Climate Science 2050:

National Priorities for Climate Change Science and Knowledge Report

Environment and Climate Change Canada
Environnement et Changement climatique Canada
Canada

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Chapter 1. Informing Climate Action

> **Science provides the evidence and data on the impacts of climate change, but it also gives us the tools and knowledge as to how we need to address it. (…) We are now clearly in the era of implementation, and that means action. But none of this can happen without data, without evidence to inform decisions, or the science that supports programs and policies.**
>
> **— Simon Stiell, Executive Secretary,**
> **UN Framework Convention on Climate Change (2022)**

The changing climate is impacting Canada's economy, infrastructure, environment, health, and social and cultural well-being. Climate change science adds to our understanding of how to reduce future warming by mitigating greenhouse gas (GHG) emissions, how to reduce the risks from warming, and how to reduce vulnerability to climate change. Thus, it supports climate action based on evidence.

Implementation and coordination of science activities must reflect the diversity of Canadians' regional and equity-based experiences of climate change. Climate change multiplies risks for all communities and regions, but may do so in different ways, and the impacts may be felt differently. Science planning must also address the broader context of Canada's progress toward a circular economy and sustainable development.

As our needs for knowledge and information evolve, the strategic planning and implementation of science must also evolve to reflect the multiple and distinct perspectives of all people and communities impacted by climate change and climate action.

1.1. Canada's First *Climate Science 2050: National Priorities for Climate Change Science and Knowledge* Report

The scientific consensus on anthropogenic climate change is clear, as is the need for urgent action to reach net-zero to avoid the most severe impacts.[1] However, scientific capacity must be focused to bring evidence to where it is most needed to guide action, to identify new opportunities to reduce GHG emissions, to develop adaptation responses, and to measure progress. Science and knowledge[2] play an essential role in helping us navigate the complex intersections, synergies, and trade-offs inherent in building a thriving, climate-resilient, net-zero[3] Canada that is just and equitable.

The *Climate Science 2050: National Priorities for Climate Change Science and Knowledge Report* (CS2050) was developed under the leadership of Environment and Climate Change Canada. It is a "what we heard" report, summarizing the results of two years of extensive engagement with more than 500 climate program leaders across federal departments and agencies and provincial and territorial governments, as well as academics and experts from the Canadian community of climate change science, and Indigenous organizations and scholars. As such, it takes its place alongside other national climate policy and planning initiatives. It identifies the science priorities—across various disciplines, from carbon cycle and Earth system science to impacts on health, infrastructure, and biodiversity—to inform science investments needed now for science results over the next six years (to 2030), and to guide ongoing science coordination.

The priorities outlined in this report reflect the information needs of those developing climate policy and programs across all levels of government. The priorities also reflect expert opinion on new lines of scientific inquiry that will enable decision makers to use emerging knowledge, data, tools, and information. In all instances, the science priorities will help advance ongoing efforts to mitigate GHG emissions and adapt to climate change, including setting emissions-reduction targets, refining existing policy approaches, and evaluating progress to date. The audience for this report is all those who have an opportunity to shape climate change science activities across Canada, including strategic planning, funding, coordination, and implementation.

Both Western and Indigenous science contributed to the report through science expert roundtables, stakeholder surveys, webinars, and numerous discussions with partners, experts, and stakeholders. This science is needed to ensure that investments in mitigation measures, adaptation, infrastructure resilience, and disaster recovery are as targeted and effective as possible. Evidence-based action limits future risk and associated costs. Canada is already experiencing costs as climate extremes and extreme weather events have become more frequent, intense, and long-lasting. These costs amount to about 5% to 6% of annual economic growth.[4] The floods, storm surges, wildfires, and extreme heat, winds, and droughts of the last two decades have translated to economic loss and financial liabilities. Going forward, these effects are projected to become more severe. Some portion of these future losses can be avoided through science-informed adaptation and mitigation.

[1] Intergovernmental Panel on Climate Change: Sixth Assessment Report.

[2] In referring to "science and knowledge," we recognize that much of the Indigenous Climate Knowledge shared by First Nations, Inuit, and Métis Nation Peoples is Indigenous science. Therefore, we have used the term "science" throughout to highlight that Indigenous science and Western science systems are equally important ways of understanding, providing both complementary and distinct findings, each important to inform climate action. The broader term Indigenous knowledge(s) is also, at times, appropriate, and both terms are used in their appropriate contexts throughout this report.

[3] "Net-zero" in this report generally refers to achieving net-zero GHG emissions at the national level, in the context of the *Canadian Net-Zero Emissions Accountability Act*. "Low-carbon" or "low-emitting" are also used in specific sector contexts to reflect situations in which net-zero is not anticipated or feasible.

[4] Canadian Climate Institute: *The Costs of Climate Change* (2020–2022).

CS2050, published in December 2020, was an important step for Canada, taking stock for the first time of the breadth of collaborative and transdisciplinary knowledge required to inform climate action. This report is the next step, identifying the most pressing science activities to enable evolution of climate action consistent with our best understanding of the challenge. Mitigation and adaptation solutions must continue to evolve as the evidence underpinning these solutions is strengthened.

Beyond guiding science investments, the process to develop this report involved ongoing dialogue on climate change science policy to **improve delivery of science results that inform both mitigation *and* adaptation**. Last, creating this **national multi-, inter-, and transdisciplinary science and knowledge** report brings strategic science planning into broader planning for climate action, aligning Canada with other international approaches.

1.2. The Science Policy Context

This science and knowledge report complements other federal mitigation and adaptation plans for Canada. Canada's strengthened climate plan, *A Healthy Environment and a Healthy Economy*, describes federal policies, programs, and investments to achieve mitigation and adaptation goals. Canada's commitment to achieving emission-reduction targets is set out in the *Canadian Net-Zero Emissions Accountability Act*, which received Royal Assent in June 2021. The Act sets out Canada's 2030 Nationally Determined Contribution under the Paris Agreement of 40% to 45% below 2005 levels, as well as Canada's target of net-zero emissions by 2050, and it requires the Government of Canada to set additional targets every five years to 2050. The Act specifies that future milestone targets must be informed by the best available science. As an important first step under the Act, the Government of Canada published the *2030 Emissions Reduction Plan* (ERP) in March 2022. The ERP is a sector-by-sector roadmap with measures and strategies to achieve Canada's 2030 target and to lay the foundation to reach net-zero emissions by 2050. The 2030 ERP builds on the progress of past climate plans, including *A Healthy Environment and a Healthy Economy (2020)* and the *Pan-Canadian Framework on Clean Growth and Climate Change (2016)*.

