist—can also help move this knowledge to action.

National and regional **climate services** organizations (e.g., the Canadian Centre for Climate Services) are another useful mechanism for synthesizing and disseminating data and information from long-term monitoring, research, and analysis about climate impacts and vulnerabilities. Expanding existing climate services and/or integrating climate-oriented data portals with a broader array of geographical, ecological, health, and socio-economic data centres will generate additional knowledge and insights. It is also important to continue climate literacy efforts and communication related to the limitations of local and regional data and scenarios.

Case studies and lessons learned are another useful tool for mobilizing knowledge. This could include, for example, accounts of projects and promising practices related to community- and sector-level adaptation and mitigation, technology demonstration, health and well-being, climate-smart conservation, nature-based solutions, and beneficial land management techniques. Doing so can support the application of these approaches and tools in other contexts and locations, thus promoting the scaling up and out of promising solutions. These case studies also need to be translated into actionable, relevant information and tools to inform individual decision making, including information about efforts individuals can take to reduce emissions and/or protect themselves and their communities from climate change impacts.

As knowledge synthesis and mobilization efforts continue and are enhanced, targeted, audience-specific approaches for communicating climate change science and uncertainties to decision makers and community members will be helpful. Continued social science research into effective climate change communications and strategies for bridging the science-policy gap will be helpful in this respect. **Climate change science and data literacy** efforts at all levels should complement this work, as should efforts to develop **professional climate-related competencies** in all sectors. Scientists and boundary organizations have an important role to play in the delivery of knowledge through the various knowledge mobilization mechanisms outlined above, and through outreach and public engagement to expand both trust and climate literacy.

Science and knowledge needs

The science and knowledge needs identified here are organized according to four outcomes that are central to building a healthy, resilient, and carbon-neutral Canada. A strong foundational understanding of Earth system climate science underpins work across all outcomes.

The outcomes and the allocation of various needs within them are imperfect and do not adequately represent the integrated nature of research that will be required. A narrow approach that explores issues individually is insufficient. Climate change research must increasingly take a holistic approach that considers the synergies and trade-offs between mitigation, adaptation, the stewardship of nature, sustainable development, and equity and justice, in order to find comprehensive solutions that advance multiple priorities at once. Quantifying these co-benefits and developing metrics to evaluate the transformative potential of climate solutions will be important areas of work as integrated action advances.

The scale and urgency of the climate challenge do not afford the science community the luxury of time, making it necessary to do research in new and different ways. Experimentation and iteratively learning by doing and by observing will be increasingly important. The use of, for example, living laboratories, pilot studies, emerging technology demonstration projects, on-the-land observations, and the co-production of knowledge with practitioners, Indigenous Peoples, and community partners can be powerful research approaches to support transformative climate action. It is crucial to develop participatory research processes that involve deep engagement with non-academic partners, including participants from civil society and Indigenous communities, to transition away from extractive research approaches toward co-developed ones. Monitoring and evaluation of climate change interventions, particularly using an equity approach, will be key in ensuring effectiveness and avoiding inadvertently creating barriers or adverse impacts for some individuals and communities. The social sciences can play a key role here in understanding the degree to which certain programs and policies are successful.

Throughout this section, there are icons showing the specific sectors or areas of interest that are covered under each topic. The list below is not exhaustive, and is meant to help readers identify content that is applicable to their specific area of expertise, interest, or focus. A detailed list of research needs organized by these areas of interest can be found in Annex 3. These icons also serve a second purpose: to demonstrate opportunities for interdisciplinary work.

- ACCELERATING TRANSFORMATIONAL CHANGE
- ECONOMICS
- HEALTH AND WELL-BEING
- AQUATIC SYSTEMS
- ECOSYSTEMS (TERRESTRIAL AND AQUATIC)
- INFRASTRUCTURE
- COMMUNITIES AND SOCIAL STRUCTURES
- ENERGY
- LAND SYSTEMS
- EARTH SYSTEM CLIMATE SCIENCE
- EXTREME EVENTS

Advancing Earth system climate science

Understanding the complexities of the physical climate system, which includes the atmosphere, ocean, freshwater, land surface, and cryosphere (glaciers, permafrost, sea and lake ice, snow) is fundamental to advancing a wide range of climate change science and knowledge. This includes better understanding the ecological, hydrological, and biogeochemical aspects that influence climate through changes in GHG emissions, land use, atmosphere/ocean processes (including clouds, precipitation, sea level, ocean waves, turbulence circulation, weather and storm processes), surface albedo, the water cycle, and heat storage in the ocean. Given the global nature of climate change, Canada's science capabilities will benefit from continued international engagement.

Canada's Earth system model (CanESM) is an integral part of the international ensemble of climate models being used to make projections under a range of future GHG emission scenarios and includes carbon, sulphur, and, increasingly, nitrogen cycle feedbacks. Downscaling techniques provide more detailed information for the various models needed to assess climate impacts (e.g., crop simulations, basin-scale hydrological models, regional and basin-scale ocean models). Satellite observation data is an important input to Earth system modelling, providing observations of climate change trends and aiding in understanding the processes that drive climate change.

An increased level of effort is needed to improve the representation of the physical and biogeochemical processes and feedbacks, including ecosystem-level processes (e.g., forests, permafrost, tundra, wetlands), that are particularly relevant to Canada and that contribute to uncertainties around the magnitude and timing of future change. The assessment of feedbacks and related processes rests on a broad range of essential activities, from *in situ* and remote observations (aerial and satellite) and monitoring, focused field studies, surveillance, and laboratory work through to global and regional modelling and data archiving and analysis. Indigenous, national, and international scientists and partners are important in advancing these activities.

Work is also needed to better assess and simulate the influence of climate change on permafrost thaw and glacial melt, including their implications for carbon cycling, sea-level change, and feedbacks, as well as their direct effects on infrastructure and operations, natural resource sector productivity, habitat degradation, climate-driven infectious diseases, aquatic biodiversity, and water quality and availability. This work will depend on improved observations and simulations of the land and ocean surface and subsurface, higher horizontal resolution, and strengthened interdisciplinary research, including in collaboration with Northern and Indigenous communities.

Freshwater supply is subject to variability and change in key stores and fluxes of the water cycle, including extreme events such as droughts and floods. Given the importance of freshwater to some ecosystems, the economy, and the health and well-being of Canadians, research is needed to connect observed and projected climate change impacts on water supply to anticipated water demand across Canada.

Targeted interdisciplinary research is also needed to evaluate the effectiveness of different mitigation strategies and their trade-offs and interactions. One area in need of further research is our understanding of the role of short-lived climate forcers (e.g., methane, black carbon) in meeting near-term climate targets. Research to provide a more comprehensive scientific assessment of climate engineering (or geo-engineering, including Carbon Dioxide Removal and Solar Radiation Management) and its potential consequences would also be of value, including an analysis of the Canadian implications of climate engineering undertaken elsewhere.

A targeted and comprehensive research effort is also required to improve the prediction of climate extremes (e.g., heat waves, cold snaps, extreme precipitation, flooding, wildfires), including in the ocean (e.g., acidification, deoxygenation, hypoxia, marine heat waves, high salinity). This includes work on flooding, erosion, and exacerbated landslide occurrence caused by extreme precipitation. On the coastline, flooding, storm surges, and erosion are increasing from local sea-level rise and the reduction of sea ice duration and extent. More work is also needed to better understand convective events leading to thunderstorms, extreme winds, and localized rain and hail, to inform resilience measures in the built environment (including natural infrastructure) and better emergency preparedness. Such work will inform improved predictive capabilities to ensure Canadians are able to better prepare for individual climate events with sufficient advanced warning.

SCIENCE IN ACTION: INCREASING CLIMATE RESILIENCY FOR BUILDINGS AND INFRASTRUCTURE

Extreme weather events can cause severe damage to residential and commercial buildings, as well as to other core public infrastructures (e.g., bridges, roads, wharves, municipal water systems, rail transit). To help prepare communities and private building owners, Infrastructure Canada and the National Research Council are collaborating with Environment and Climate Change Canada and others on research to inform the planning of new buildings and the rehabilitation of existing ones, with the ultimate result of integrating climate resiliency into building and infrastructure design, guides, and building codes. These guidelines and codes (e.g., wildland fire urban interface, flood resiliency of buildings, adaptation of existing stormwater management systems) will enable adoption and enforcement by provinces, territories, and municipalities to increase resilience.

The development of downscaling techniques must continue in order to provide more spatial detail and information tailored to specific sectors or regions. This will improve the utility of climate projections for communities, biodiversity, agriculture, fisheries and aquaculture, infrastructure, transportation, ocean and coastal impacts, natural resources, health, and other domains. Downscaling efforts would benefit from the improved use of existing, emerging, and novel approaches for observing the Earth system, including space-based observations (particularly for Canada's data-sparse Arctic and North) and from data analytics and synthesis techniques that leverage shared data and research infrastructure (e.g., ships, aircraft). Further developing techniques to assimilate satellite and surface observations efficiently and enhance the spatial detail in model and downscaling outputs will enable better prediction of climate extremes and help extend the range of climate variables covered by the seasonal to decadal predictions used in climate services.

BOX 5. EVENT ATTRIBUTION

Increasingly, there is a desire to identify the extent to which extreme events and their impacts can be attributed to anthropogenic climate change. That is, to quantify the extent to which human activities (GHG emissions, aerosols, land-use change) have made certain events more intense and/or frequent. By being explicit about the role of human activities in changes in extremes and extreme events, attribution strengthens the business case for, and acceptance of, climate action. It also helps facilitate the development of cross-jurisdictional governance, multi-stakeholder decision-making frameworks, emergency management plans for disaster risk reduction, and financial assistance related to extremes (e.g., disaster relief, insurable risks).

Extreme events are associated with substantial physical and mental health issues and economic costs. Increasingly, government and non-government actors are seeking to understand attribution in the context of investment risk disclosure, insurance payouts, culpability related to due diligence in implementing climate action, and financing for infrastructure renewal. There are, however, very few studies that have attributed trends in Canadian extremes and specific extreme events in Canada to anthropogenic climate change. Additionally, there are challenges in defining which extremes or extreme events are relevant, as this can differ between sectors.

The spatial and temporal resolution of both observed and simulated Canadian climate extremes datasets (e.g., extreme heavy precipitation) are currently insufficient to support regional detection and attribution studies and additional capabilities are needed for the routine attribution of individual extreme events as they occur. A better understanding of the processes that drive extreme events is also integral to their improved prediction on timescales of days through decades. Comprehensive attribution of extreme events in Canada requires the study of the full range of climate, weather, and environmental variables and processes. This includes consideration of compound extreme events, when extremes occur concurrently or consecutively (e.g., extreme hot temperatures alongside very low precipitation).

Extending the analysis through to the attribution of the impacts and related socio-economic costs requires even broader data on how a sector or community is affected. Evaluating individual, community, corporate, and government impacts and responses relies on an understanding of historical event attribution and improved prediction of extremes, and is constrained by the limited availability of socio-economic data at an appropriate scale.

Healthy and resilient Canadians, communities, and built environments

The impacts of climate change put the health and well-being of Canadians, communities, and infrastructure at risk, and increased resilience is needed on all levels (e.g., individual, local, regional, national, global). To ensure that efforts to build resilience are effective, a nuanced and thorough understanding of vulnerabilities, strengths, and risks is needed, given that these are not distributed uniformly across all regions and social, cultural, and economic groups. Strengthening our understanding of the similarities between climate change adaptation and disaster risk reduction—two areas with similar objectives—will also help build resilience by contributing to a more integrated and efficient use of resources.

Overall, research to quantify the costs and benefits of impacts and adaptation action in Canada is needed, including how these costs would evolve in different scenarios (e.g., in the case of delayed mitigation action, abrupt non-linear changes). This research and analysis is key to understanding the value of investments in adaptation and resilience, and full lifecycle analyses will be critical here, supported by robust data and curated databases. Research on methods and governance for financing adaptation would be helpful, including insights related to balancing and mobilizing both private and public financing.

Developing a place-based, intersectional understanding of vulnerability and resilience

Climate change impacts and actions are not experienced in the same way by all Canadians, with the already marginalized and economically vulnerable often being disproportionately affected. In many cases, the quality of determinants of health and other social characteristics drive vulnerability to climate change and influence individual and community adaptive capacity. Research is needed on these drivers (e.g., sex, gender, race, sexuality, age, language, ability, income, education, location) and how they shape experiences of climate change impacts, vulnerability, strengths, and the ability to adapt. Work to explore how individual and community assets and resources can contribute to adaptation efforts would complement this research.

Understanding the impacts that climate change policy, programs, and legislation have from an equity and gender perspective is needed, as is work to understand the exclusion some groups face in adaptation and mitigation efforts. Identifying opportunities to use climate actions to address broader social and health inequities (e.g., poverty, unemployment, colonialism, language barriers, and lack of access to healthcare and public health services, education, energy, and housing) will also be useful. Given the heterogeneous experiences of climate change, place-based perspectives that enhance and leverage the agency of communities to act are essential, especially for vulnerable communities (e.g., coastal, forest, agricultural, rural, remote, Arctic and Northern, and on- and off-reserve Indigenous communities) and those facing climate change-induced displacement.

Longer-term economic studies of the differing effects on key demographic groups and geographic regions—including intergenerational effects—are needed, and could explore the job market, food prices/cost of living, energy accessibility and security, and food security. Work to develop costed options for minimizing impacts, to understand the consequences of cost shifting (e.g., between groups, regions, generations, etc.), and to identify options for minimizing undesirable impacts of climate action on different groups will be beneficial.

Developing partnerships between researchers, knowledge holders, cities, Indigenous Peoples, and communities will help advance knowledge related to the process of transformative climate action. Examining how novel approaches are implemented, understanding their transferable lessons, and studying how communities can motivate local governments to take action can all directly inform climate action at the local level. Better understanding the mechanisms of inclusion, transparency, and collaboration when building political legitimacy will help minimize the disruptive effects of transformative change, especially for marginalized communities and community members, and can help expand the positive impacts of climate change interventions.

Research is also needed to develop an integrated understanding of risk that takes into account social, cultural, ecological, health, and economic factors. Qualitative methods can make an important contribution to developing a nuanced understanding of how communities feel about the risks and stresses they are facing and the decisions being made to address them. This work will contribute to understanding the broad impact of extreme events, as well as the more gradual (slow-onset) impacts of climate change—including exposure, vulnerability, and risk management—and their effects on individuals, communities, and the interconnected systems on which they rely.

Supporting healthy Canadians and resilient health systems

Climate change poses significant direct and indirect risks to the physical and mental health and well-being of Canadians. It also affects health systems, for example through extreme weather events that damage health infrastructure and lead to hospital evacuations, disrupted delivery and supply chains, and increased health costs and pressure on the public health system. Continued research is needed to assess climate-driven risks and vulnerabilities across the health system (e.g., workforce, information systems, infrastructure, service delivery), and identify adaptation actions.

To reduce these risks, Canadians and communities, health and public health professionals and authorities, allied professionals, and decision makers in other sectors all require relevant and actionable research, laboratory diagnostics, knowledge, and evidence. Public health can play a critical role by providing climate change and health information, influencing and empowering behavioural change among Canadians, and supporting decision making to mobilize action. Understanding the impacts, risks, and opportunities for human health will require investigating climate impacts across the health research spectrum—bio-medical, clinical, health system services, population health—as well as research into understanding interactions with other sectors and disciplines. Addressing challenges related to the availability and accessibility of high-quality, timely data and the interoperability of environmental and climate data with health data will allow the measurement of climate change health impacts.

In particular, there is a need to better understand climate-related risks to the health of Canadians, such as those associated with extreme weather events (e.g., heat waves), natural hazards, emerging climate-driven infectious diseases, impacts to mental health and well-being, and changes in air quality. For example, research is required to support an integrated understanding of how climate change will affect air quality (including outdoor air pollution, wildfire smoke, aeroallergens, and indoor air quality) and the associated health and economic impacts, as well as how climate action can lead to air quality health and economic co-benefits. Innovative and collaborative actions are needed to support novel, integrated, and multi-disciplinary surveillance and monitoring, and to enhance prediction and modelling capabilities for greater foresight. This includes new or advanced approaches for data collection and analysis, early warning systems, community science, novel laboratory diagnostics, meta-genomics, and geospatial mapping in partnership with other sectors, disciplines, academia, Indigenous Peoples, and all levels of government.

Climate-related health risks are experienced differently across populations (e.g., Indigenous Peoples, seniors, children, the socially and economically disadvantaged, people with chronic illnesses or mobility challenges, women, immigrants) and communities (e.g., urban, rural, remote, Indigenous, Northern, coastal). Research is needed to understand these differential impacts, strengths, and vulnerabilities, and their implications for population health and health equity. This work should include considerations of the intersection of climate change and colonialism on Indigenous mental health.

The health of humans, plants, animals, and entire ecosystems is connected, necessitating a multidisciplinary 'One Health' approach to understanding the complex interactions between human, environmental, and animal health. This includes understanding how this interrelation is driving changes in the geographic distribution, seasonality, and/or transmission of infectious diseases, pests, and related food security implications. This also provides a critical opportunity to build on the experiences and learning of other disciplines and sectors. For example, there is a need to identify where and when climate-driven infectious diseases may emerge or re-emerge in Canada, such as the climate impacts on zoonotic, food-borne, and water-borne diseases.

Understanding how climate change will impact the systems that support health, such as water, sanitation, and food and nutrition (e.g., through impacts on fisheries, aquaculture, and agriculture) is an important area of interdisciplinary work, as is work to understand how the actions of non-health decision makers influence the health impacts of climate change (e.g., transport, water, urban planning, energy, agriculture, conservation). Health co-benefits and risks can be associated with climate change measures taken in other sectors. For instance, investments in active transportation infrastructure can increase physical activity and air quality, landscape management actions to lessen urban heat or infectious disease risks can provide carbon sequestration or flood protection, and the deployment of nuclear generation can also provide medical radioisotopes. Research into these kinds of no-regrets solutions will be beneficial in identifying and designing climate solutions that also have positive spillover effects in terms of mental and physical health and well-being, health equity, community health, and climate resilience.

SCIENCE IN ACTION: BRINGING PARTNERS TOGETHER IN A ONE HEALTH APPROACH

'One Health' is a multi-sectoral approach that brings together human, animal, plant, and environmental health disciplines to integrate data, science, and research and work collaboratively to achieve better public health outcomes. The ECO2 Prototype is a One Health pilot collaboration between the Public Health Agency of Canada, Environment and Climate Change Canada, Agriculture and Agri-Food Canada, and the Canadian Food Inspection Agency in the South Nation Watershed in Eastern Ontario. It monitors infectious disease emergence, environmental change, and biodiversity, while supporting the development of regional partnerships with individual citizens (farmers, landowners/managers, communities), local universities, and local and provincial government scientists and officials within human, livestock, wildlife, and environmental health fields. By working collaboratively, the prototype enables the collection of field, laboratory, climate science, and Earth observation data needed to understand how climate/environmental changes influence infectious diseases. This science and knowledge generated is used to forecast disease outbreaks and support early warning systems that inform decision making and action at the local level.

Supporting healthy communities will require more than just research to understand impacts. It will also require research on how to design and test interventions that could provide long-term, scalable, and impactful solutions. Interdisciplinary intervention research and implementation science focused on maximizing health and resilience outcomes will be key. Given that the health sector plays an important role in supporting a stable society and economy, there is a need to understand how climate change related-health issues may affect other aspects of society, such as economic performance and productivity, and social cohesion and functioning.

BOX 6. UNDERSTANDING THE MENTAL HEALTH CONSEQUENCES OF CLIMATE CHANGE

The need to understand the mental health effects of climate change has increased in response to a growing number of Canadians experiencing climate-related grief, traumas, and anxieties. This field of study is growing, and a large part of the work to date in this area has been Arctic- and Inuit-specific.

Health decision makers and those in other sectors (e.g., emergency management, occupational health) need tools and capacity to measure and monitor the mental health effects related to specific climate hazards (e.g., traumas related to experiencing wildfires or flooding; violence, aggression, and suicide related to extreme heat) and the mental health effects of experiencing climate change more broadly (e.g., eco-anxiety, ecological/climate grief). Further, there is a need for research to understand and support psychosocial adaptation to a changing climate. Future adaptation efforts will benefit from a greater understanding of the mental health impacts of climate change on specific population groups, for example, the effects on children and youth who appear to be experiencing eco-anxiety or eco-grief, as well as impacts from more frequent exposures to climate-related hazards. Effectively planning for climate change impacts on health will also benefit from greater knowledge of affirmative mental health outcomes, like psychosocial resilience, altruism, and compassion after experiencing climate hazards. Finally, there is a need to understand the best ways of communicating about climate hazards in a way that does not induce more anxiety or overwhelm Canadians, but rather motivates action and supports individual and social well-being.

Advancing knowledge in these areas is limited by a lack of population-level data on mental health that is interoperable with ecological and environmental data. Expanded surveillance of mental health in a changing climate is necessary to understand the health effects of climate change.

Building climate-resilient communities and infrastructure

Adapting to climate change will require significant changes to where and how our communities are planned and built, from their overall design to their individual infrastructure assets. Infrastructure (e.g., buildings, transportation, energy) is one of the sectors most at risk from climate impacts, and those impacts can have negative effects on ecosystems, health and well-being, cultural resources, and the economy. It is also one of the sectors with the greatest potential to reduce vulnerability and GHG emissions.

To inform efforts to increase community and infrastructure resilience, there is fundamental work needed to better understand risk. An integrated approach to risk assessments that examines climate risks, vulnerabilities, system interdependencies, and cascading impacts will support a deeper understanding of current and future climate risks and their associated costs at a variety of scales. An improved understanding of risk will also benefit from continued work on natural hazards, extreme weather events, and slow-onset climate change impacts, such as how changes in frequency and intensity of extremes will affect the resilience and reliability of infrastructure (e.g., increased loads, accelerated aging of materials, increased energy demand) and which impacts are likely to have the greatest consequences both now and in the future. In the rapidly changing context of the Arctic and North, it is particularly important to better quantify climate impacts over time (e.g., precipitation, temperature, wind, permafrost thaw, sea-level change, sea ice, waves, storm surges) and determine their effects on already-vulnerable infrastructure, including for Indigenous communities, and mechanisms for mitigation and adaptation. Economics work on non-linear change and tipping points as they relate to vulnerable infrastructures, including questions of loss and damages, liability, and compensation, will inform a more integrated understanding of risk.

In addition to understanding climate-related risks to Canadian communities and infrastructure, there is a need to understand the value of resilience measures and their co-benefits. This includes better evaluation of the cost-benefit or return on investment of both design-phase and retrofit traditional, hybrid, and natural infrastructure solutions, as well as analyses of how energy efficiency measures and construction and maintenance quality affect emissions from built infrastructure, including from heritage assets. Furthermore, a more integrated understanding of the economic, social, health, ecological, cultural, and reconciliation implications and co-benefits of different resilient infrastructure solutions is needed across all scales, as this will be crucial in developing resilient, equitable, and culturally appropriate infrastructure in Canada. For example, it would inform the development of housing, energy and transportation systems, and coastal infrastructure in Arctic and Northern and Indigenous communities.

Developing and implementing infrastructure solutions will require knowledge mobilization and increased professional capacity. Qualitative methods can help researchers and practitioners to understand the challenges different professionals are facing in building climate-resilient communities and infrastructure (e.g., urban planners, engineers, economic development directors, emergency managers, park directors, utility managers).

At the asset level, the location, design, repair, and replacement of built assets will benefit from data and analyses on the types and condition of existing assets, as well as from greater coverage of information related to the impacts of climate change on geological materials and processes (e.g., erosion, permafrost, landslides). Asset management is a promising point of entry for adaptation efforts, and work is needed to develop better asset monitoring, identify best practices for building resilience, and better understand the intersection of adaptation and mitigation (e.g., lifecycle assessments of costs and emissions).

In terms of infrastructure solutions at the broader landscape and community levels, work is needed in two areas: natural infrastructure and community design / the built form. Natural infrastructure solutions, landscape naturalization, and nature in general (including networks of protected areas) can make important contributions to building resilience, in addition to offering multiple co-benefits. Work is needed to help decision makers understand how and where to apply them. Research related to resilient community design and the built form is also needed to determine how to implement transformational community design changes in ways that are practical and actionable, that respect the environment, and that maximize health co-benefits. This research is needed for a range of contexts (e.g., urban, rural, remote, Arctic, Northern, Indigenous). Pilot projects could play an important role in engaging communities in co-developing, testing, and evaluating context-specific interventions (e.g., increasing densification).

Resilient communities rely on a range of systems (e.g., health facilities, water, energy, transportation) that need to remain operational during extreme events or come back online quickly following these events. Research is needed to advance the resilience of these systems and their various intersections, including through the development of revised codes and standards. This includes focused work related to critical infrastructure (e.g., hospitals and health facilities) and the community infrastructure needed to support it (e.g., roads, water and sanitation). A deeper understanding of the attributes of resilience (e.g., redundancy, diversity, modularity) and how they can be incorporated into Canadian communities and the systems they rely on will also be beneficial.

Enhanced capacity to project future water availability and quality will ensure that municipalities can make informed decisions in planning for and responding to climate change impacts on their water supply, and will also contribute to planning, preparedness, and responses to water-related disasters. This should be complemented with research on inclusive governance for integrated water management at the local and regional scales.

Canadian society depends on diverse energy inputs, and increasing the resilience of the processes and infrastructure through which that energy is produced, delivered, and consumed is crucial. Research is needed to develop communication strategies, control algorithms, modernized monitoring, and appropriate and adapted technologies to reduce reliance on diesel. In addition, implementing modular, multi-application (e.g., co-generation), scalable, and resilient non-emitting energy systems will require a holistic approach to research to find synergies and advance multiple priorities at once. Planning for these solutions, particularly in Arctic, Northern, Indigenous, and remote communities, will require insights into how to balance energy infrastructure needs with energy security, the maintenance of ecological integrity, and the ability to provide nature-based climate solutions.

BOX 7. FLOODS: UNDERSTANDING RISK AND RESILIENCY

Many parts of Canada are anticipated to experience increased flood risk resulting from climate change, owing largely to more intense rainfalls, local sea-level rise, changing sea-, river- and lake-ice conditions, storm surges, increasing wave heights, and other environmental changes. These impacts sometimes intersect with land-use planning decisions that do not account for climate and flood risks.

Flooding across Canada causes over $1 billion in damages annually, with certain populations (e.g., First Nations on reserves and Métis communities, coastal communities) having a higher risk for evacuation and longer recovery periods. Flooding events exacerbated by climate change can increase the risk to public health and safety, damage infrastructure, impact landscape stability, disrupt municipal drinking-, storm-, and waste-water systems, and cause sudden contaminant or nutrient releases from agricultural, industrial, and urban areas with significant public health and ecosystem impacts.

Climate change and human activities (e.g., clearing vegetation, diverting water, paving) have impacted many surface landscape features, including forests and wetlands, which can affect a region's hydrology and associated flood risk. However, there is a limited understanding of how these changes will impact future flooding and what interventions can be used to reduce flood risk (e.g., ecosystem restoration).

There is a growing amount of quantitative information about flood risks and impacts (including economic and property damages), as well as qualitative information from Indigenous communities based on teachings of adaptation to past land changes and recent stories of flood events. However, continued work involving many ways of knowing is required to better understand future flood regimes. This includes a better understanding of future flood risk due to extreme precipitation events, as well as the more complex spring floods driven by factors like changing winter snowpacks, earlier spring runoff, river ice-jams, and prevailing ground conditions. For coastal regions, improved knowledge about long-term changes in local sea level and reductions of sea ice is critical, since this will result in more frequent damage to coastal infrastructure and ecosystems supporting the fisheries and tourism sectors.

In terms of implementing risk reduction efforts, there is the perception that healthy and resilient ecosystems, such as forested watersheds, peatlands, and wetlands, have an essential role to play in buffering communities from flooding. The extent to which these ecosystems ameliorate flood risks is site specific and not always well quantified, nor are the impacts of a warming climate on these ecosystems in flood-prone regions.

Reducing flood risk is a key element of emergency management planning. Beyond the critical step of updating flood maps, the science must continue to evolve by integrating climate, weather, and hydrological modelling tools with enhanced land-cover information to improve planning and engineering design through detailed analysis of the accelerating hydrological cycle. Enhanced operational flood predictions for inland, riverine, and coastal communities and regions are required, which rely on improved predictions of the changing intensity and frequency of extreme precipitation. Coastal communities will be even more prone to increased flooding due to sea-level rise, increased storm occurrence and severity, and increased storm surges.

Developing a better understanding of inclusive governance mechanisms for integrated water management, including managing flood risk, at local and regional scales, will inform risk reduction measures. Work is also needed to understand how flood risk and disaster risk reduction interventions (e.g., enhanced spillways, wetland retention, community relocation, zoning changes, adjustments to disaster relief financing and flood insurance) could affect vulnerable communities, in order to avoid exacerbating social and health inequities. This work should draw on the lessons learned from Indigenous and non-Indigenous communities that have experienced flooding.

Research is also required to better understand the mental health and community impacts of flooding. Additionally, work to understand the societal response to flood risk will provide insights into how to encourage adaptation at many levels, including the implementation of climate-resilient building codes, standards, and guidelines. Finally, given the broad range of impacts (public health, multiple economic sectors, ecosystems, infrastructure), research into economic valuation or avoided costs of adaptation and resilience is important to inform action, including economic analyses that compare long-term flood mitigation costs against relocation costs.

Understanding climate impacts on trade, migrations, development, and governance

Climate change will impact socio-economic systems, such as trade, migration, and international cooperation. It also has the potential to worsen geopolitical tensions and social conflicts, trigger humanitarian crises and the displacement of people, and affect global trade systems. Research is needed to assess the scope and likelihood of these risks and the role of adaptation in reducing them.

Work to understand the potential of climate change to act as a threat multiplier and magnifier in the international and global security context should examine potential impacts on domestic and international trade (e.g., climate policy impacts on trade disputes, impacts on trade-related transportation infrastructure), as well as its impact on domestic and international treaties, boundaries, and agreements. Work to assess the effectiveness of existing environmental provisions in Canada's trade agreements in reducing the negative impacts of trade on climate and the environment is also needed, as is research to advance international collaboration on climate-friendly trade. Strengthening our understanding of the resilience of trade routes, the potential impacts of climate change and extreme events on them, and ways to address vulnerabilities and build resilience will also be helpful.