Even with rapid and deep global emissions reductions, some further warming in Canada is inevitable (*Canada's Changing Climate Report*, 2019). Canada's National Adaptation Strategy recognizes the current impacts and risks of climate change through both slow-onset changes and extreme events and lays out the objectives for building resilience across Canada. A foundational principle of the strategy is that science will inform forward-looking, effective, and targeted actions to build resilience.

The *Canadian Net-Zero Emissions Accountability Act* and Canada's National Adaptation Strategy set the overarching framework guiding the climate change science priorities identified in this report. The priorities have multiple benefits, tackling many concurrent climate-related challenges facing society. In particular, this report recognizes the contributions and benefits of science to the numerous climate-related challenges facing society, including in the areas of biodiversity conservation, water security, emergency preparedness, and sustainable development. Thus, climate change science supports the goals and objectives of multiple national and international policy commitments and strategies (Figure 1.1).

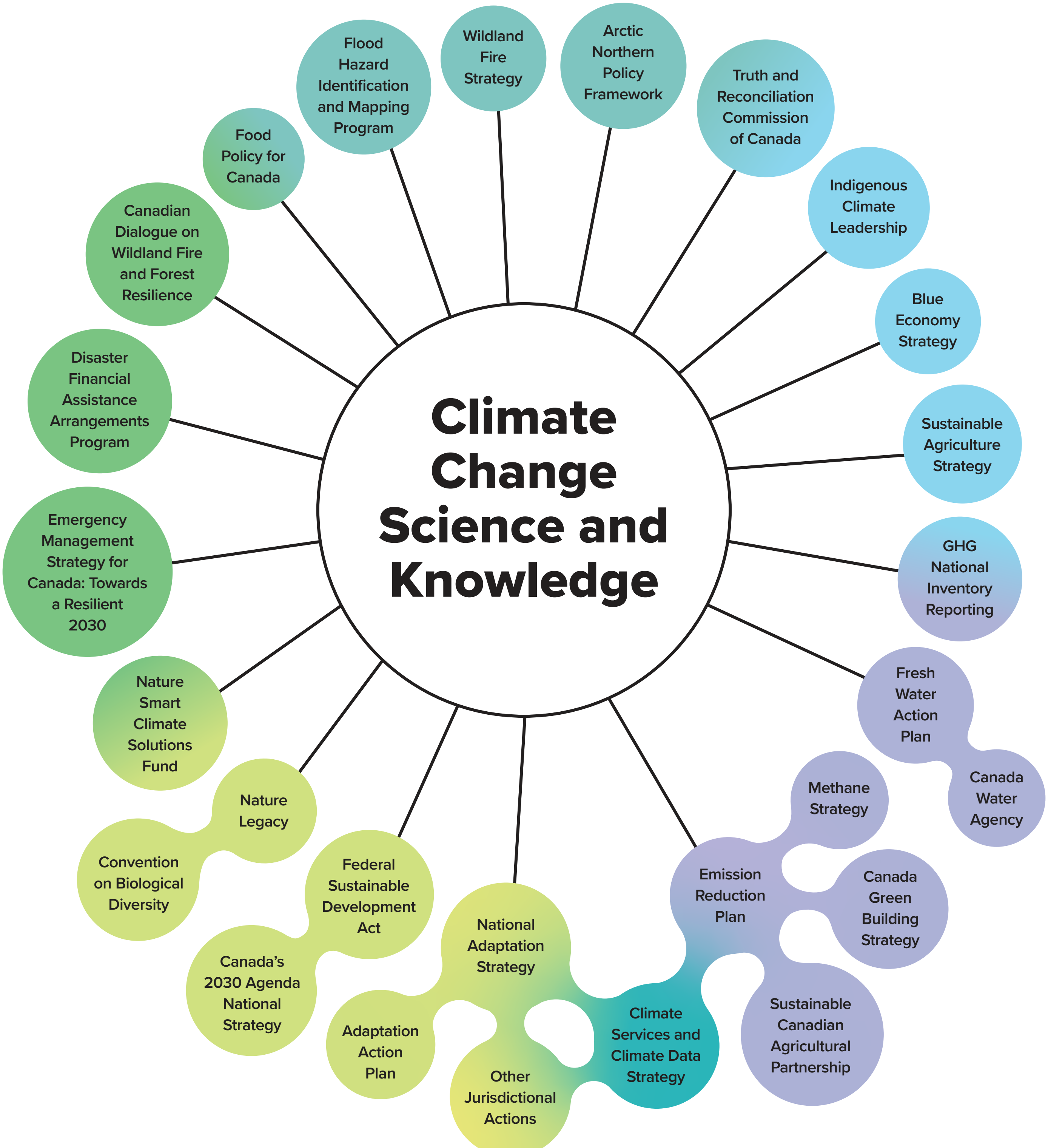


Figure 1.1. Schematic "crosswalk" between this report and its national policy context, illustrating the policies and programs that benefit from climate change science and knowledge.

This report addresses the need for investments in science at all scales, from discipline-focused discovery science to transdisciplinary research frameworks. It identifies science priorities that deliver ongoing results, including knowledge synthesis and mobilization, to provide information and data to respond to the urgent need for climate action. Hence, this report creates space for transdisciplinary science and participatory research, both critical to addressing knowledge gaps. The report identifies *what* science activities are needed, rather than *how* those activities should be implemented. While decision making and climate action (i.e., climate services, policies, and regulations) are crucial and must be informed by climate change science and knowledge, they fall outside the scope of this report.

Furthermore, this report does not address clean technology research and development (R&D), as there is already considerable planning and investment in these areas, such as the Federal Energy R&D Science Planning Process that brought together federal scientists and external stakeholders across 12 focus areas in energy R&D. This process is informing the next five years of federal energy R&D activities, some of which are complementary. The concurrent planning for clean technology, energy, and economics are outside the scope of this report. However, understanding the potential of renewable energy, carbon sequestration technologies, and other mitigation strategies is necessary to determine their potential in Canada to meet our net-zero objectives. This understanding informs net-zero pathway science, which is in the scope of this report. Targeted and sector-specific science is not included here, but that does not mean it is unimportant. The work and guidance of the Net-Zero Advisory Body, the Canada Energy Regulator, and the Canadian Climate Institute are particularly important in guiding research and knowledge synthesis and mobilization activities in this area.

This report reflects the guiding principles for climate change science developed in 2020, which have further evolved in response to ongoing science policy dialogue and engagement (Box 1.1). These principles are intended to shape all aspects of science planning, coordination, funding, data collection, research, and knowledge synthesis and mobilization.

To achieve the guiding principles, the Government of Canada supports Indigenous approaches and ways of doing by acknowledging Indigenous science as part of First Nations, Inuit, and Métis knowledge systems and ways of knowing. All those in Indigenous and Western climate change science and knowledge should listen and work collaboratively and respectfully to achieve equity among knowledge systems, while increasing opportunities for Indigenous self-determination, in fulfillment of Canada's commitment to the *UN Declaration on the Rights of Indigenous Peoples* and to Indigenous climate change science leadership (Chapter 3).