Climate change threatens to reverse the significant development gains achieved globally over the past decades, and could push many people in developing countries below the poverty line. Research on the effects of climate change and climate-related policies on the poorest and most vulnerable could help improve the adaptation results of international assistance in developing countries. Work is also needed to understand the impacts of climate change on global migration patterns and Canada's immigration and resettlement programs, and strategies for preparing to meet those needs, for example with respect to the provision of health and social services.

Moving from the global to the local governance level, more research is needed to understand the degree to which municipalities are autonomous, how this affects their implementation of climate policy (especially policy set at the federal and provincial levels), and ways to develop and increase the flexibility of municipal governance tools to ensure implementation reflects local realities. Given the movement of people and products, research to support more effective multi-jurisdictional governance and regional coordination on climate action will be beneficial, as will work to better understand governance fragmentation and regionalization and its impact on effective action.

A carbon-neutral society

Exceeding Canada's 2030 GHG emissions reduction goal under the Paris Agreement and achieving net-zero emissions in Canada by 2050 will require transformational change across society and the economy. It will mean substantial decarbonization in all sectors, particularly in the energy sector, which accounts for the majority of emissions. This will require significantly changing how we produce and use energy, as well as protecting and enhancing our carbon sinks. A range of economic and policy instruments will be needed to drive this change and support emerging technologies that could contribute to decarbonization. While technology and economics are important parts of the solution, decarbonization is also a behavioural challenge, and social science work will be critical in understanding what limits or inspires action.

Accelerating social and behavioural change

Engaging the public on policy responses and motivating action is the foundation of ambitious and successful mitigation efforts. Economic and behavioural shifts may be challenging to maintain in the long-term through policy design without strong and continued social license. Understanding Canadians' perceptions of evolving climate policy (e.g., through the Canadian Surveys on Energy and Environment) and their attitudes towards behavioural shifts over prolonged time series will help shape policy design that is consistent with climate science and that increases the level of stringency in socially acceptable ways that move Canadian society towards positive tipping points that result in rapid changes. This understanding could also be key in leveraging buy-in from communities that have relied on carbon-intensive industries for their livelihood and economic prosperity over many decades.

Similar work is required to better understand behaviours that lead to climate resilience, and it will be important to explore adaptation and mitigation jointly where appropriate in order to maximize co-benefits. Beyond approaches focussed on individual behaviour change, insights are needed for the systemic normalization of sustainability across society. Understanding how to structure education to strengthen environmental sustainability and climate action will play an important role here, as will social research on processes of environmental education and social learning.

Research related to the effective communication and appropriate framing of messaging is needed in order to encourage awareness and action, address complacency and/or the tendency to respond to urgent rather than slow-developing risks, and build support for proposed measures. This is especially important given that this messaging is dynamic, evolving as individuals shift their values and behaviours.

Continued psychological, economic, and social science research into behavioural change will be beneficial, as will better integration of existing knowledge from these fields into decision making and planning. This includes work to understand the factors that motivate or prevent action at the individual and collective levels, including the positive reinforcement between behavioural change and structural change. Understanding the possible future states of our systems and structures (e.g., social, economic, political) is key to identifying policy mixes that support environmentally sustainable behaviours that reinforce climate-related goals. Finally, insights into where individual and social behaviour can play the greatest role will help accelerate progress to reduce emissions and build resilience.

Identifying pathways to decarbonization

As Canada pursues decarbonization efforts on the path to reaching net-zero in 2050, a significant amount of research will be required to understand the process of decarbonization, the various levers that can be used, and potential barriers. The process of decarbonization will not be linear. In fact, attempts to measure early progress may not even reveal that changes are underway. As such, research is needed to develop measurable indicators of transformative change.

Foresight practices will be useful in identifying pathways to transformational change, while applied decarbonization pathway research and analyses that model the impact of various mixes of policy instruments will support the development of detailed mitigation strategies. This work should aim to improve understanding of the technological, social, health, political, and economic perspectives related to these pathways. Given that policy instruments can lead to large-scale, long-term change and increased public support, work to evaluate the transformative potential of the various interventions will be a useful complement.

Integrated assessment models (IAMs) can deliver a synthesis of knowledge across multiple social, economic, and future climate contexts. In a climate context, IAMs link social and economic drivers with Earth system climate models. IAM results are interdisciplinary by nature and can illustrate the potential risks and benefits across multiple simultaneously changing pathways. However, there is limited IAM capacity in Canada.

Nurturing analytical and modelling capacity in Canada is a prerequisite for understanding the inherent trade-offs and synergies in climate policy and regulations. Doing so will support the development of emission mitigation pathways and adaptation priorities that respond to diverse societal, cultural, health, economic, and environmental priorities and values in Canada. Greater collaboration and capacity in academia, government, and Indigenous communities will foster future enhancement and extensions of IAMs that are attuned to Canadian contexts. Areas of priority in IAM development could include damages and feedbacks (e.g., effects of permafrost thaw, impacts on and effects of air pollutants), technological learning and transitions for mitigation options, the costs and benefits of mitigation and adaptation, the integrated inclusion of nature-based climate solutions, and the effects of socio-economic transformations (e.g., circular economy).

As work to decarbonize progresses, advances in economics and social sciences will be needed to inform a just transition. Social science research can help communities plan for new energy futures and navigate any unintended social impacts during the transition. Analyses are needed of alternative employment and economic strategies that are both creative and ambitious enough to address the necessary shifts in the Canadian economy. Specific labour market-related questions include how workers from different sectors will be affected by climate change and Canada's response to it, as well as the gender breakdown of employment in fields designed to mitigate climate change, such as clean energy or sustainable transport. In addition, studies of structural changes are needed to ensure that the burden of this transition does not fall on those who can least afford it, as is work to understand issues of clean energy affordability and reliability. Finally, decarbonization strategies may have implications and unintended consequences (positive or negative) on, for example, human health and well-being. Understanding these impacts, ways to navigate trade-offs, conflict, and resistance, and opportunities to maximize co-benefits and build climate resiliency, will be required.

Advances in socio-technological systems can contribute to sustainability transitions, and energy is one area where this will be key. Decarbonizing the energy supply will play a critical role, and there is a broad need for science related to full lifecycle assessment of clean (e.g., solar, wind, nuclear, water, geothermal, hydrogen, biomass) and fossil energy sources and pathways, energy efficiency, and electrification. Advances in artificial intelligence, big data, non-technical and social barriers, and advanced materials will be essential. In terms of energy efficiency, research is needed to help foster next-generation technologies and infrastructure to improve the efficiency of vehicles and related infrastructure, industrial processes (e.g., via energy management systems), and buildings (e.g., smart appliances, net-zero design, space heating and cooling). It will also be critical to understand the role of carbon capture, utilization, and storage technologies and to develop marketable products out of carbon dioxide to render these technologies economically viable in order to reduce emissions from sources that are more difficult to replace with lower-emitting alternatives.

For electrification, advances in innovative technologies are needed, including smart and distributed energy technologies and systems, integrated technologies for cleaner energy, and clean heat and combined heat and power. Research to develop small modular reactor and energy storage technologies to be applied at the community level will help address the variability of some renewable technologies. Electrifying transportation will require work to develop more advanced zero-emission technology where practical solutions for reducing emissions are not available. Key gaps here include those related to medium- and heavy-duty vehicles, off-road equipment, marine, and rail. Research to address barriers to infrastructure installation, operation, and management will also contribute to electrifying transportation.

The development of cleaner future fuels requires an improved understanding of their full lifecycle impacts, and insight into how existing systems and infrastructure must be adapted to enable their use. Effectively supporting the integrated assessment modelling of potential risks and benefits of future fuels requires science-based lifecycle analyses (LCAs) that accurately establish the emissions of short-lived climate pollutants, criteria air contaminants, and toxics across multiple simultaneously changing renewable and non-renewable fuel pathways. Effective policy development will require that new LCA science provide highly resolved spatial and temporal differentiation of the health and environmental risks and benefits of future renewable and non-renewable fuels across all production and consumption pathways. For instance, the design of

SCIENCE IN ACTION: REDUCING AVIATION-RELATED GHG EMISSIONS THROUGH BIOFUEL BLENDS

A collaborative research project between several partners, including Chevron Lummus, Agrisoma Bioscience, the National Research Council (NRC), and the Green Aviation Research and Development Network, led to the world's first civil jet flight powered by 100% biofuel in 2012. The work to advance sustainable aviation is continuing. For instance, the partners in the Civil Aviation Alternate Fuel Contrail and Emissions Research project gather data to test the environmental benefits of biofuel use in commercial flights. Advanced sensing equipment mounted on an NRC research jet is measuring the impact of biofuel blends on contrail formation from an aircraft in commercial operation. Results of this work have shown that the emissions of a commercial airplane in cruise mode are considerably reduced when using a biofuel blend compared to conventional jet fuel.

future energy systems requires research into resilience, reliability, economic cost, energy security, and land-use minimization, while renewable fuels policies must be informed by research to ensure that biofuel development does not endanger food security. The development and integration of cleaner fuels will require community engagement to foster leadership and ownership of these initiatives.

From an infrastructure standpoint, the choices made today regarding the construction and management of built infrastructure and natural assets will have long-term consequences for decarbonization in Canada. It is essential to better understand the mitigation potential of infrastructure, as well as the co-benefits of joint mitigation and adaptation action. Accurate, transparent, and trusted LCA tools, methods, and data are needed to support infrastructure decision making and should incorporate future climate projections and resilience considerations. A better understanding of when and where to apply natural and hybrid infrastructure solutions and the ability to quantify potential reductions and co-benefits associated with them is also needed, including a standardized methodology for measuring emissions and embodied carbon in natural and engineered materials and assets. In terms of energy efficiency retrofits, estimates of the capacity to cost-effectively retrofit building stock and heritage sites will be beneficial. The challenges for Canadian heritage buildings and sites are unique for both mitigation and adaptation, and research is needed to provide guidance on retrofitting these sites.

Protecting and enhancing our carbon sinks

Net carbon removals in land and aquatic systems will be an important tool in achieving net-zero emissions. Action on this front will require an improved fundamental understanding of carbon stocks and GHG fluxes and transfers. Special emphasis is required in northern ecosystems, given the complex interactions between the landscape and permafrost systems and the atmosphere-sea ice-ocean system. There is an opportunity here to partner with Indigenous Peoples in the North to build capacity, collect consistent and accurate data, and leverage synergies with Indigenous Knowledge, ensuring Northern participation in research for the North.

Currently about one quarter of the CO_2 entering the atmosphere through human activities is taken up by the oceans. However, there are uncertainties surrounding the capacity of the oceans to absorb carbon in the context of a changing climate that will require further research (e.g., ocean warming, changes in primary production, retreating sea ice). Research is also needed to better understand carbon movement in aquatic systems, as well as between terrestrial and aquatic environments. An integrated framework could enable collaboration and address interactions and linkages across land and aquatic systems (e.g., wetlands, forests, grasslands, croplands, inland and coastal aquatic systems).

Given the asymmetry of risk that exists between the slow natural uptake of carbon and the potential for its fast release in the event of a disturbance, work is needed to better understand and estimate the impacts of climate change and human activity on carbon stocks and GHG fluxes, particularly at a regional scale. There are specific knowledge gaps here related to wetlands, lakes, rivers, permafrost, and northern soils and peatlands. Improving how disturbances (e.g., agricultural drainage, resource extraction) and management actions (e.g., related to forests, silviculture, and soils) are observed, quantified, and modelled will reduce uncertainty with respect to the mitigation potential of these systems.

In examining mitigation strategies, the full environment-economy system should be considered, including net GHG and other climate-forcing impacts across ecosystems and human use of them (e.g., for wood products, food, energy). Additionally, as climate change causes shifts in land suitability, agricultural zones may shift at the expense of forests or wetlands, and work is required to assess the impact of these shifts on carbon and GHG fluxes, and other environmental and socio-economic consequences.

The need for rapid and deep emission reductions means that work to better understand carbon stocks and GHG fluxes must be paired with applied research aimed at understanding and developing regional and local mitigation best practices and actions in the land and aquatic sectors. For instance, this could include the conservation of carbon-rich areas, facilitated through the use of perennial crops in agriculture, macroalgal crops in the ocean, the protection of natural kelp and eelgrass beds, and the creation of protected areas and Indigenous protected and conserved areas. This would also contribute to achieving the goal of protecting 25% of Canada's land and 25% of our oceans by 2025. Decision makers need research results relevant to their specific land type or aquatic zone, the management options available to them, and the expected impacts and risks. Monitoring the results of carbon sink management interventions will encourage learning from experience.

Understanding the economic aspects of carbon neutrality

There are still important knowledge gaps related to the economics of mitigation options, including the cost effectiveness of various technologies and practices, and this work will help identify trade-offs associated with different pathways to carbon neutrality. This includes research aimed at developing the social cost of carbon, marginal abatement costs, and measures of technological innovation. Further research and modelling is also needed on the design and impact of carbon pricing instruments, options for revenue recycling, and complementary policies, particularly as they relate to the Canadian context, which should be undertaken with an intersectional lens. Research on the impact these pricing instruments and complementary policies have on competitiveness will also be valuable. In addition, research into the economic valuation of health and environmental co-benefits of mitigation is required, as these can yield large immediate societal benefits and help offset the costs of emissions reductions.

Economic research related to infrastructure is needed on two fronts: (1) measuring the economic value of infrastructure solutions (natural, hybrid, and built) that sequester carbon and (2) measuring the economic value of potential housing stock retrofits in northern and remote contexts, where this work is especially complex. Research here will need to incorporate interdependencies between social, well-being, and reconciliation aspects to ensure equity. In the North, this work could inform immediate decision making to address acute housing needs while making informed short-, medium-, and long-term choices related to low-carbon development pathways.

Finally, there are knowledge gaps to fill related to the financial implications of climate change (e.g., sustainable finance, climate finance, insurance, international markets), including mobilizing private financing for a just transition, incorporating climate risks into financial decisions, and ensuring development aid is consistent with climate goals.

BOX 8. CLEAN TECHNOLOGY FOR CLIMATE SOLUTIONS

Clean technology—any process, product, or service that reduces environmental impacts—is critical for the transition to low-carbon growth in all sectors. The emerging green economy represents a significant economic opportunity. Meeting Canada's emission reduction targets will require developments in net-zero emission technologies (e.g., renewable energy, zero-emission vehicles, smart grids and storage, small modular reactors, carbon capture, storage, and use), as well as broader deployment of existing clean technologies.

Technology can provide alternative approaches for producing the goods and services we rely on in ways that are low-carbon, resilient, and aligned with the principles of a circular economy. However, it is likely that the time required to scale up and deploy new technologies means that their contributions to reducing emissions would take some time, as there are still barriers to implementing these technologies that need to be understood.