The following chapters outline the science needed to allow us to understand and assess potential impacts of climate change for Canada and the world, take informed and ambitious action, and reduce climate risk for a more resilient, net-zero Canada by 2050.

Box 1.1. Climate Science 2050 Guiding Principles

The guiding principles in CS2050 (published in December 2020) have directed development of this science and knowledge report. They offer guidance on how science planning, knowledge synthesis and mobilization, and research efforts can build on existing knowledge and understanding in a respectful, inclusive, and interdisciplinary way that benefits all Canadians. These principles continue to evolve, reflecting the discussions held and advice received in developing this report. These principles are to:

- 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 can be bridged, braided, and woven to respectfully co-exist and co-create new knowledge.
- Embrace **multi- and transdisciplinarity** to produce science and knowledge that reflect the complexity and interconnections inherent in responding to climate change and that encompass different kinship systems and spiritual relationships with the land, oceans, and waterways.
- Emphasize **collaboration** across generations, disciplines, sectors, levels 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 priorities 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, while removing systemic barriers and promoting well-being.
- Respond to **local and regional** contexts, needs, priorities, protocols, cultures, and ways of knowing by involving communities affected by the research to produce tailored and effective adaptation and mitigation efforts.
- Further **Indigenous self-determination in research** to support an approach to climate change science that is holistic, place-based, and responsive, and that respects Indigenous sovereignty and ownership of data.
- Consider climate change **mitigation, adaptation, and sustainable development** in an integrated way to maximize multiple benefits and complementary, mutually reinforcing responses.

Chapter 2. Approach and Methods

Summary

The approach and methods used to develop this report were holistic and grounded in societal outcomes, which the science informs. The report's primary goal is to support net-zero and adaptation objectives. The identified science priorities also aim to achieve interconnected national goals for climate action, biodiversity conservation, and sustainable development. The primary drivers of science priority selection are relevance and responsiveness to information needs for climate change policies and programs. However, identification of priorities was also influenced by understanding of current knowledge gaps, anticipated scientific developments, and opportunities to advance science through increased national coordination and/or collaboration.

This report was developed through engagement with a broad range of climate program leaders across governments and sectors, as well as experts from the Canadian climate change science community, in 2021-2022. This built on the broader Government of Canada engagement on the 2030 Emissions Reduction Plan and Canada's National Adaptation Strategy.

This engagement process found that Canada should prioritize both **foundational** research, to address challenges in scientific disciplines, and **transformative** research, to address complex challenges that require the collective and integrated contributions from social, economic, natural, and health sciences. The key messages and findings from the engagement are synthesized in the science priorities presented in Chapters 3 to 6.

The full suite of science priorities addresses the information needs of users—those who design, implement, and evaluate climate policy and programs.

This chapter outlines how the report was developed, including engagement and prioritization of the science activities. Aligned with the guiding principles (Box 1.1), development of the report took a holistic approach, grounded in societal outcomes, which need to be informed by the science. Throughout the report's development, the process emphasized advancing science to achieve domestic climate objectives and Canada's sustainable development in a net-zero world. However, the report also anticipates opportunities for Canadian science to contribute to a broader international response to climate change and to climate-resilient development.

While Canada's domestic net-zero and adaptation objectives drive this report, multiple benefits can also arise from these scientific efforts. The science activities outlined in the report are relevant to diverse climate-related challenges (Figure 1.1). Understanding of these challenges and connections with multiple benefits (e.g., for biodiversity, health, and sustainable development) also influenced the identification of science priorities.

The first CS2050 report (published in December 2020) took stock of the broad range of science aligned with climate action. This follow-up report prioritizes science activities and is intended to inform investments in research and knowledge synthesis and mobilization to align with ambitious climate action. This is similar to approaches taken in other countries with relevant jurisdictional, cultural, and/or geographical contexts. Many of the science priorities in this report represent a common science foundation for mitigation and adaptation planning, which are increasingly integrated. The common science foundation is designed to help guide these efforts so that they also become mutually reinforcing. As a result, this report identifies science priorities that span multiple disciplines, regions, and sectors, building on the initial CS2050 framework.

2.1. International Examples

Understanding how other nations or international bodies have approached planning for climate change science can inform Canada's approach. The core precept is that climate action should be based on the best possible scientific knowledge, in order to manage risk and inform effective mitigation strategies. To find international comparators, a number of science plans or strategic program plans were reviewed (below). No science plans from other jurisdictions were grounded in societal outcomes and informed both mitigation and adaptation from a holistic perspective, like the approach taken for this report.

- The **European Union Joint Research Program** consists of distinct research areas, which predominantly include mitigation-focused science and an integrated sustainability research program. The Horizon Europe 2021-2024 strategic plan also includes climate science.
- The **Danish Meteorological Research Institute** hosts a National Centre for Climate Research, an interdisciplinary collaborative that emphasizes Danish priority topics, including the cryosphere, extreme weather, and green transition through renewable energy sources.
- There are many organizations involved in climate science in **Australia**, notably the Commonwealth Scientific and Industrial Research Organisation and the Bureau of Meteorology. The Australian Academy of Science is responsible for reviewing climate science capability and identifying the current position of the climate science sector and future climate research needs.
- In the **United Kingdom**, the Met Office Hadley Centre Climate Programme provides leadership and strategic planning in climate change science, supported by the Department of Business, Energy and Industrial Strategy as well as the Department for Environment, Food and Rural Affairs. The UK Royal Society produces briefings on a range of topics to inform climate action and research priorities. Advice is coordinated through the UK Climate Change Committee.
- In the **United States**, the US Global Change Research Program, a collaboration of 13 US federal departments and agencies, is responsible for strategic science planning and science assessments. This is laid out in the Global Change Research Needs and Opportunities for 2022-2031.
- In **Austria**, the Austrian Climate Research Programme guides climate research related to climate change impacts, adaptation, and mitigation.
- Aotearoa New Zealand reflects the Crown-Māori relationship under the Te Tiriti o Waitangi (The Treaty of Waitangi), recognizing the application of te reo Māori (the Māori language) and mātauranga Māori (the unique Māori way of viewing the world, encompassing both traditional knowledge and culture), within an environmental context and specifically in New Zealand's national adaptation plan.

2.2. Engagement

Climate Science 2050: National Priorities for Climate Change Science and Knowledge was developed as part of an ongoing science policy dialogue, led by Environment and Climate Change Canada, that started in 2018 with engagement for the first CS2050 report. This process involved convening a broad range of climate program leaders from across governments and sectors, as well as experts from the Canadian climate change science community. In developing the report, it was important to address knowledge gaps identified by climate policy and decision-makers across jurisdictions to better understand their priorities for climate action and what information is most needed to help this climate action succeed. The scientific community was also asked to consider what new science or knowledge syntheses are needed to meet these information needs, and where future scientific developments will enable policy makers to fill knowledge gaps and achieve climate change goals.

Working with the Office of the Chief Science Advisor's network of Departmental Science Advisors, a Science Advisory Group was established to guide engagement and report development, prioritization, and peer review. Federal science leaders from multiple departments[5] analyzed input from the engagement and wrote this report. Throughout this process, it was evident that the organizing structures required for effective national science coordination and planning are limited, especially in light of the ambition and diversity of climate objectives.

The engagement conducted in 2021-2022 benefited from input to the broader Government of Canada engagement on the 2030 Emissions Reduction Plan and Canada's National Adaptation Strategy. In addition, the process involved engagement specifically for CS2050, including provincial and territorial engagement (Box 2.1); a targeted stakeholder survey; a Request for Information to academic organizations; and a series of seven expert science roundtables (Figure 2.1). The science roundtables discussed scientific "grand challenges" fundamental to success in mitigating GHGs and adapting to climate change. These discussions were framed by climate program leaders' information needs, as expressed through the initial engagement process.

A small workshop of Indigenous academic scholars complemented the science roundtable exercise, to garner insights from First Nations, Inuit, and Métis knowledge systems. This workshop further shaped the report, and, in particular, guided the development of Chapter 3, reflecting the importance of Indigenous science and capacity in weaving together Indigenous and Western science approaches.

The draft report was peer reviewed by 14 Canadian and international experts with multidisciplinary perspectives, grounded in their own specific areas of expertise. All had an appreciation of the Canadian science context through substantive engagement and/or collaboration with Canadian scientists.

[5] The federal scientific leadership included Agriculture and Agri-Food Canada, Environment and Climate Change Canada, the Canadian Food Inspection Agency, Fisheries and Oceans Canada, Health Canada, Infrastructure Canada, Ingenium, Natural Resources Canada—Canadian Forestry Service and Lands and Minerals Sector, National Research Council Canada, Parks Canada, and the Public Health Agency of Canada.

Box 2.1. Provincial and Territorial Engagement: What We Heard

Provincial and territorial governments are important users of climate change knowledge. They apply science results to reduce GHG emissions and implement adaptation that will be effective in their geographic and decision-making context. The information needs of all levels of government need to continue to inform climate change science, notably to:

- improve coordination of research across sectors and actors and improve mobilization of knowledge;
- create space and equity for Indigenous knowledge;
- improve emissions performance reporting, estimation methods, disclosure, and targets for accountability;
- improve monitoring; data collection; research on climate, risks, hazards, and opportunities; research to support vulnerability and risk assessments; and metrics, monitoring, and evaluation of interventions—in particular, in fisheries, forestry, agriculture, biodiversity, and ecosystems;
- improve prediction of climate extremes and extreme weather events;
- project climate impacts on water demand, supply, and management;
- develop hydrological, flood, and coastal hazard maps for planning, navigation, and emergency response;
- predict climate change on a local scale, and understand impacts for infrastructure, health, safety, culture, and heritage;
- develop projections, observations, data, and indicators to inform nature-based solutions and management of land, waters, wildlife, and ecosystems;
- co-develop information for mitigation, adaptation, and planning tools that municipalities, communities, local stakeholders, emergency management personnel, urban planners, engineers, and others can use to respond to climate change;
- develop integrated assessment tools, which factor climate change into policy as well as financial and economic planning; and
- understand and predict climate impacts on food security, including country foods and sustainable harvesting.

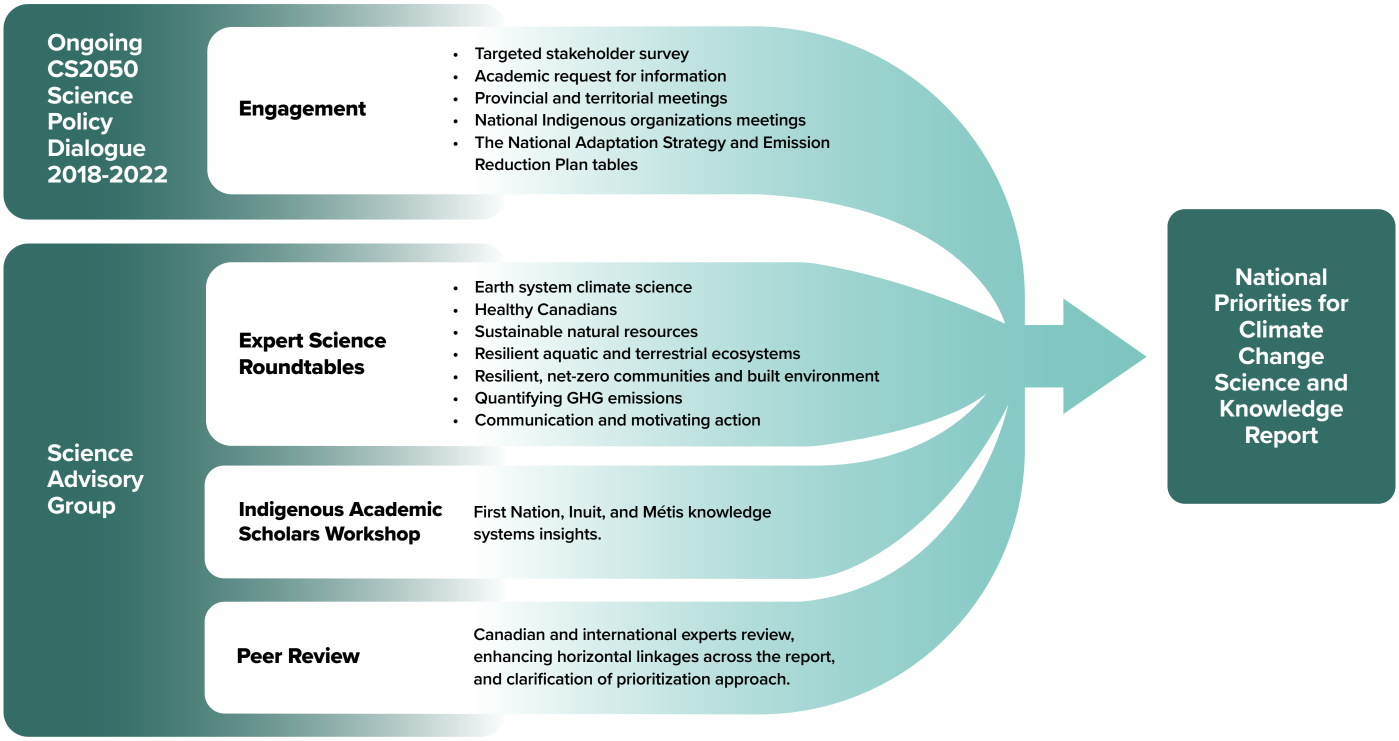


Figure 2.1. The development process for
Climate Science 2050: National Priorities for Climate Change Science and Knowledge.