Priorities in clean technology research that will contribute to achieving climate goals and that will position Canada as a global leader in clean technology include:

- Developing strategies for the research, development, demonstration, and deployment of clean technology, considering its unique risk profiles and the economic, environmental, social, technical, and non-technical barriers to large-scale deployment in different sectors (e.g., drinking water and wastewater, smart grids, smart modular reactors, nature-based solutions, carbon capture technologies).
- Undertaking analyses to identify Canadian clean technology strengths and opportunities, including in global markets, to prioritize further investment and anchor intellectual property in Canada.
- Developing holistic methodologies to identify non-emitting technologies with multiple applications (e.g., heat and power co-generation, hydrogen production, water desalination), synergies with other technologies (e.g., hybrid energy systems), and co-benefits for other sectors (e.g., health and sanitation, transportation).
- Improving methodologies (top-down and bottom-up) for comprehensive measurement of GHG emissions to identify mitigation opportunities and verify the validity of clean technology claims.
- Understanding the broad range of health, environmental, and social implications of a given technology through prediction tools and integrated analyses in order to understand its unintended and intended consequences (e.g., on air, water, soil quality, biodiversity, land use, health).
- Developing a full lifecycle understanding of the health and environmental impacts of goods and services on energy use, GHG emissions, air and water pollution, site decommissioning, and waste disposal to avoid the selection of lower-cost available technologies that may have longer-term negative impacts.
- Developing methods and good practices for scaling up and deploying new technologies.
- Developing pilot projects to study and demonstrate the potential of low-carbon and non-emitting technologies and systems, hence reducing financial, regulatory, and technical risks and attracting investors.
- Understanding the social, cultural, and psychological barriers to the adoption of existing and new clean or alternative fuel technologies, including potential conflict or resistance stemming from unintended impacts or trade-offs of their implementation.

Resilient terrestrial and aquatic ecosystems

Climate change is threatening Canada's landscapes and seascapes, the valuable ecosystem goods and services they provide, and the spiritual, cultural, and traditional significance they hold. Already species ranges are shifting, predator-prey relationships and seasonal patterns are changing, and new pests—including insects, pathogens, and invasive species—are emerging. A warming ocean is becoming more acidic and losing oxygen, resulting in multiple stressors for marine ecosystems, and coastal ecosystems are facing additional threats from sea-level rise and erosion.

Healthy, thriving, and resilient ecosystems have an essential role to play in addressing climate change. They provide a buffer against flood and drought, cool cities, sequester carbon, provide food and materials for communities, and contribute to the health and well-being of Canadians, in addition to providing many other climate- and non-climate-related ecosystem services. The research needed to ensure that Canada's ecosystem resilience is restored, maintained, and enhanced will be based on a foundational understanding of how climate change is impacting and will impact Canada's biodiversity and ecosystems. It will also need to explore ways we can help Canada's species and ecosystems adapt to the challenges of climate change and the ways that nature can help us build resilience, including by exploring and drawing on the synergies between western science and Indigenous stewardship in maintaining resilient ecosystems.

Understanding how climate change will impact biodiversity and ecosystems

Understanding how climate change is impacting and will continue to impact Canada's terrestrial, freshwater, sea-ice, and marine ecosystems and ecosystem services will set the stage for subsequent research and action. There is a need to better understand the impacts of climate change on the various components of aquatic and terrestrial systems, as well as the biophysical and biogeochemical processes that underpin the functioning of healthy ecosystems (e.g., nutrient cycling; vegetation dynamics; aquifer recharge; water storage and movement; ocean-ice-atmosphere, ocean-land-seafloor, surface water-groundwater interactions).

In addition, a more robust understanding of ecosystem and species sensitivity, resilience, and adaptive capacity is needed at all levels of biological organization (e.g., gene, species, population, community). This must include a better understanding of how climate change will affect species' life histories, ecosystem composition and function, and the interactions among species and between species and their environments. The co-application of Indigenous Knowledge and science, as well as a variety of tools and approaches (e.g., genomics, environmental DNA, trait-based approaches, on-the-land observations), will be important in advancing this work.

SCIENCE IN ACTION: COLLABORATION AND CAPACITY BUILDING THROUGH THE INUIT FIELD TRAINING PROGRAM

Canada's Arctic is warming faster than the rest of Canada. Carrying out research in this vast region is a challenge, and Inuit—who are experiencing firsthand the impacts of climate change—have a crucial role to play in the future of climate monitoring and research. Environment and Climate Change Canada's Inuit Field Training Program introduces Inuit youth to the skills and techniques required to work in a northern research camp. Delivered in collaboration with Inuit communities, and with training delivered by a team of Inuit mentors and scientists, this hands-on experience is designed to build confidence and enthusiasm, and act as a stepping stone towards further training or employment opportunities in environmental research or monitoring. The program builds capacity, so that Inuit can play a leading role in the future of Arctic climate change research.

Even if species and ecosystems are resilient enough to adapt to one aspect of a changing climate, the cumulative impacts from a wide range of other stressors could override this resilience. Thus, there is a need to develop a better understanding of changing stressors and their influence on species and ecosystem response. This includes how climate-related stressors (e.g., temperature, precipitation, ocean acidification, hypoxia, extreme events) are changing, how natural and anthropogenic non-climate stressors are changing as a result of climate change and other factors (e.g., algal blooms, emerging pests, contaminants, shifts in land cover/use, resource use), and the cumulative effect these stressors have on the adaptive capacity of species and ecosystems. Arctic ecosystems are particularly vulnerable and warrant a specific research focus in collaboration with Indigenous partners.

Helping species and ecosystems adapt to a changing climate

Proactive adaptation measures are required to minimize threats to vulnerable species and ecosystems. These measures will require improved predictions and projections of impacts and responses, including an improved ability to forecast emerging and novel ecosystems, sensitivity, resilience, and adaptive capacity, as well as changes in key relationships (e.g., predator-prey, plant-pest, physical-biological). Models are important assets in this endeavour. Work is needed to better integrate physical, ecological, biogeochemical, and social processes into models. In addition, it will be useful to better understand when, where, and for which species and ecosystems different kinds of models can be used. It will be important to understand how results from these various approaches align or differ, and how multiple sources of uncertainty affect outcomes and, by extension, action.

There are also research needs related to developing and testing adaptation measures and identifying barriers (e.g., behavioural, economic, regulatory) to the proactive implementation of these measures. This includes work on pest management, assisted migration, conservation of genetic diversity, habitat restoration, and species protection and recovery, as well as the design and use of a variety of landscapes and seascapes—from human-modified systems to protected areas—to promote adaptation, ensure connectivity, and provide refugia. Decision makers will benefit from work aimed at testing and improving existing prioritization tools and developing new ones where needed. Multiple lines of evidence will be needed to advance this work, including predictive modelling and laboratory and field experiments. Field-based landscape- and seascape-level studies will be important in assessing the effectiveness of, and full ecosystem response to, these interventions, and identifying possible unintended consequences.

Working with nature to advance climate action

Nature-based solutions (NbS) and related terms (e.g., natural infrastructure) are actions that protect, enhance, manage, and restore ecosystems while simultaneously addressing environmental, social, and economic needs and challenges. NbS can potentially play a role in addressing the interrelated challenges of climate change and biodiversity loss, while also providing a range of other co-benefits (e.g., for human health). In a climate change context, NbS can be used to increase carbon storage and/or build resilience, and could include, for example, planting trees in degraded habitats, urban areas, and agricultural landscapes, implementing appropriate agriculture practices, adjusting forest management practices, and restoring wetland, grassland, macroalgal, and eelgrass ecosystems. Expanding terrestrial and marine protected area networks also contributes to NbS, in addition to helping improve the adaptive capacity of species, ecosystems, and landscapes (e.g., by providing climate refugia, landscape connectivity), though must be done in a way that protects Indigenous rights and is integrated with work on Indigenous protected and conserved areas.

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services *Global Assessment of Biodiversity and Ecosystem Services* identifies climate change as one of five principal drivers of biodiversity loss. The report also anticipates that its effects are likely to become more significant as climate change accelerates and interacts with and amplifies other drivers of change. This can result in unexpected non-linear change, with possible irreversible impacts on biodiversity and the benefits nature provides to people and to society. One of the report's key messages is the need to address biodiversity loss and climate change simultaneously, identifying synergies and acknowledging trade-offs. Climate change interventions can pose risks to, or have negative impacts on, nature, and there is a need to study and consider the potential impact of climate change interventions on biodiversity and ecosystems. This includes NbS to climate change, which have the potential to both support nature and biodiversity and harm biodiversity and ecosystem function.

Given that not all NbS have conservation value, research to evaluate the effectiveness of NbS approaches for conservation priorities (e.g., addressing biodiversity loss) is an important knowledge need. There is also a need to better understand the climate change mitigation values of ecosystems. Developing, testing, monitoring, and evaluating NbS solutions will help understand the trade-offs and opportunities to maximize co-benefits.

Work to address knowledge gaps related to resilient ecosystems, land and aquatic management practices, the carbon cycle, and carbon sinks will benefit the understanding and application of NbS; however, there are some research needs specific to these interventions, both generally and in the context of a changing climate. These include better understanding and quantifying the potential of these actions to impact radiative forcing, reduce/avoid emissions, and build resilience, avoiding unexpected negative effects (e.g., increasing the spread of pests or exposure to infectious disease risks, including the introduction of invasive species or habitat for infectious disease pathogens and vectors), and generally understanding how and where to deploy them in the most effective way. It will also be important to develop a deeper understanding of how climate extremes and extreme events will influence NbS. Given the potential of wetlands, grasslands, forests, and macroalgal/eelgrass beds as a nature-based solution, work will be required to identify and address knowledge gaps related to the impacts that climate change will have on them.

NbS and natural infrastructure can provide a wide range of benefits when deployed alone or in tandem with traditional built infrastructure. Developing a greater understanding of these benefits and a standardized way to measure their economic value will be helpful, and should take into consideration the costs associated with their initial construction and ongoing maintenance. In a similar vein, research on payments for ecosystem services and natural assets management may benefit the implementation of NbS. There are specific knowledge needs related to valuing these goods and services (economically, socially, culturally), navigating the environmental and economic trade-offs inherent in managing an ecosystem for a particular good or service, and eliminating barriers and concerns related to accounting and financing.

Finally, while interest in these approaches has been growing, implementation has been slow and relatively small scale. Interdisciplinary research that integrates different knowledge systems to understand and minimize the barriers to implementation would be beneficial, particularly given that Indigenous Peoples have been practicing NbS since time immemorial. Efforts to include land managers (e.g., agricultural producers) in NbS research would also be of value, particularly in connecting knowledge to action.

BOX 9. INFORMING URGENT ACTION ON CLIMATE CHANGE AND BIODIVERSITY LOSS

Clean technology—any process, product, or service that reduces environmental impacts—is critical for the Biodiversity is declining at a rate unprecedented in human history, and climate change and biodiversity loss are twin threats. It is becoming increasingly urgent to address them both, particularly in areas where these two crises intersect. Nature plays a critical role in regulating the climate. The impacts of climate change on biodiversity and ecosystem services are expected to accelerate, and the loss of nature and natural carbon sinks further contributes to climate change. Climate change poses a threat to some species, and could exacerbate the decline of populations already at risk. In working to address the biodiversity and climate crises, deepening our understanding of the impacts of climate change on biodiversity is essential. This will help us identify which species and ecosystems are most vulnerable and where, develop more accurate predictions of the impacts they could face, and understand how healthy and resilient ecosystems can buffer these impacts on biodiversity and ecosystem services. Understanding the full complexity of impacts is necessary. For instance, one knowledge gap that is often overlooked is the effect of human responses to climate change, and how these may have cascading effects on species, ecosystems, and ecosystem services.

A deeper understanding of impacts is essential in identifying effective and efficient climate-smart conservation and adaptation strategies, especially ones that integrate a dynamic view of climate change and the variability of its effects over space and time at both the ecosystem and species levels. Protected area networks are a cornerstone conservation strategy and are increasingly important in a changing climate. There are important knowledge gaps related to protected and conserved areas, including understanding their long-term viability in a changing climate, as well as the gaps in the current network in order to provide refugia and corridors. While many research needs remain, delaying conservation and management action can accelerate loss. Adaptive management can provide a way to iteratively learn by doing, advancing knowledge while protecting Canada's biodiversity and upholding our international obligations related to conservation (e.g., under the Convention on Biological Diversity, the Ramsar Convention, and the North American Bird Conservation Initiative).

Sustainable natural resources

Ensuring Canada's natural resource sectors remain resilient and productive in the face of climate change is a key factor in Canada's continued prosperity, and research to inform climate-smart, sustainable practices is needed. The agricultural, forestry, fisheries, aquaculture, water management, mining, and energy sectors are already facing threats from climate change, including extreme events, existing and emerging pests, shifting water availability and quality, and ocean acidification, among others. Building resilience across many of the natural resource sectors will rely on work to ensure the resilience of Canada's ecosystems. Overall, resilient natural resource sectors will benefit from a deeper understanding of the place-based risks they face, as well as a more integrated understanding of how to advance multiple natural resource and land/aquatic-use goals. Applied research to inform on-the-ground action will also be necessary to help ensure action is evidence-based, efficient, and effective.

Understanding risks to natural resource sectors

A better understanding of and ability to predict changes and risks to natural resource sectors will help ensure that they remain competitive in a changing climate and are positioned to contribute to mitigation and adaptation efforts. In addition, new and innovative tools to assess the threats facing resource systems are needed.

Improving information about the frequency, potential severity, and location of extreme events will help resource sectors manage their operations to reduce the effects of these events and build resilience into their operations. In all sectors, short-term/seasonal predictions of extremes are required, as is longer-term modelling to predict changes and risks.

There is also a need to better understand how multiple stressors and compound conditions affect natural resource sectors (e.g., combinations of temperature, soil quality, pest and disease viability on land, or combinations of acidification, increased temperature, and deoxygenation in the ocean). For fisheries and aquaculture, an improved understanding of ecosystems and fishery responses to extremes is needed. More broadly, a better understanding of the climatological sensitivity of pests, disease, and invasive species that affect crop, forest, and fishery health will be beneficial. Additionally, science-based information about current and future freshwater availability will inform the development of protection targets for freshwater areas.

A large number of communities were settled and developed around the operations of natural resource sectors and are vulnerable to the impacts of climate change, and research is needed on decommissioning and cleaning up infrastructure from these industries as these communities transition. Social science can play a strong role in helping envision, plan, and implement community transformation. It can also help to better understand the long-term local impacts of economic transformation and transition and the corresponding social and cultural issues and changes.

BOX 10. ENSURING FOOD AND WATER SECURITY AND SAFETY FOR CANADIANS

Climate-related disruptions in food and water systems impact human health and well-being by diminishing food and water security. These disruptions include direct impacts (e.g., drought, pests, shifting species distributions, marine heatwaves, ocean acidification), impacts on food transportation and storage, and indirect impacts, such as shifts in job opportunities and cost of living increases (including food costs). Lack of access to safe drinking water and disruptions to the food system will disproportionately affect marginalized and vulnerable communities, as well as those who depend on the land and oceans. They also make eliminating hunger and poverty and preventing certain diseases—among other sustainable development objectives—more difficult.

There are many knowledge gaps related to sustaining a robust, nutritious, and accessible food supply for all Canadians, from production (agriculture, fisheries, aquaculture, country foods) and imports to harvesting, processing, and distribution. These gaps include:

- the food system components most vulnerable to climate change (slow-onset change and extremes);
- ecosystem capacity to sustain biodiversity, freshwater supplies (surface and groundwater), and soil health;
- use of land and water for food and non-food production (e.g., renewable energy, carbon sequestration, conservation of biodiversity and ecosystem services);
- strategies to ensure sufficient staples can be produced for and delivered to all Canadians;
- the risk of food- and water-borne disease;
- climate risks and pressures to Indigenous Peoples and coastal, remote, and Northern communities;
- climate vulnerabilities of country and market food systems;
- the potential for economic transition to exacerbate existing food insecurity among vulnerable populations and regions; and
- behavioural insights to inform sustainability in dietary choices.