2.3. Transdisciplinary Science and Convergence Research

The engagement and expert roundtables found that research frameworks must align with the increasing complexity of decision making for mitigation, adaptation, and sustainable development. This alignment requires advancing these frameworks toward transdisciplinary science (Box 2.2). Related to this alignment, several “nexus” topics, in which disciplines intersect, and “convergence” research topics (Box 2.2) emerged in discussions.

Box 2.2. Research Paradigms for Transformative Science

The most challenging knowledge gaps require transdisciplinary science frameworks in order to include social, economic, natural, health, and Indigenous sciences and to integrate climate change, health, and economic well-being. The 2017 report Investing in Canada's Future: Strengthening the Foundations of Canadian Research notes that the multifaceted challenges facing society require science that goes beyond disciplines, bridging previously disconnected fields of knowledge and creating new disciplines.

Developing climate change knowledge requires participatory research paradigms, creating stronger relationships among disciplinary experts and between experts and decision makers. Furthermore, giving equal value and respect to Indigenous knowledge, alongside Western science, is itself a research paradigm that continues to develop.

In this science and knowledge report, the following terms are used (adapted from The Difference Between Multidisciplinary, Interdisciplinary, and Convergence Research | Research Development Office (ncsu.edu) and Research Types - Learn About Convergence Research | NSF - National Science Foundation). Transdisciplinary frameworks should enable equity and unity.

Interdisciplinary science involves two or more disciplines coming together to develop a coordinated and inclusive definition of the research problem and to design and execute the research project.

Multidisciplinary science connects researchers from different disciplines, each contributing their disciplinary perspective.

Transdisciplinary science creates a unity of intellectual frameworks, integrating approaches beyond disciplinary perspectives and resulting in a synergistic and novel approach to defining the research problem, modalities, and knowledge synthesis and mobilization.

Convergence research brings together diverse researchers to communicate across disciplines in pursuit of a common research challenge, resulting in an intermingling of knowledge, theories, methods, data, and communities. It is similar to transdisciplinary research but intentionally creates new paradigms or disciplines.

Two-Eyed Seeing, a concept proposed by Mi'kmaq Elder Alber Marshall, refers to learning to see from one eye with the strengths of Indigenous knowledges and ways of knowing, and from the other eye with the strengths of Western knowledges and ways of knowing, taking advantage of multiple perspectives (see Guiding Principles (Two-Eyed Seeing) | Integrative Science).

2.4. Report Structure

The structure of this report[6] is closely aligned with the themes in the original CS2050, but also reflects the need for transdisciplinary science to address convergence research topics. This also reflects the importance of advancing science on multiple fronts in parallel, as climate change continues to affect decision making in every region, community, and economic sector.

The priorities in this report emphasize bringing social sciences more fully into climate change science, as an essential element in advancing work across all theme areas and in empowering action. Specifically, behavioural science is needed to design and evaluate climate change communication to increase awareness and understanding and to inform and motivate action. Figure 2.2 illustrates the conceptual framework for this report.

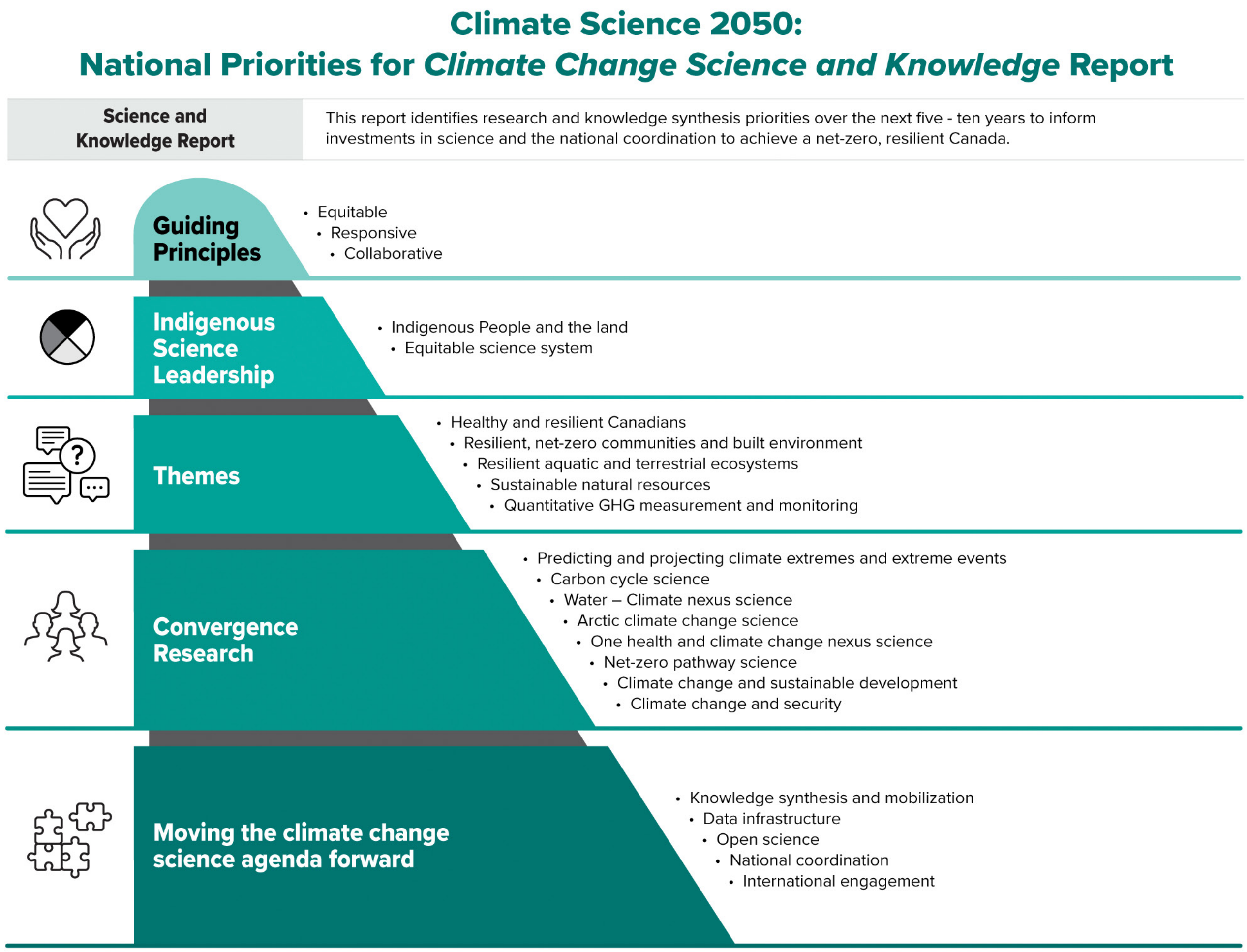


Figure 2.2. Conceptual framework for *Climate Science 2050: National Priorities for Climate Change Science and Knowledge*.