Advancing knowledge in these areas is limited by a lack of demographic and socio-economic data and monitoring, particularly in formats that allow interoperability with ecological and environmental data. Expanded surveillance of food security-related indicators is necessary to understand the complex relationships among the factors noted above and to develop quantitative projections of food and water availability and quality.

Advancing an integrated understanding and valuation of natural resources

Given the importance of advancing climate actions that maximize co-benefits, it is important to develop an integrated understanding of natural resource and land/water goals and opportunities. This work will support integrated planning and management, and will benefit from research to develop effective and inclusive governance structures for decision making in the context of a changing climate.

Fundamental work related to water resources management, land-/aquatic-use planning (including ecological restoration in areas disturbed by industrial activity), traditional food security, resource sector productivity and profitability, carbon sequestration, and ecosystem carrying capacity will be key to developing an integrated understanding. Specific areas of integrated understanding to explore could include:

- ensuring food, water, and energy security while also considering cultural practices, human health, carbon sequestration, and climate resilience;
- advancing clean energy production (e.g., bioenergy, hydroelectricity, solar, wind, nuclear, hydrogen, geothermics) in ways that also advance food and fibre production, carbon sequestration, and Indigenous self-determination in resource production;
- managing forest, agriculture, fisheries, and aquaculture systems in the context of climate-induced geographic shifts, while minimizing development pressures and protecting biodiversity; and
- conserving terrestrial and aquatic areas and biodiversity while advancing NbS and protecting ecocultural landscapes and seascapes.

Research related to the valuation of natural resources and land use is required, from both an economic and a more holistic perspective. Enhanced economic and societal analyses of climate change impacts on natural resource sectors, particularly for food and fibre, are needed from local to global scales. In addition, research is required into how the socio-economic value of land and aquatic systems is determined and how this influences land/aquatic-use choices for natural resource sectors, energy production, ecosystem conservation, and urban/industrial development.

Beyond this, it will be important to develop an integrated understanding of the economic, social, environmental, health, cultural, and place-based value of land and aquatic systems to inform the integration of multiple uses that respect the broad range of benefits and impacts. For instance, the lands and oceans used by Indigenous and Northern communities for harvesting, hunting, and gathering traditional foods and medicines for subsistence and cultural revitalization hold greater overall value as climate change exacerbates already-high rates of food insecurity in these communities. Other examples of the diverse values of multiple land/aquatic uses include the joint consideration of adaptation and mitigation in natural resource sectors, the development of renewable energy systems, the study of the potential for carbon sequestration and geothermal energy, and the resilience of natural ecosystems.

Enabling climate action in Canada's natural resource sectors

Effective climate mitigation and adaptation in natural resource sectors requires regionally and locally relevant technical information to inform risk assessments, ensure continued productivity, and enable any necessary transitions in response to the implementation of climate action. This includes research to inform the development of resilient, climate-smart / low-GHG practices (e.g., clean energy technologies), and assess their costs and benefits, as well as research to inform sector resilience to variability and extremes. Knowledge mobilization efforts, along with monitoring, measurement, and evaluation of the measures put in place, will be important. In addition, improved monitoring—for instance, for soil conservation, fresh water availability, enhanced carbon storage, ocean acidification and deoxygenation—and access to telemetry in regions where access is difficult will also be of value.

For the oceans, fisheries, and aquaculture sectors, there is a need for blue-carbon technology and actions to address ocean acidification and deoxygenation, as well as research on science-based decision tools that can detect climate impacts (and related uncertainty) for resources and their management. There is also a need for greater understanding and assessment of cumulative impacts of multiple stressors (e.g., temperature, pH, oxygen). Work to better reflect changes in aquatic ecosystem/resource services, activities, and human well-being in the prioritization of actions aimed at increasing the sustainability of aquatic systems in the context of a changing climate is also needed.

In agriculture, there is a need for continued research into regionally appropriate resilient crops and livestock that can withstand seasonal variability and extreme weather events. There is also a need to continue developing and incentivizing low-emission-intensity crops and accelerating the adoption of climate-smart management practices that increase carbon sequestration, reduce GHG emissions, and contribute to on-farm resilience (e.g., natural infrastructure like wetlands and agroforestry, integrated cropping systems, precision application of nutrients). The participation and active involvement of agricultural producers in this research will ultimately benefit its uptake. Improved definition and monitoring of soil health will be essential in advancing soil conservation, restoration, and enhanced carbon storage, and facilitating access to new or expanding agricultural regions.

For forestry, research is required to develop management practices that increase resilience, community safety and well-being, economic opportunity, and carbon sequestration, taking into account both forest management and how wood is used. This should extend to an examination of forest policy and opportunities to harmonize with other sector-based policies in order to enable more effective and coordinated climate action. There is also a need to

SCIENCE IN ACTION: USING CATTLE DIETS TO REDUCE EMISSIONS

Cattle in Canada can contribute up to 25 million tonnes of CO_2 equivalent annually from the methane generated during digestion. Researchers from Agriculture and Agri-Food Canada and Australia collaborated to find the best feeding practices for addressing this problem, and evaluate them for their efficiency, safety, and long-term sustainability, as well as the potential synergies between them. They found that feeding cows a rapidly digested starch like wheat has been shown to reduce methane emissions by up to 50% compared with slowly digested starches (e.g., corn, barley). They also examined an experimental feed additive that blocks methane formation in the cow's stomach (shown to lower methane emissions by up to 60%) and a nitrate product that provides an alternative pathway to the formation of methane (shown to reduce methane by up to 20%). By working to address one mitigation challenge, this research is helping develop options for producers that are practical and cost-effective for a range of market conditions, farm management practices, and types of cattle.

understand forest management decisions for a range of future climate conditions, including management options that could support both mitigation and adaptation (e.g., Indigenous traditional forest management practices) in the context of increasing wildfire risk.

In the energy sector, research is needed into the social, political, economic, and technological factors that would raise the environmental performance of the oil and gas sector. This includes, for example, understanding how to accelerate and facilitate the use of non-emitting technologies (e.g., small modular nuclear reactors, hydrogen-powered trucks, electric vehicles) in resource extraction operations. There is also a need for additional work to demonstrate and deploy emerging renewable energy technologies (e.g., tidal, geothermal), and inform the resilience of energy-related natural resource operations (e.g., freshwater availability and hydropower; extreme events and energy security, accessibility, and infrastructure).

With respect to the mining industry, there are several adaptation research and development gaps related to assessing and reducing risks surrounding mine waste management (e.g., sulphide oxidation, tailings management, the effect of permafrost thaw on impoundment structures). Research on waste management reclamation in a changing climate would support this work. There is also a need to assess and reduce risks associated with water/effluent management and changes in the water balance. In addition, research on ecosystem risk, including species diversity and tolerance to mining impacts in the context of a changing climate, is required. Finally, an assessment of the impact of seasonal variability and extreme weather events will help understand and address climate change-related mining infrastructure risks.

BOX 11. ARCTIC AND NORTHERN CONSIDERATIONS

The Arctic and North's[6] climate and environment are changing more rapidly and unpredictably than anywhere else on Earth. The region is warming at about three times the global rate, and the widespread and wide-ranging environmental impacts of this warming will continue. In addition, the Arctic Ocean suffers from the highest rate of acidification on the planet. The region's unique and culturally significant environments and species are disproportionately vulnerable to anthropogenic and natural stressors. Changes in wildlife behaviour and habitat use pose a threat to the viability of traditional subsistence activities, health and well-being, and cultural practices, while impacts to physical infrastructure jeopardize community safety, security, and resilience. The Arctic and North are critical to Canada's sovereignty and natural resource potential, and interest in the region is intensifying as the loss of sea ice makes the region more accessible to economic growth, resource extraction, and transportation.

Climate change knowledge creation, synthesis, and mobilization in the Arctic and North should be centred on meaningful and respectful collaboration, working with Arctic and Northern stakeholders, rights holders, and decision makers and moving towards increased agency, self-determination, and leadership of Indigenous Peoples. There are foundational documents, such as the *National Inuit Climate Change Strategy* and the *National Inuit Strategy on Research* [7], that can guide this meaningful and respectful collaboration. *Canada's Arctic and Northern Policy Framework* also provides a co-developed roadmap for collaboratively achieving progress on a range of priorities, including science, knowledge, and research that are meaningful for communities.

Conducting climate change research in the region can be logistically challenging and costly, and it requires a large and varied inventory of infrastructure. There is a need to work in partnership to maintain, enhance, and augment

[6] While there are numerous definitions of Arctic and North, this document adopts the one used in Canada's Arctic and Northern Policy Framework, which "includes the entirety of Inuit Nunangat—the Inuvialuit Settlement Region in the Northwest Territories, Labrador's Nunatsiavut region, the territory of Nunavik in Quebec, and Nunavut—the Inuit homeland in Canada."

[7] www.itk.ca/national-strategy-on-research/

monitoring networks in key areas to ensure adequate regional coverage, especially in more remote and sensitive areas, including those of value to Indigenous Peoples or with high potential for resource development. This physical monitoring infrastructure must be complemented by enhanced capacity for community-based monitoring, as well as digital infrastructure and data and knowledge management approaches that are appropriate for the region and its communities in order to effectively share relevant data between Arctic and Northern stakeholders and rights holders.

It is essential to fill data gaps and to develop a more complete baseline understanding of the biophysical environment and how it may change over time. The protected area network of the Canadian Arctic and North can provide excellent locations and logistical support for benchmark monitoring for global ecosystem change. Improved data collection using consistent methods (e.g., *in situ*, space-based Earth observation) and involving Indigenous Knowledge holders is key in building a better understanding of priority areas and climate-sensitive ecosystem components of cultural, traditional, conservation, and commercial value.

Benchmark and trend data will contribute to a better understanding of the state of Arctic and Northern ecosystems, how they will change, and their adaptive capacity, which are all crucial for identifying tipping points and assessing their potential impacts. This data, as well as the integration of existing datasets and their interpretation, is critical for contextualizing, understanding, and improving the prediction of the impacts of climate change across the breadth and complexity of the Arctic and Northern environment. Enhanced datasets can support research aimed at developing solutions to increase food, water, and energy security in the region, including through the provision of clean and renewable energy.

Foundational capacity

Addressing the gaps and priorities outlined above will require a solid foundation of monitoring and digital infrastructure, as well as a strong commitment to making all stages of the climate change research process more open and accessible, while respecting Indigenous data sovereignty and ownership of Indigenous Knowledge. Strengthening this foundation will be key in supporting Canada's contribution to, and leveraging of, international climate change science. Enhanced coordination among partners, networks, and programs will be critical, as will sustained efforts to attract and train the highly qualified personnel needed to undertake all aspects of climate change research.

Monitoring and observations

As the climate changes, ongoing integrated monitoring and surveillance systems will be key assets in providing situational awareness (e.g., in the context of extreme events), assessing change, informing action, and measuring progress. They will also help identify unanticipated responses to climate change (e.g., disorderly socio-economic responses) and to climate action (e.g., broad-scale implementation of NbS).

Additional effort and investment is needed to maintain and strategically fill spatial and temporal gaps monitoring networks across all atmospheric, terrestrial, freshwater, and marine systems, deploy novel and innovative approaches, integrate socio-economic indicators, adopt standardized monitoring and reporting protocols, and integrate datasets from multiple sources and disciplines. Satellite technology is progressing rapidly, enabling improved surveillance, especially in the high Arctic region.

Increasing collaboration with Indigenous communities and organizations in monitoring projects will improve the quality and quantity of data collected, especially given the critical and unique nature of the knowledge held by Indigenous Peoples regarding their local environment and climate change impacts. Community-based science activities can also provide surveillance data while increasing education, awareness, and engagement to empower individuals in acting on climate change.

Canadian monitoring reflects, for the most part, the international guidance and data quality objectives identified for Essential Climate Variables[8]. Future monitoring should build on and strengthen existing efforts, partnerships, programs, and infrastructure (e.g., research vessels, multi-disciplinary monitoring sites, buoy networks, satellite observing systems) and draw on a range of surveillance and monitoring designs, including community science. Critical considerations for sustaining and strengthening monitoring and observations include:

- Enhanced monitoring (spatially and temporally) to capture benchmark conditions and to improve projected trends, impacts, and extremes in climate, cryosphere, marine, freshwater, terrestrial, and landscape variables, particularly in the Arctic and North.
- Adequate and high-quality observations of extreme precipitation, solid precipitation (snow, ice), soil moisture, evapotranspiration, surface and groundwater levels, and other variables related to understanding freshwater availability, flood, and drought.
- Sustained monitoring of ocean physics (e.g., marine heatwaves), chemistry, and biology, with increased effort in the Arctic and North and in nearshore zones.
- Freshwater monitoring of rivers and lakes for water quality, distribution, and availability, as well as groundwater quality and quantity.
- A national, long-term, holistic network to collect consistent and interoperable data across a range of disciplines, scales, ecosystems, and environmental gradients using both professional and community science.
- Monitoring of biodiversity and ecosystem integrity to inform conservation and valuation of ecosystem services, and to improve understanding of the impact and possible unintended consequences of NbS.
- In situ and remote sensing-based measurement networks to quantify climate change impacts on land and aquatic systems and validate carbon stocks, stock change, and GHG flux estimates.
- A national, long-term vision for space-based Earth observation systems and access to international and commercial datasets to populate a central hub of satellite data.
- Novel, integrated, and multi-disciplinary surveillance systems for emerging zoonotic, food-borne, and water-borne diseases and plant pests, particularly in the health, forestry, aquaculture, fisheries, and agricultural sectors.

[8] https://gcos.wmo.int/en/essential-climate-variables

- Sector- and community-level monitoring that brings together socio-economic, infrastructure, health, and environmental monitoring activities, including monitoring of the effectiveness of adaptation measures and differential impacts and outcomes for various populations (e.g., urban/rural, seniors, women, children, Indigenous Peoples).
- Building capacity for sustained monitoring networks at various scales, including building Indigenous leadership in monitoring while supporting Indigenous self-determination in research.
- Adoption of new technologies, such as space-based monitoring, drones, and low- or medium-precision / lower-cost *in situ* sensors where they can be integrated in the long-established and international networks to maintain and complement multi-decadal records.

BOX 12. THE ROLE OF SPACE-BASED EARTH OBSERVATION FOR CLIMATE KNOWLEDGE

Canada's vast geography makes collecting national environmental intelligence a challenge. Our dynamic environment requires systematic monitoring, but it is not feasible to do so entirely from the ground. Satellites are an efficient and effective observational tool and have become a cornerstone of multiple services to Canadians (e.g., weather forecasting, agricultural monitoring, ice mapping, atmospheric and ocean monitoring, disaster response). Satellite data, combined with data from the ground, helps Canadians deal with the impacts of climate change on a daily basis, from crop forecasting tools for agricultural producers to web applications for information on ice location for northern communities.

The space-based Earth observation (SBEO) landscape is evolving, with a focus on open data, international collaboration, and long-term visioning to address key climate challenges, and Canada's SBEO capabilities must keep pace. Advances in SBEO technology can provide faster, more accurate, and cost-effective ways to address Canada's climate challenges. A sustained, long-term vision for data acquisition and distribution from national, international, and commercial satellites is vital to the future of Canadian climate knowledge.