[6] Since publication of CS2050, the "carbon neutral" theme has been renamed "net-zero greenhouse gas emissions." Responding to the engagement and prioritization exercise, science priorities related to the "Earth system climate science" theme have been captured under the convergence research topics. These themes are inform our understanding of climate extremes and extreme weather events, the carbon cycle, and the water–climate nexus. They remain faithful to the input related to the Earth system climate science theme.

2.5. Analysis and Prioritization

Chapters 3 to 6 identify priorities for research and knowledge synthesis and mobilization. The priorities reflect the need for both **foundational** research (advancing science to address challenges in scientific disciplines) and **transformative** research (addressing complex challenges that require the collective and integrated contributions from social, economic, natural, and health sciences), both of which are required to inform and evaluate progress in meeting Canada's climate objectives.

To select the priorities for science and knowledge, the **guiding principles** identified in CS2050 (Box 1.1) were used. Three additional principles were developed specifically for this report to ensure that the highest-priority science activities reflect:

1. **relevance and responsiveness** to the needs of climate change policy and program information, to help achieve the challenging transformative climate action needed to reach a resilient, net-zero Canada;
2. **scientific excellence**, guided by emerging science and scientific foresight; and
3. benefits from increased **national coordination and/or collaboration**.

As well, **eight criteria** were developed to guide discussion of the science priorities. Science priorities should:

- result in substantial opportunities to develop ***science assessments*** and ***knowledge synthesis products*** that mobilize the investments already made in climate change science;
- advance knowledge and capacity through increased ***national coordination*** and ***collaborative research partnerships*** that extend across federal departments and encompass provincial/territorial, Indigenous, municipal, academic, environmental non-governmental, and industry organizations;
- enable ***multi-scale responses to climate change*** from national to regional and local contexts;
- build on leadership and participation in ***international science and knowledge*** to mobilize knowledge and tools in Canada's interest and context;
- reflect a ***multi- or transdisciplinary approach*** to advance research and knowledge synthesis and mobilization, where integration of understanding across disciplines is required;
- identify ***readiness*** in the state of knowledge or tools, in order to make rapid progress with targeted and modest investment;
- apply an ***intersectional lens*** to develop solutions that tackle climate change, sustainable development, and social inequity; and
- ***intersect multiple disciplines and interdependencies***, so that advances in climate science have co-benefits for other social or environmental objectives (e.g., health, biodiversity conservation, air and water quality) or specific economic sectors (e.g., agriculture, fisheries, forestry).

Following from these principles and criteria, the process identified **convergence research** topics that:

- intersect multiple themes and science disciplines;
- are transdisciplinary;
- are relevant across regions and sectors; and/or
- share complex interdependencies, interactions, and feedbacks across environmental, ecological, socio-economic, and health systems.

These convergence research topics reflect where investments in research, facilitated national coordination and collaboration, infrastructure, and knowledge synthesis and mobilization activities will have the greatest impact on achieving a resilient, net-zero Canada. They also reflect critical science needed to evaluate our progress toward our climate goals.

The key messages and findings from the engagement discussions and expert roundtables were then synthesized. In this process, we acknowledged the importance of perspectives of users—those who design, implement, and evaluate climate policy and programs—and we listened to their information needs and knowledge gaps. This perspective shaped the prioritization of science activities for research, knowledge synthesis, and knowledge mobilization (Chapters 3 through 6). As a final step, a holistic review of the science priorities against the engagement input confirmed that science must advance on multiple fronts to address the diverse set of information needs expressed during engagement.

Chapter 3. Indigenous Climate Change Science and Knowledge

This chapter has been written by the CS2050 Secretariat in Environment and Climate Change Canada (ECCC), reflecting many conversations and materials prepared in the context of other national climate programs. Specifically, it summarizes findings from the federally led National Adaptation Strategy engagement and Table discussions, the three Joint Indigenous Nation-Canada Tables for the Pan-Canadian Framework on Clean Growth and Climate Change, the federal Indigenous-STEM (science, technology, engineering and math) community, the Environmental Damages Fund-Climate Action and Awareness science theme scoping, a small Indigenous academic scholars workshop, and the ECCC Indigenous Science Division. While this chapter is specific to Indigenous science and knowledge for climate change broadly, the subsequent chapters also identify specific areas in which Indigenous science and knowledge are important to addressing knowledge gaps and mobilization.

The First Nations, Inuit and Métis Peoples, their knowledge, and their relationship with the land, water, and ice make a critical contribution to developing solutions and responding to environmental challenges, including climate change. The reconciliation pathway—as guided by the *Truth and Reconciliation Commission of Canada: Calls to Action* report of 2015—calls for all Canadian institutions to re-envision relationships, policies, and programs to heal the wounds of the past.

Colonization has increased the susceptibility of Indigenous Peoples' physical, cultural, economic, and spiritual well-being to climate change. Indigenous Peoples have unique relationships and responsibilities between Indigenous knowledge systems, and the land, water, and ice. These concepts among Indigenous Peoples are multi-faceted and place-based, with traditions, languages, ceremonies, and knowledge systems driving the unique world views of communities and Indigenous nations. The responsibilities inherent in those knowledge systems and ways of being are known as *Natural Laws*. In Indigenous contexts, land represents more than simple physical landforms, territories, or ecosystems. Across Indigenous cultures, land, water, and ice are understood to be foundational elements of Indigenous identity. They serve as the landscape upon which human and more-than-human relationships evolve and develop. At the same time, they create reciprocal relationships that define the obligations of all entities to each other. This concept of land, water, and ice as interacting elements in the web of life and as arbiters of responsibility makes Indigenous science and knowledge essential to addressing climate change and co-developing solutions for all Canadians.

Indigenous science priorities and Indigenous leadership must be integrated into the entire spectrum of science practice, from hypothesis generation to policy development and implementation, to support Canada's commitments to reconciliation with Indigenous Peoples. The respectful bridging of Indigenous and Western science enables this reconciliation but must be sensitive to the capacity of Indigenous communities to engage equitably. One of the ways we reconcile is by creating equitable spaces that acknowledge the role of academia, science, and colonialism and their impact on Indigenous science.