Digital infrastructure

The magnitude and diversity of climate change data and knowledge requires unprecedented advances and capacity in data storage and management, high-performance computing, and methods and algorithms. Sharing, reuse, and integration of data are currently limited by the fact that data is managed according to discipline and producer/custodian. There is a critical need to implement data and computing systems, standards, and analytical tools that enable the integration of, and common access to, climate, ocean, ecological, environmental, social, health, and economic data. This digital infrastructure is an intrinsic part of monitoring, analysis, and modelling efforts, and should include tools for data management, extraction, manipulation, visualization, standardization, and interoperability. Artificial intelligence could play an important role in helping identify trends and relationships in large complex datasets, in forecasting, and in optimizing solutions. As digital infrastructure advances, a deeper understanding of jurisdictional and environmental (e.g., energy consumption) issues related to cloud-based high-performance computing, large data storage, and computational/data facilities will be required. Access to affordable and reliable high-speed internet will also enable broader participation in research activities that rely on this digital infrastructure.

Targeted effort, complemented by local/regional capacity building, is needed in the following areas:

- Dedicated data centres to facilitate access to and integration of data.
- Digital infrastructure, platforms, and tools for Indigenous Peoples to manage their knowledge and data and contribute to Indigenous research capacity, data sovereignty, and self-determination in research.

- Enhanced participation in the development of data standards and governance to support interoperability, facilitate sharing across domains and jurisdictions, and enable access to international data.
- High-performance computing environments to better use and augment observations through synthetic observations, re-analysis methods, data assimilation, and Earth system and numerical modelling.
- Methodologies and protocols for addressing privacy concerns related to socio-economic, health, and demographic data to enhance its use in metrics and indices for impacts and evaluating action.
- Enhanced capacity for the submission of open data from Canadian sources to international data centres and vice versa.

Open science

Ensuring that climate change science is open and accessible at each stage of the research process is crucial for advancing the evidence base needed for ambitious action. Open climate change science and knowledge will increase transparency, maximize investments, accelerate progress, and lead to new and unexpected insights. It can also connect decision makers with the information they need and, more generally, improve science literacy. Canada's Chief Science Advisor's *Roadmap for Open Science* provides a series of recommendations and overarching principles to guide open science activities in Canada, which could be helpful in advancing the openness of climate change science and knowledge.

Open science principles can be applied from the outset of the research process. Being open when identifying research questions—for example, through community engagement, open proposals, and innovation challenges—can enhance collaboration and integrate multiple ways of knowing. It can also bring knowledge users and communities implicated by the research into the process early on to ensure the research aligns with their needs, and to increase their understanding of potential climate change solutions that emerge from the research.

When data is open, it is easier to access, reuse, and integrate. While there is no one-size-fits-all solution to open data, making data FAIR (Findable, Accessible, Interoperable, and Reusable) is one established best practice. Ensuring that data is fit for use by unanticipated users for novel purposes will accelerate climate change science across disciplines. FAIR data can also be seamlessly incorporated into big data workflows or used as input to artificial intelligence. However, despite the benefits of making data open, not all data should be open by default.

Open climate change science and knowledge should respect Indigenous Peoples' sovereignty of the data, information, knowledge, and traditional cultural expressions of their communities. Indigenous communities and knowledge holders own their knowledge and information, and their consent and validation should be obtained for its collection, use, application, or interpretation in open science, including through formal agreements. These agreements could be specific to data and should respect the rights, self-determination, self-governance, and data sovereignty of Indigenous Peoples as they relate to their data and knowledge (e.g., the OCAP® principles).

As a general practice, researchers and data users should clearly identify whose knowledge is being opened by whom, and for whose benefit and/or risk. If data is managed with respect for privacy and data sovereignty, openness can contribute to the democratization of knowledge and a restructuring of institutionalized power structures and values.

Continued effort is needed to bring climate change-related publications out from behind paywalls, as this is an integral part of making climate change science and knowledge more accessible and usable by both researchers and practitioners. This can be accomplished by publishing in open access journals, archiving a copy in a repository after embargo periods have elapsed, or publishing a preprint on public archive systems to make results available more quickly. In addition, research outcomes should be communicated to decision makers and implicated communities in a clear and accessible manner.

Moving forward

Science and knowledge are essential in guiding the development and implementation of climate policy and actions to limit warming and future risk. By providing a common and transparent foundation for evidence-based action, science and knowledge can contribute to depolarizing the public discourse around climate action. In order to accelerate the transformational changes necessary to build a resilient, net-zero Canada, both climate change research and action must move quickly towards more holistic approaches that integrate mitigation, adaptation, and sustainable development.

Each community, discipline, and sector has its own particular expertise and perspective to bring to the table in order to work together to solve the climate change challenge. CS2050 profiles a broad spectrum of work, and recognizes that much of it must proceed in parallel. The urgency of the challenge means that decision makers should not and cannot wait for all the science to be in before taking action. As such, knowledge synthesis efforts must also occur while research continues to unfold, ensuring that decision makers can integrate the latest results and insights into their ongoing efforts.

While the focus of climate change science efforts has traditionally been on the natural and health sciences, there is a pressing need to support and integrate the social sciences, as these will be essential in motivating the human behaviours that are ultimately at the heart of taking swift, ambitious action on climate change.

Given the broad impact of climate change across all regions, sectors, and communities, decision makers must navigate multiple knowledge gaps simultaneously. This is particularly clear when it comes to highly interdisciplinary areas of work, such as:

- understanding and predicting the national, regional, and local impacts of climate extremes and extreme events across economic sectors and communities, which will inform disaster risk reduction responses, economic and non-economic valuation of climate impacts, energy security, resilient infrastructure, and community-level health and socio-economic risk reduction;
- increasing the understanding, monitoring, and forecasting of climate change impacts on the health of Canadians and health systems, including maximizing the health co-benefits of climate actions in other sectors, as well as integrating environmental, human, animal health, and socio-economic information;
- developing and understanding the socio-economic and climate implications of Canadian pathways to net-zero, as this work requires an integrated understanding of climate behaviour, carbon sinks (including feedbacks), NbS, alternative energy pathways, economic transitions for emissions-intensive sectors, and community-level implications;
- improving the economic valuation of the costs, benefits, avoided costs, and externalities associated with climate action and ecological services, which includes developing methodologies for and applying various global emission pathways or climate scenarios, as well as options for Canadian pathways that integrate the full range of science and knowledge;

- enabling and accelerating a just transition, recognizing and exploring implementation challenges and developing effective climate change communications that empower action and enable constructive engagement opportunities; and
- applying our understanding of climate change to advancing sustainable development, as the intersection of climate change and sustainable development research objectives has the potential to identify multiple benefits and advance implementation for each.

Science infrastructure is a critical enabler for advancing climate change science and knowledge. There is already a solid foundation of infrastructure on which to build. Going forward, it will be necessary to not only maintain this capacity, but also strengthen and diversify it in a way that fully addresses the complexities of the climate emergency and that expands efforts into areas where little work has been done so far. The respectful and meaningful inclusion of information from all knowledge systems, and a committment to collaborative approaches, will be crucial.

CS2050 represents an opportunity to more deliberately examine climate change science and knowledge priorities, funding, and collaborative activities where Canadian climate change research can make a difference and can develop knowledge specific to the Canadian context. As Canadians continue mobilizing to build a resilient, carbon-neutral society, science and knowledge will be essential in guiding the way.

Annex 1 – The state of climate science

Warming of the Earth's climate, and Canada's climate, is unequivocal and is being driven primarily by global emissions of carbon dioxide from human activity. Some additional warming is inevitable; therefore, adaptation is imperative to build climate resilience among communities and ecosystems in Canada. Global efforts to mitigate emissions will determine how much future warming occurs globally, and in Canada.

Human activities are estimated to have caused approximately 1.0°C of global warming above pre-industrial levels. Parties to the Paris Agreement have committed to limiting global warming to well below 2°C above pre-industrial levels recognizing that this would significantly reduce the risks and impacts of climate change in all regions. Both past and future warming in Canada is about double the magnitude of global warming. Northern Canada has warmed and will continue to warm at more than double the global rate.

To stabilize global temperature at any level, global carbon emissions from human activity must become net zero (that is, remaining emissions must be offset by withdrawals of carbon from the atmosphere). In other words, to stabilize temperature at any level there is a total amount of carbon dioxide (CO_2) that can be emitted; this is referred to as a carbon emissions budget. To stabilize global temperature at well below 2°C above pre-industrial levels, global carbon emissions must become net zero early in the second half of the century. If global emissions exceed the carbon emissions budget for limiting global warming to well below 2°C, then net negative global carbon emissions will be required later in the second half of the century. Deep emission reductions in non-CO_2 emissions affecting climate are also required. The scale of mitigation required to meet the Paris Agreement global temperature target is understood to be extremely challenging, requiring major transitions in all aspects of society.

To realize the Paris Agreement global temperature goal, Canada and all countries need to shift towards carbon neutrality within a few decades. Canada's National Greenhouse Gas Inventory is prepared and submitted annually to the United Nations Framework Convention on Climate Change (UNFCCC). Under the Paris Agreement, Canada has committed to reducing GHG emissions by 30% below 2005 levels by 2030. Canada's and other Parties' commitments have collectively been assessed as broadly consistent with cost-effective pathways that result in warming of about 3°C by 2100. Science is needed to improve understanding of Canadian emission sources across all sectors, including the land sector, and of the capacity for enhanced removal of atmospheric carbon by sinks (primarily on land).

Between 1948 and 2018, Canada has warmed by 1.8°C, while northern Canada has warmed by 2.4°C. The effects of widespread warming are evident in many parts of Canada and are projected to intensify in the future with additional warming. These effects include more extreme heat, less extreme cold, longer growing seasons, shorter snow and ice seasons, earlier spring peak streamflow, thinning glaciers, thawing permafrost, warmer and more acidic oceans, and rising sea level. The projected increase in extreme hot temperatures will increase the severity of heatwaves and contribute to increased drought and wildfire risks. More intense rainfalls are projected for the future, and these will increase urban flood risks. Coastal flooding is expected to increase in many areas of Canada due to local sea level rise. Ocean acidification is expected to intensify, especially in Arctic regions, due to increased CO_2 uptake. Changes in climate are increasingly affecting Canada's natural environment, economic sectors, and the health of Canadians, and climate change is increasingly exacerbating the impact of other stressors on natural ecosystems in Canada and on the well-being of Canadians.

While global mitigation efforts will determine how much future warming occurs, some additional warming and consequent impacts are unavoidable. Canadians need to understand how climate change is already impacting them and what further impacts are anticipated, in order to plan and prepare for the challenges that climate change brings, and to empower their engagement and support for ambitious mitigation. Adaptation is a necessary response to climate change, in addition to mitigation; it enhances the economic and social resilience of Canadians to climate change impacts. Northern and coastal communities and Indigenous Peoples are among the most exposed to changes in climate in Canada. Indigenous Knowledge and science, including social science, can provide a more holistic perspective on climate change action.

The Government of Canada has capacity and the mandate to undertake science to inform effective climate action. Obligations to do this work are part of commitments under the *Canadian Environmental Protection Act, 1999*, the Federal Sustainable Development Strategy, and the United Nations Framework Convention on Climate Change. Provinces, territories and Indigenous governments also have a wealth of capacity to undertake scientific work and build knowledge systems within their jurisdictions and in cooperation with others. Climate change science activities generate and disseminate new knowledge and data to improve our understanding of climate system behaviour, the human influence on climate, future climate changes globally and in Canada, and associated impacts on natural and human systems. Climate change science activities are undertaken jointly through core government programs (mainly federal), academic institutions, and collaborative research networks. These activities involve federal, provincial, municipal, academic, and private sector partners.

The federal government provides most of the essential science infrastructure for climate system research and modelling, and long-term systematic observations programs for monitoring the state of the climate system and atmospheric concentrations of greenhouse gases. This work is complemented primarily by research and observation activities undertaken by the Canadian academic community, whose focus is on enquiry driven science. Productive partnerships have been established between the two communities and both continue to make substantial and essential collaborative contributions to Canadian and international programs. The federal programs then play a major role in the provision of scientific findings (knowledge synthesis and translation) and services to inform decision making on climate change mitigation and adaptation domestically, as well as internationally.

Numerous scientific disciplines from a range of government and academic institutions are involved in research on the climate system and climate change in Canada. Much foundational climate research in Canada is coordinated with international research efforts through the World Climate Research Programme and other international fora. Such strong international coordination has the dual benefits of supporting international climate policy and research obligations under the UNFCCC, thereby allowing Canada to take a credible and constructive role at domestic and international climate negotiations, while also leveraging international research, observations and modelling of the global climate system to ensure climate projections for Canada are based on the best available science.

Annex 2 – Knowledge synthesis and mobilization opportunities

THEMES	KNOWLEDGE SYNTHESIS AND MOBILIZATION OPPORTUNITIES
Communities and social structures	Synthesis of existing knowledge on social, cultural, economic, and mental health impacts of climate change on communities to better identify the needs specific to communities, especially in the Arctic.
	Assessment of synergies between mitigation, adaptation, and sustainable development actions, including strategies adopted across sectors (particularly the forestry, fisheries, aquaculture, and agriculture sectors, and in protected areas, related to carbon sequestration).
Economics	Scenarios, including second-order impacts, such as anchoring Canadian intellectual property and impacts on the financial system (e.g., high insurance payouts, stranded assets, divestment).
	Analyses of mitigation approaches, including decarbonization pathways aligned with domestic and international targets, to help assess the level and distribution of domestic and international efforts.
	Analyses of costs and benefits, including direct and indirect health and social costs and benefits, associated with climate change impacts and adaptation actions to transition to a climate-resilient economy, including macro-economic models.
	Analyses of the impacts of large-scale non-marginal changes associated with climate change (e.g., domestic and international perspectives on issues that could inform consideration of loss and damage caused by climate change).
Ecosystems	An assessment of climate change impacts on biodiversity and ecosystem services for Canada's terrestrial and aquatic ecosystems.
	Synthesis of trends in agro- and ecosystem land indicators to report on the status and trends of land indicators across the full range of ecozones of the Canadian landmass.
	Assessment of land and aquatic system-based mitigation options, including risks and socio-economic feedbacks considering net GHG and other climate-forcing impacts across ecosystems and human use of those ecosystems (e.g., wood products, macroalgae, food, energy), with international considerations related to the export of bioenergy feedstocks and the possible impact of foreign investments in land or mitigation activities in Canada.
	Assessment of synergies between mitigation and adaptation options in the forestry, fisheries, aquaculture, and agriculture sectors, as well as in parks and protected areas, to identify options that maximize co-benefits and synergies and minimize trade-offs for adaptation and mitigation actions.

THEMES	KNOWLEDGE SYNTHESIS AND MOBILIZATION OPPORTUNITIES
Ecosystems (cont'd.)	Integrated assessment of freshwater quality, quantity, and availability including sector and municipal implications, leveraging publications, public databases, and recent compilations of historical source and drinking water quality and cryosphere data in order to assess freshwater security.
Energy	Synthesis of the scale and current and future potential of non-emitting generation, emerging technologies (e.g., small modular reactors), and alternative energy systems required to meet net-zero (or low-carbon) targets across municipal, provincial, and national climate action plans.
	Synthesis of existing knowledge on social, economic, ecological, and health impacts of current and future energy assets to better identify the needs specific to communities and sectors.
	Integrated energy infrastructure risk assessments at the national, provincial, regional, community, or asset levels, that examine vulnerabilities, system interdependencies, cascading impacts, and associated social and economic implications.
Extreme events	National syntheses of risks from changes in extremes (e.g., extreme temperatures, precipitation, winds, floods, wildfires, sea-level rise, storm surges and waves, and combinations of those) and the impacts on human health, ecosystems, forestry, fisheries, aquaculture, and agriculture.
	Science assessment to integrate understanding of climate trends and extremes in the context of natural disasters to inform disaster risk reduction efforts, mechanisms to reduce public health impacts, health system resilience, and relief programming, including financial assistance, and reconstruction planning and implementation.
Health and well-being	Synthesis and mobilization of knowledge of direct and indirect climate change impacts on physical and mental health of Canadians and health systems, including in relation to actions taken in other sectors to mitigate or adapt to climate change.
	Integration and analysis of environmental, human, and animal health, and social data to better understand current and emerging climate change impacts on human health, and to monitor, including in real-time (e.g., syndromic surveillance, novel laboratory diagnostics) and forecast health impacts and outcomes (e.g., Earth observation, risk assessment).
	Integrated assessment of air quality impacts under multiple climate and/or emission pathways.

THEMES	KNOWLEDGE SYNTHESIS AND MOBILIZATION OPPORTUNITIES
Infrastructure	Integrated infrastructure risk assessments at the national, provincial, regional, community, or asset levels that examine vulnerabilities, systems interdependencies, cascading impacts, and associated ecological, social, economic, and cultural implications.
	Tools to understand the value of climate resilience and mainstream incorporation of climate considerations in infrastructure and community decision making.
	Efforts to foster the understanding and implementation of climate-informed codes, standards, guidelines, and best practices in new and retrofit infrastructure projects (e.g., buildings, transportation), aided by regional infrastructure asset management tools and guidelines, including the scalability and implementation of natural infrastructure.
	Building capacity to use climate knowledge, data, and tools in infrastructure decision making, including community- and system-level adaptation strategies, risk assessments, and asset management plans. For example, mobilizing knowledge and expertise and developing technical professional competencies related to northern infrastructure, especially on coastal and ground conditions (including permafrost) for planning major infrastructure and resource development and informing adaptation strategies in the Arctic and North.
	Mobilize existing knowledge about the synergies between mitigation and adaptation measures in the built environment (e.g., insulation material selection that also contributes to thermal resilience, fire resilience, passive survivability in prolonged power outages), which will help prioritize investments.
Arctic and Northern	Synthesis of baseline and future climate and environmental knowledge and data characterize the state and variation of biophysical environments and strengthen the capacity of Arctic and Northern communities and Indigenous Peoples to acquire and apply available data and research, specifically: (1) current state of sampling to identify and address gaps in key datasets, and (2) integration and analysis of information on natural ecosystems to facilitate improved understanding of the complex linkages and cumulative effects.
	Synthesis of existing knowledge of social, cultural, economic, and mental health impacts of climate change in communities to better identify their specific needs.

Annex 3 – Science and knowledge needs

THEMES	SCIENCE AND KNOWLEDGE NEEDS
Accelerating transformational change	Understand what affects youth and other populations most, how to cope with grief, and how to develop behaviours that lead to resilience and greater literacy related to environmental sustainability.
	Understand how socio-economic and technological systems may evolve through foresight and disruptor prediction to identify individual and structural changes that are positively reinforcing (e.g., aligning self-interest with the public good).
	Develop alternative metrics to evaluate progress based on catalytic and transformative potential, so that reporting becomes an agent of change and equips individuals to adopt environmental policy and/or sustainable development actions.
	Understand and develop communication strategies and messaging that motivates and enhances behavioural change (rather than changes attitudes) that break barriers to adoption (e.g., SHIFT: Social norms, Habit, Individual self, Feelings and cognition, and Tangibility) and utilizes choice architecture.
	Develop and deploy emerging technologies that enable the assessment of, and response to, threats to natural resource-based sector productivity, vector-borne disease, novel agriculture/aquaculture production systems, and nature-based solutions to achieve multiple objectives (e.g., conservation of protected areas, carbon storage, migration corridors).
	Quantify co-benefits associated with climate policy and develop ways to measure progress.
	Understand the synergies and opportunities for integrated adaptation and mitigation to achieve better climate outcomes.
Aquatic systems	Improve fundamental understanding of the processes and impacts of warming, deoxygenation, hypoxia, and acidification in marine and freshwater environments. Expand monitoring of key variables (e.g., temperature, alkalinity, salinity, pH, CO_2, water levels, stream flows, oxygen) both spatially and temporally. Key ecosystems of concern are the Arctic and nearshore areas, where little data is available.
	Identify related place-based vulnerabilities, risks, and impacts on ecosystems and resources, including on species of concern, ocean and fisheries management, aquaculture, and infrastructure.
	Examine impacts of key variables and their interaction on growth, survival, behaviour, productivity, and physiology of a variety of species and socio-economic variables to understand impacts on aquatic resources and coastal communities.

THEMES	SCIENCE AND KNOWLEDGE NEEDS
Aquatic systems (cont'd.)	Improve understanding of aquatic system components of the carbon cycle, including relationships between terrestrial carbon input, mineralization, and sediment mobilization. Improve understanding of carbon capture and storage and ability to quantify carbon sink potential in coastal areas (i.e., blue carbon). Identify impacts of wetland, macroalgal/eelgrass beds, and permafrost changes on carbon reservoirs and transfers of carbon between aquatic, land, cryosphere, and atmospheric systems to quantify carbon cycles and budgets.
	Improve basin-scale physical and biogeochemical ocean circulation models to enhance climate downscaling capability and improve regional climate projections and seasonal to decadal predictions of aquatic ecosystem variables. Improve projections of freshwater quality, quantity, and availability and study their related impacts on human well-being and activities.
	Examine response of rivers, lakes, wetlands, marshes, and coastal areas to changing temperature, salinity, oxygen, acidification, and seasonality effects to inform climate feedbacks.
	Study climate change impacts of nutrient release, contaminant distribution and transport, and metals toxicity in aquatic systems related to a warming climate, changing precipitation patterns, and ocean changes.
	Develop science-based adaptation tools for current climate-change impacted management issues.
Communities and social structures	Understand how climate change mitigation and adaptation will each and collectively impact diverse groups of people within communities, the extent to which such groups have been engaged in developing climate action, and the impact of these interventions on drivers of vulnerability.
	Develop place-based or local perspectives on risk and vulnerability in coastal, forest, rural, remote, urban, Indigenous, and Arctic and Northern communities to leverage the agency of these communities to mitigate and adapt to climate change.
	Improve understanding of the extent to which municipalities are autonomous from other levels of government, and the implications for climate policy and action. This should extend to understanding how local efforts can feed into regional efforts, and methods for effective coordination. Improve understanding of how local governments can be empowered to increase the flexibility of their governance tools.
	Develop a better understanding of how conditions and mechanisms of inclusion, transparency, and collaboration contribute to building political legitimacy to minimize the disruptive (positive and negative) effects of transformative change, especially for marginalized communities and community members. This includes going beyond a focus on individuals to the broad normalization of sustainability.

THEMES	SCIENCE AND KNOWLEDGE NEEDS
Communities and social structures (cont'd.)	Develop "living labs" or approaches to "learn by doing" in partnership with cities and communities to understand successes and opportunities related to climate change communications, citizen and political mobilization, climate services, technological innovations, and funding and governance models.
	Understand how to measure progress towards decarbonization and develop indicators for measuring transformative change.
	Understand the implications of sector, gender, and occupational health and safety in the context of the labour force in response to climate change and economic and sector transformation (e.g., energy, transportation, long-term care services).
	Understand the potential of climate change to act as a risk multiplier in the international and global security context, such as domestic and international trade; treaties, boundaries, and agreements; immigration and resettlement infrastructure; sovereignty and national security; and socio-economic outcomes, including physical and mental health of communities.
	Develop methodologies and approaches for climate change science communication and the development of professional capacity and competencies in climate change science, knowledge, and action across public and private sector enterprises.
Earth system climate science	Improve understanding and representation of climate-ecosystem feedbacks in models across the physical climate components (atmosphere-ocean-land-cryosphere) and ecosystems (terrestrial, inland freshwater, marine). Within this, a focus on landscape/hydrology and carbon cycle processes, including the response of permafrost and glaciers, to improve understanding of feedbacks and freshwater availability.
	Improve understanding of the behaviour of aquatic components and their interactions with the atmosphere, cryosphere, terrestrial, and aquifer systems and the seafloor, and improve their representation and integration in models.
	Explore the climate response to the mitigation of short-lived climate forcers (methane, black carbon, ozone, sulphates, ozone-depleting substances) and climate engineering (Carbon Dioxide Removal and Solar Radiation Management).
	Develop and evaluate more skillful climate predictions on seasonal to inter-annual and decadal scales, including initialization techniques and use of observations.
	Further develop climate projection downscaling techniques, including better use of observational data.

THEMES	SCIENCE AND KNOWLEDGE NEEDS
Economics	Explore distributional and differential impacts of climate change on the economy and society (e.g., employment, cost of living, urban infrastructure investments, Emission-Intensive Trade-Exposed industries) and ways to minimize these impacts, including developing methodologies to account for vulnerabilities, responsibility, capacity to adapt, and income levels.
	Improve the design, selection, and implementation of climate policy instruments, including decarbonization pathways analysis, carbon pricing instrument design, enablers of non-emitting technologies, incentives for zero-carbon energy generation, and estimates of payments for ecosystem services to preserve non-market benefits.
	Explore costs and benefits of climate action, including Integrated Assessment Model analyses and Social Cost of Carbon estimation; monetization of the disruption of public services, social services, and health services; costs of inaction; avoided costs; economic valuation of resilience/adaptation actions; competitiveness and mitigation; adaptation costs in scenarios of delayed global mitigation efforts or abrupt non-linear changes; and technological innovation opportunities (e.g., small modular reactors).
	Understand the finance implications of incentives and financing models targeting municipalities and remote communities, infrastructure asset management, the health sector, and urban planning and design within the broad categories of physical risks (e.g., extreme events) and transition risks (e.g., climate-related risk financial disclosure). This work would capture potential economic opportunities (currently not well defined), including the dynamics of clean technology, sustainable finance, and climate finance.
	Conduct a holistic cost-benefit analysis of current and new non-emitting technologies by considering the full spectrum of techno-economic, environmental, and energy requirements and drivers (e.g., lifecycle GHG emissions, ecosystem impacts, land use, reliability, flexibility, scalability, co-generation applications, Canadian intellectual property, and global trade potential). This work would create a methodology to appraise and select technologies best suited to decarbonize the Canadian economy at national, provincial, and regional levels.
	Continue research on behavioural economics as it relates to understanding and support for climate policy.
	Explore the economic implications of, and policy options for, enabling a just transition for workers, sectors, and communities impacted by the transition to a low-carbon, resilient economy.
	Identify how climate change will influence socio-economic drivers, such as population growth, globalization, urbanization, governance, and social structures.
	Understand how to enable better uptake of publicly funded adaptation measures and remove barriers to adaptation.

THEMES	SCIENCE AND KNOWLEDGE NEEDS
Ecosystems	Understand the impact of climate change on the biophysical processes fundamental to healthy ecosystems (e.g., nutrient and carbon cycling, permafrost, vegetation dynamics, aquifer recharge and water storage, natural disturbances such as pests and wildfires) and the subsequent impact on ecosystem function and productivity.
	Advance understanding of ecological community and species interactions (e.g., pests, invasive species, migration, range expansion) and how these relationships will respond to climate and non-climate stressors (including contaminant behaviour and re-release/distribution in water, sediments, air), and various climate scenarios, which will inform understanding of cumulative ecosystem effects.
	Develop process models and integrate species adaptive capacity into predictive models to understand how ecosystems will respond under various climate scenarios, forecast emerging and novel ecosystems, and understand and project how changes will affect wildlife. This includes developing alternative statistical or ecological niche approaches and genomic analyses.
	Develop measures and indices to enable species and ecosystem adaptation and advance management approaches to conserve habitats and biodiversity. These measures should integrate as many issues as possible to provide simple (and ideally single) measures to multiple concerns (e.g., biodiversity conservation, carbon sequestration, species at risk, productivity).
	Investigate NbS for mitigation and adaptation to understand their implications for carbon sequestration, biodiversity, wildfires, pests, invasive species, freshwater, food and fibre, the bioeconomy, and communities.
	Develop new surveillance and monitoring tools for emerging zoonotic diseases and plant/animal pests in natural and managed ecosystems.
Energy	Enhance the safe, affordable, accessible, and reliable development, demonstration, and deployment of non- and low-carbon emitting energy and energy technologies, including biomass gasification, large-scale hydrogen production from renewable energy, hydrogen energy and small modular reactor technologies, renewable natural gas, and hydrogen distribution, while providing economic benefits.
	Develop carbon capture, utilization, and storage technologies (CCUS) and related marketable products, as well as understand the potential scalability and deployment of direct air capture technologies (Carbon Dioxide Removal).
	Improve energy efficiency across sectors, including in buildings, transportation, and industry to reduce energy demand and optimize thermal energy generation, transmission, and storage; and support the use of low-carbon energy sources, feedstocks, and non-emitting technologies (e.g., renewables).

THEMES	SCIENCE AND KNOWLEDGE NEEDS
Energy (cont'd.)	Develop smart technologies to optimize the supply and use of energy, and to support high-efficiency and net-zero design energy systems, including modular, regional (i.e., district), and resilient energy systems.
	Advance electrification-focussed research in key sub-sectors (e.g., on-grid, off-grid, resource extraction, transportation), including generation (blended systems: renewable, nuclear, thermal), storage, smart technologies, and barriers to implementation (e.g., for electric vehicles).
	Advance understanding of the infrastructure, economic, and technological requirements of the energy transformation needed to achieve net-zero emissions by 2050.
	Advance understanding on the opportunities and barriers associated with next-generation clean technologies, such as net-zero energy ready homes, hydrogen energy, small modular reactors, and smart grids and devices.
	Develop an integrated and discrete energy dispatch model for the supply-demand balancing of the Canadian power grid, including GHG emission assessment, at the national and provincial levels.
	Develop scientific knowledge, including on the role of minerals, nature-based solutions, and technology on clean growth, to inform the transformation needed in the energy sector to achieve net-zero emissions by 2050.
	Advance understanding of wood and pellet heating solutions, particularly in northern, rural, and remote areas on climate change, land-use change, and environmental and health concerns, such as air pollution and habitat loss. Consideration should be given to recent energy efficiency advances in technologies, economic opportunities, and GBA+ considerations.
	Better data availability to adequately understand and model local and regional energy supply and demand across all sectors, as this data is not universally accessible across Canada.
Extreme events	Improve prediction and projection of climate extremes, extreme events, and storms, including quantitative predictions to inform disaster risk reduction.
	Improve attribution of historical and contemporary extreme events to anthropogenic climate change.
	Understand risk posed by extremes and develop methods for integrating climate risks with changes in exposure and vulnerability for social/cultural systems, forestry, wildlife, health systems, infrastructure, fisheries, aquaculture, and agriculture. This includes understanding compound or simultaneously occurring extreme events and developing indices and sector-specific thresholds.