Box 3.1. Indigenous Science

Indigenous science is a culturally specific method of accumulating knowledge, refining hypotheses, and changing practices associated with First Nations, Inuit, and Métis Peoples' deep understanding of the natural world. Indigenous science is "wholistic" (a term used to describe the ecosystem as a whole), and deeply braids, or weaves, new information over a longer-term perspective, while respecting expected codes of conduct and due diligence toward the collective benefit of all components, including humans, in ecosystems. Indigenous research paradigms have a number of common components; for instance, relational accountability, wholistic use and transmission of data and information, and respect for people as part of processes that can influence scientific outcomes.[7]

3.1. Creating an Equitable Science System Through Indigenous Science

Distinction-Based Approach

The term "distinctions-based approach" acknowledges the distinct histories, interests, and priorities of the three major groups of Indigenous Peoples recognized in Canada's constitution: First Nations, Inuit, and Métis Peoples.

Indigenous leadership has historically been silenced, unrecognized, and devalued. Only very recently has the development of climate change science and global climate change policy involved Indigenous leadership, with self-determination and governance as core concepts shaping environmental science and policy. Establishing a representative, diverse, and inclusive science system in Canada requires continued and renewed relationship-building. The system must readily incorporate both Western and Indigenous methods and ways of knowing in a strengthened path forward.

Research and science activities that are Indigenous-led and/or co-developed with Indigenous communities foster grassroots participation and allow communities to benefit from current information to make decisions.[8] Such activities can also lead to community engagement on a long-term basis, reducing "consultation fatigue." Locating government facilities, research infrastructure, and personnel in Indigenous and remote communities further increases the potential for long-term relationships with Indigenous communities and builds the community's capacity.

Equitable outcomes of climate change science must include Indigenous science methods to inform mitigation and adaptation. The following priorities are designed to build Indigenous science and strengthen equity across knowledge systems. However, Indigenous-developed research strategies are the primary articulation of Indigenous Peoples' priorities.

ISK1. Develop Indigenous leadership in climate change science and Indigenous science networks; support science and knowledge clusters and networks that actively build relationships with Indigenous Peoples in creating pathways that respect local grassroots climate science concerns and priorities. This includes preparing the existing system for the influx of Indigenous science—training existing professionals, incorporating Indigenous science into science education materials at all levels nationally, working with licensure bodies, and others. It also includes building relationships, learning jointly with Indigenous communities, and developing Indigenous climate change and science youth leadership or mentorship programs to restore and increase the number of knowledge-holders in communities, Indigenous nations, academia, industry, and the public service.

[7] How Indigenous knowledge advances modern science and technology. Accessed March 25, 2023 from https://theconversation.com/how-indigenous-knowledge-advances-modern-science-and-technology-89351

[8] Sawatzky A., Cunsolo A., Jones-Bitton A., Gillis D, Wood M., Flowers C., Shiwak I., The Rigolet Inuit Community Government, & Harper S. L. (2020) "The best scientists are the people that's out there": Inuit-led integrated environment and health monitoring to respond to climate change in the Circumpolar North. *Climatic Change*, 160(1), 45–66. 10.1007/s10584-019-02647-8

ISK2. Braid and weave Indigenous and Western science planning and implementation with Indigenous governments, organizations, and citizens to craft approaches to climate change science and knowledge that are relevant to regions, based on distinctions, and uphold Indigenous rights and self-determination. This includes building networks of regional distinctions-based forums to guide climate change science. It also includes developing Indigenous-determined indicators that track Canada's progress in engagement of Indigenous climate change science, so that science outcomes inform measures to mitigate the socio-cultural and socio-economic impacts of climate change.

ISK3. Create materials for Indigenous climate change science and knowledge that are responsive to Indigenous Peoples' goals of cultural revitalization, and develop policies, programs, and initiatives respecting Indigenous languages. This approach requires the production of technical and communications materials in Indigenous languages, grounded in co-development.

ISK4. Strengthen scoping and funding mechanisms to establish Indigenous science research capacity. This could include mechanisms to create research programs, hubs, or a fourth[9] Indigenous-led research funding council/agency, at the national or regional level, to lead research and administration of science programs by Indigenous science organizations (e.g., Indigenous Centre of Excellence for Climate Change), as well as Indigenous science programs at the community level with dedicated Indigenous science liaison people (see section 3.2 below).

ISK5. Train and build capacity in Indigenous local and regional place-based science and knowledge practice. Practice could include Indigenous-led monitoring and data infrastructure; community-level knowledge and environmental management systems; training opportunities for Indigenous youth; lifelong learning and technical skills related to local environmental and Indigenous science; and Indigenous project leadership and implementation (see section 3.3).

3.2. Indigenous Peoples' Sacred Relationships to Land, Water, and Ice

It is through the human lens that we observe, interpret, and build the ethical framework that drives how we interact with the land, water, and ice. Relationships to the land, and ultimately climate, are encoded in Indigenous identities, languages, practices, and stories. Historical and contemporary climate and environmental knowledge can take a range of forms that might not be understood without culturally specific interpretation and translation. Establishing relationships between communities and researchers, and between the Crown and settler populations, necessitates rebuilding trust and collaboration. Canada's constitution recognizes three groups of Aboriginal Peoples: First Nations, Inuit, and Métis. Honouring the inherent rights of Indigenous Peoples means acknowledging the culturally distinct and diverse First Nations, Inuit, and Métis Peoples' rights, agreements, treaties, interests, and circumstances. This distinctions-based and place-based approach remains essential to Indigenous science and knowledge.

The *National Inuit Climate Change Strategy* and the *National Inuit Strategy on Research*, the First Nations – Canada *Joint Committee on Climate Action 2021 Annual Report*, and the *Métis Nation Climate Change & Health Vulnerability Assessment* all highlight the need to develop local capacity to address the unique challenges of Indigenous Peoples, governments, organizations, and nations. Indigenous science and knowledge systems have developed responsibilities that are culturally defined. For example, the unique role and relationship of Indigenous women to water has traditionally been encoded within cultural practices and protocols, representing a branch of knowledge that can be accessed only through specific, local, community-defined processes.

[9] Government financial support for university research and research training is predominantly made available through three federal granting councils: the Natural Sciences and Engineering Research Council of Canada (NSERC), the Social Sciences and Humanities Research Council of Canada (SSHRC), and the Canadian Institutes of Health Research (CIHR). Granting councils continue to adapt approaches; for example: Setting new directions to support Indigenous research and research training in Canada 2019 - 2022 - Canada.ca

Box 3.2. Respecting Indigenous Peoples as Climate Scientists

Indigenous Peoples have an unbreakable and sacred connection with the land and water. The relationships between Indigenous Peoples, land, water, ice, animal life, and surrounding habitats are the foundation of Indigenous science and knowledge. In turn, this science and knowledge can provide context, interpretation, and deep insight. Article 25 of the *United Nations Declaration on the Rights of Indigenous Peoples* affirms Indigenous People's rights to maintain and strengthen their distinctive spiritual relationships with the land and water. Indigenous science and knowledge are highly integrative and reflect an understanding that humans are part of ecosystems and must remain in balance with them. Indigenous land stewardship practices are inherently systems-oriented and wholistic in scope. The First Nations, Inuit, and Métis are well-positioned to be guardians and stewards of ecologically sensitive landscapes, especially those involving their traditional lands.