THEMES	SCIENCE AND KNOWLEDGE NEEDS
Extreme events (cont'd.)	Investigate how climate extremes and extreme events will influence the efficacy of mitigation and adaptation measures, including nature-based solutions and energy systems.
Health and well-being	Identify where and when climate-driven infectious diseases will emerge or re-emerge in Canada, including understanding the climate impacts on zoonotic, food-borne, and water-borne diseases, both exotic and endemic, related to surveillance and monitoring, modelling, laboratory diagnostics, and public health prevention and promotion efforts.
	Understand health risks and drivers of vulnerability to climate-related extreme weather events (e.g., extreme heat), including effective adaptation actions to protect health.
	Understand mental health and psycho-social impacts of acute climate impacts and longer-term impacts on mental health and well-being, including impacts to children and youth, knowledge of affirmative mental health outcomes, and ways of communicating about climate hazards in such a way that does not induce or exacerbate mental health issues.
	Improve understanding and models of the impact of multiple climate change projections on air quality (anthropogenic air pollution, wildfire smoke, aeroallergens, indoor air quality) and associated health and economic impacts.
	Understand how climate-related impacts may affect different populations, the implications for health equity, and effective and culturally appropriate adaptation measures for these populations.
	Understand the climate-related risks, vulnerabilities, costs, and effective adaptations for health systems and services, including on health policies, programs, services, and infrastructure; health human resources planning, management and training; and supply chains critical for health.
	Improve understanding of needs, methods, and novel approaches for health, social, and environmental data collection, integration, analysis, and dissemination to support timely and accurate information for health sector decision making.
	Understand the health impacts of climate change on food safety and security, including impacts on supply chains and prices; as well as pests, pathogens, and bio-toxins that can infect plants, animals, fish and seafood, including species traditionally harvested by Indigenous Peoples.
	Understand direct and indirect health co-benefits and risks of climate actions taken by other sectors (e.g., transportation, energy, urban planning), and the economic and social returns of investing in climate-resilient health systems.

THEMES	SCIENCE AND KNOWLEDGE NEEDS
Infrastructure	Continue research to understand current and future extreme weather, natural hazards, and other climate change impacts (e.g., floods, storms, wildfire, urban heat islands, local sea-level rise, permafrost thaw, erosion) and the related impact on current and planned infrastructure (e.g., built, natural, energy, transportation). This includes developing seasonal to decadal prediction of how extremes will change (intensity and frequency).
	Increase climate data in coastal communities, Indigenous communities, the North, and remote areas. Quantify climate impacts over time in the North (e.g., precipitation, wind, permafrost, sea ice, sea level, waves, storm surges) and determine their effects on Northern infrastructure, including for Indigenous communities.
	Develop standardized methodologies to predict and measure emissions from engineered and nature-based construction materials, structures, retrofits, and hybrid approaches.
	Develop technical and behavioural solutions to developing low-carbon, resilient infrastructure and communities, including economic implications (avoided costs, return on investment) of new and retrofit approaches, managed retreat and re-location options, associated economic impacts and implications for social equity in an inclusive systems-wide approach. Links to disaster risk reduction are key.
	Understand implications of low-carbon and resilient infrastructure development and energy retrofits for Northern and remote community housing stock.
	Investigate the economic, social, ecological, and cultural implications of infrastructure resilience and adaptation solutions at national, provincial, regional, local, and asset-specific scales. This includes research to understand the full range of benefits of natural infrastructure solutions.
	Develop tools that ascribe value (economic and non-economic) to hybrid and natural infrastructure solutions that sequester carbon.
	Advance integrated approaches to better understand and address risks, vulnerabilities, and interdependencies within the transportation sector and across interdependent sectors and systems, as well as to address challenges (e.g., governance, data).
Land systems	Improve our understanding of terrestrial carbon stocks and links with landscape features and hydrology, GHG fluxes, and associated processes driving transfers among ecosystems, across landscapes, and to and from the atmosphere. This requires more accurate measurement of above- and below-ground living biomass, dead organic matter, and soil carbon using in situ, airborne, and space-based observations. Special attention is required for northern and permafrost regions.

THEMES	SCIENCE AND KNOWLEDGE NEEDS
Land systems (cont'd.)	Produce accurate estimates of the impact of current and historic human activities on carbon stocks and GHG fluxes, including quantification and mapping of carbon and nitrogen transfers between managed and natural environments.
	Understand current and projected impacts of climate change on terrestrial carbon stocks and GHG fluxes, such as vulnerability of carbon stocks, impacts of disturbances including fires, inter-annual variability, and impacts of shifts in land use in response to climate change.
	Understand land-based mitigation and adaptation actions to identify synergies and to enable the development of tools, best practices, and actions that integrate mitigation and adaptation objectives for regional and local implementation while addressing ecological, economic, and social objectives under a range of future climate scenarios.
Arctic and Northern	Develop digital infrastructure, monitoring, and data strategies that enable the participation of Northerners in research, and access to Canadian and international research results and observations.
	Develop Arctic-appropriate and adapted technologies to reduce reliance on diesel related to renewable energy systems and storage, heat recovery, and energy efficiency.
	Include and encourage leadership and self-determination of Inuit and Northerners in the continued development of climate research and monitoring to address the significant existing gaps in knowledge across the Arctic and North at all scales.
	Include and encourage leadership of Arctic and Northern partners in multidisciplinary research to understand the economic and health impacts of climate change at the community level, and the resulting needs of these communities. This includes research to support community-led clean energy projects.
	Understand the physical, landscape, and community impacts of the scientific priorities identified above in an Arctic and Northern context.

Annex 4 – Science in action vignettes

Below are examples of climate change science in action to supplement those found in the main body of this document.

Tracking greenhouse gases at our doorstep

Urban areas have many sources of GHG emissions. Tracking emission changes and identifying mitigation opportunities is key to reducing the carbon footprint of urban residents and businesses. Environment and Climate Change Canada (ECCC) researchers are using measurements of local atmospheric GHG enhancements to quantify the impact of industrial and urban emissions. They have combined socio-economic and atmospheric data to generate maps of GHG emissions for Southern Ontario, and have analyzed the relative importance of different sectors (e.g., on-road transportation, residential, commercial) and shown that understanding the contribution of natural sources is crucial. Furthermore, they did over 10,000 km of mobile surveys in the greater Toronto and Montreal areas to find mitigation opportunities related to methane, which showed that the waste sector is a major contributor, while natural gas infrastructure is a smaller source than in other North American cities. These techniques can be expanded to other urban areas in Canada and used by academic and private sector partners.

Tuktoyaktuk Community Climate Resilience Project

The Tuktoyaktuk Community Corporation has developed innovative partnerships with researchers and institutions in the Inuvialuit Settlement Region to build climate monitoring capacity and research skills. Trained monitors track permafrost variables, ice thickness, ice thaw dates, snow depth, and water quality at monitoring locations informed by Traditional Knowledge. Climate monitoring and time-lapse photo monitoring is generating timely weather information, supporting improved decisions about whether it is safe to go out on the land. This is particularly important as Inuit Elders have indicated difficulty in predicting weather due to the rapidly changing climate.

Protecting children from heat-related illnesses and injuries in playgrounds

Playgrounds can present serious risks to the health of children during extreme heat events, such as burns from metal slides and heat exhaustion. The latest scientific information on heat health risks to children is being used to inform an initiative on playground design led by the Standards Council of Canada and Health Canada through their support for the National Program for Playground Safety at the University of Northern Iowa. The project will develop guidance on how to include temperature and comfort in playground building standards as part of efforts to make such infrastructures climate resilient across Canada. Using this information, the Canada Standard Association's Children's Playspaces and Equipment Standard will be updated, giving municipalities, affordable housing providers, and schools a tool they can use to renovate existing playgrounds, or build new ones that are cool, comfortable, and safe for children and caregivers in summer.

International collaboration on satellite data and applications through the Polar View project

The Polar View project uses operational satellite data to establish services for Arctic communities. The Community Ice Service project provides one of these critical services to several northern Inuit communities. Due to climate change, the location and extent of ice and seasonal ice edges is rapidly evolving and additional information is valued greatly to complement Indigenous Knowledge. Through a collaboration between scientists at the European Space Agency and the Canadian Space Agency, routine ice data is provided and used by Inuit communities to inform daily activities. Other Polar View services related to iceberg monitoring and glacial observation have become an integral part of northern tourism and transportation, in which natural features act as both attraction and hazard. Using these services, tourism operators can identify areas for recreational viewing, while keeping vessels at a safe distance from sensitive ecosystems or hazards. Overall, the project has successfully transformed and applied satellite-derived data to the daily lives of Canadians.

Coastal infrastructure

Many of Canada's coastal areas are of great economic, social, historical, or environmental significance. Climate change is resulting in rising sea levels and water temperatures, increasing ocean acidity, and decreasing sea ice and permafrost, all of which pose considerable challenges for vulnerable coastal communities. Coastal infrastructure damage represents a high risk for these regions. For example, Fisheries and Oceans Canada's Small Craft Harbours program manages more than 750 core commercial fishing harbours with approximately 7,000 structures and a replacement value of $5.2 billion. In response to the risks associated with climate change, Fisheries and Oceans Canada invested in scientific research that has resulted in the development and implementation of decision-making tools to provide engineers and managers with science-based advice on where best to invest in adaptation projects.

Which oilseeds make good biofuel?

Biofuels are a promising way to reduce the carbon footprint of air travel. It is estimated that using a fuel mixture containing 50% biofuel would cut flight emissions by 50-70%. Currently, biofuels account for a small part of the fuel mix, but Agriculture and Agri-Food Canada (AAFC) scientists are working to change that. Although biofuels can be made from a variety of feedstocks, their cost compared to fossil fuels makes their widespread use a challenge. To find a way to make biomass feedstock more efficient and less expensive, AAFC scientists studied five different oilseeds grown on the Canadian Prairies. They found that, overall, canola appeared to be the most efficient biomass feedstock for biofuel, given that it had the highest growth rate, highest seed yield, and was the most efficient at using water. While it may be a few more years before flights are predominantly fuelled by plants, AAFC's research is helping advance this work and grow the aviation industry of the future.

Reducing transportation-related GHG emissions through zero-emission vehicles

Using a hydrogen fuel cell to power an electric motor allows for a zero-emission vehicle, with the advantage of a relatively short refuelling time (3-5 minutes) and a range of over 500 km on one single tank. But cost, durability, and the availability of hydrogen refuelling infrastructure are still challenges to the commercialization of fuel cell electric vehicles (FCEV). Work is ongoing to understand and optimize costeffective processes for the technology used in fuel cell electric vehicles, as well as to assess the economics of scaling up the production of this technology and the feasibility of commercialization. Combining the techno-economic analysis results and the engineering and production knowledge shows that zero-emission vehicles must not be overlooked as a technology that enables the reduction of transportation-related GHG emissions.

Accelerating the clean energy transition through small modular reactors (SMRs)

In our effort to achieve a resilient, carbon-neutral society, SMRs can contribute to decarbonizing the Canadian economy by serving as a reliable, flexible, and clean energy solution. More than just electricity generation, SMRs could be the key to building an overall low-carbon energy system with other non-emitting technologies, providing high temperature heat for applications such as district heating, resource extraction, desalination, hydrogen production, and remote off-grid applications. Natural Resources Canada convened stakeholders to develop Canada's SMR Roadmap, which charts a path forward for this technology in Canada. SMR innovators are currently collaborating with laboratories, universities, and operators on R&D work to make them simpler in design and capable of factory fabrication, while incorporating enhanced safety features and reducing waste volumes, with some even capable of recycling waste as fuel. To advance these technologies toward demonstration and commercialization by the late 2020s, current areas of scientific focus include reactor physics, thermalhydraulics, fuel fabrication, and plant safety. Following on the Roadmap's recommendations, researchers, industry stakeholders, governments, and international partners, are working to assess technologies, reduce costs, mobilize private finance, and establish policy and regulatory frameworks to pave the way to deployment.

Impacts of the 2013-2015 marine heat wave on Canada's west coast

A warming event of record magnitude started offshore of the west coast of British Columbia in 2013. It became evident in British Columbia coastal waters by summer 2015, with an increase in water temperatures of 3°C above normal. This warming of coastal waters was accompanied by harmful algal blooms, record high levels of large gelatinous zooplankton, and invasion of warm water species.

The event had cascading ecosystem consequences, such as the extraordinary bloom of a colonial waterborne tunicate (an animal with no backbone that is rarely found north of California) observed along the whole west coast of North America in 2017. This bloom had substantial negative impacts on commercial and recreational fishing operations due to fouling of fishing gear, illustrating that anomalous events can have unforeseen impacts on coastal fisheries. This Marine Heat Wave was unprecedented and DFO stock assessment and resource management included observations of this extreme event in the 2016 forecasts of Pacific salmon returns to British Columbia river systems. The linkages of warm ocean conditions to poor quality prey items for Pacific salmon informed the pre-season outlook for salmon returns and fishing opportunities, with expected variability across salmon stocks and general below average abundance.

Accelerating the co-development and adoption of solutions through living laboratories

All too often, one-dimensional solutions are applied to individual components of the climate change problem, overlooking the complexity between them and impeding broad-scale success or sufficient adoption rates. Through Agriculture and Agri-Food Canada's Living Laboratories Initiative, farmers, scientists, and other partners are working together to co-develop, test, and monitor new practices and technologies in a real-life context. This nationwide network of living laboratories provides an integrated approach to agricultural innovation that can address complex relationships in the development of agricultural climate change adaptation and mitigation actions. This initiative will accelerate the adoption of new technologies and beneficial management practices to build greater resilience in agricultural landscapes, including adaptation to climate change, improving agri-environmental performance (including greenhouse gas mitigation), and achieving sustainable intensification of agricultural production.

Predicting extreme weather

The Extreme Weather Indices are a suite of interactive maps showing short-term forecasts throughout the agricultural season, which will help agricultural producers assess the risks of extreme weather to their operations. They are a result of nearly a decade of scientific collaboration between Agriculture and Agri-Food Canada and Environment and Climate Change Canada, drawing on shared climate data, high-performance computers, complex models, and large datasets. The information in the indices is tailored to agriculture, with maps showing where extreme weather is forecast and the magnitude and the probability of its occurrence. Users can choose to view and explore maps from categories such as temperature, heat, wind, and precipitation prediction up to a month ahead. Having access to this information helps farmers assess the spread of pests, plan when to spray their crops, assess the risk from frost, and plan when to harvest.

A national crop yield forecasting tool to help Canada's agricultural sector adapt and thrive in a changing climate

Through a collaboration between Agriculture and Agri-Food Canada and Statistics Canada, satellite and land management data are combined to provide early warning information for crop conditions under current and future climate scenarios. The Integrated Canadian Crop Yield Forecaster (CCYF) tool was created by integrating critical satellite-derived information (e.g., soil moisture, plant health) with complex agro-climate data. The tool provides predictive lead times of two to three months for crop growth rate. As a result, the agricultural value chain is better able to anticipate, mitigate, and respond to climate risks while maintaining sustainable food production. As more detailed and frequent data become available from satellite platforms such as the RADARSAT Constellation Mission, crop yield predictions are expected to become even more accurate.