More recently, there has been a shift toward supporting Indigenous community ownership and control of data, information, and research outputs gathered by Indigenous communities (e.g., First Nations Information Governance Centre and the *National Inuit Strategy on Research*). Efforts to blend the best available Indigenous and Western scientific information have led to meaningful, long-term partnerships that are place-based. In many Indigenous Nations, Indigenous-led and/or co-developed research programs are the new minimum (e.g., Mi'kmaq partnership tenets). In the Inuit Nunangat (the Inuit homeland in Canada), partnerships with Inuit are essential to assess and address the impacts of climate change (see Chapter 5.4. Arctic Climate Change Science). To put in place the data infrastructure fundamental to evidence-based decision making, Indigenous rights and protocols must be recognized, and Indigenous data must be recognized as inseparable from the people and the methods used to collect that data (see Chapter 6.1. Data Infrastructure).

The Canada Research Coordinating Committee has prioritized the development of Indigenous research capacity in responding to the Truth and Reconciliation Commission of Canada's calls to action and in contributing to reconciliation in Canada. Such approaches, although beneficial, are not yet specific or responsive to challenges facing Indigenous Peoples, such as food and energy security or access to clean water. There is a need to create space and capacity for Indigenous leadership in funding bodies by enhancing Indigenous leadership and participation in scoping, review, and decision making that reflects the relationship with land, water, and air. Flexible funding and Indigenous-led programs that avoid competition among First Nations, Inuit, and Métis knowledge systems are particularly important.

As noted in the fourth priority (Strengthen scoping and funding mechanisms to establish Indigenous science research capacity), novel Indigenous-led funding models are needed to enhance the scope and funding mechanisms for Indigenous science research capacity. This capacity can be achieved through new, culturally appropriate, Indigenous-led granting programs, councils, or hubs. Science coordination is a key part of this report, and such coordination can bring together Indigenous and Western science voices in Canada. Among other benefits, coordination could provide better opportunities for Indigenous scholars and knowledge holders to publish their work, thereby bringing the voices of Indigenous Peoples to other scientists, scholars, and communities.

3.3. Learning From, and Stewardship of, the Land, Water, and Ice

Land, water, and ice are the essential components that drive relationships between people and ecosystems and from which Indigenous Peoples derive their responsibilities. These relationships are celebrated, encoded, and learned through traditions and ceremony. This is not a uniquely Canadian concept, as Indigenous Peoples are being recognized globally as leaders in landscape and biodiversity conservation. Indigenous science is about the long-term understanding of ecological cycles and environmental processes that are embedded in the intimate knowledge of environment and in traditional and cultural activities. This understanding has served as a resilient force in Indigenous adaptation and mitigation strategies, as Indigenous communities monitor and respond to changes in the environment (Box 3.1).

A key element of the human–environment relationship in many Indigenous cultures is the concept of stewardship. Being part of the land provides a rich knowledge of ecosystems and biodiversity. Through Indigenous concepts such as "living well with Earth," "all my relations," and "kinship relationships" with the land, oceans, waterways, and animals, Indigenous science can help promote understanding and guide future human interactions with land, water, ice, and the climate. Indigenous science can also foster a longer-term strategic vision for the protection of resources that is inclusive, collaborative, and advances reconciliation.

Box 3.3. Indigenous Climate Change Programs Enabling Science and Knowledge-Sharing

These programs foster Indigenous leadership in building and maintaining resilient ecosystems that are key to mitigating and adapting to climate change and revitalizing culture.

- In 2017, the Government of Canada launched the Indigenous Guardians program, which gives Indigenous Peoples opportunities to exercise responsibility in stewardship of land, water, and ice, as well as rights and responsibilities in protecting and conserving ecosystems, developing and maintaining sustainable economies, and continuing the profound connections between natural landscapes and Indigenous cultures.
- The Indigenous Community-Based Climate Monitoring Program supports Indigenous Peoples across Canada to monitor climate and the impacts of climate change using Indigenous knowledge systems and science.
- The United States Bureau of Indian Affairs' Branch of Tribal Climate Resilience has **regional liaisons** who serve as key links between Indigenous communities and the Department of the Interior's Climate Adaptation Science Centers. The nine Climate Change Adaptation Centers are regionally representative, managed by the US Geological Survey's National Climate Adaptation Science Center, which aims to develop "actionable science, information and products that address identified science needs and are directly usable in supporting resource management decisions, actions, and plans." This network of science centres is responsible for developing leaders in climate change science through a variety of research, fellowships, and training programs.
- The Canadian National Collaborating Centre for Indigenous Health supports the health of First Nations, Inuit, and Métis Peoples by improving evidence-based public health practice through a wholistic, strengths-based approach.

Approaches are needed in which priorities are determined by Indigenous Peoples and are designed to work with Indigenous capacity and community contexts. Such approaches lead to more successful and relevant science outcomes and are inclusive of culturally relevant training and Indigenous representation.[10] These outcomes should, to the greatest extent possible, be produced by Indigenous Peoples. This requires ongoing, meaningful inclusion of Indigenous Peoples in Western science research activities and programs as equal partners, to further trust and relationship-building. Such inclusion also helps build capacity in community-based Indigenous science (see priority 5 in this chapter). Combining Indigenous science and knowledge with strategic investments and support for coordination or partnerships can be a powerful tool for Indigenous Peoples, governments, and stakeholders to combat climate change. An example is the Indigenous Innovation Initiative, a challenge-based funding program that relies less on "competitive aspects in favour of a more holistic, community-oriented frame that values interconnection and communal values over individual triumphs." This can inform novel funding models addressing the needs of communities and grounded in values based on culture, place, and distinctions. Models should avoid silos, be led by Indigenous science leaders, and favour a "one-window" approach, in which all programs are coordinated and accessible through a single system or application.

[10] A report on Indigenous resilience, to be released in 2024, draws on Indigenous knowledge, perspectives, and experiences to explore multidimensional and intersecting aspects of climate change impacts and adaptation. This report is part of a national assessment process being led by Natural Resources Canada that looks at how and why Canada's climate is changing, impacts on communities and the economy, and how we're adapting in Canada (*Canada in a Changing Climate: Advancing our Knowledge for Action*).

3.4. Knowledge Gaps and Mobilization Opportunities

While the impacts and risks posed by climate change vary by region and community, common knowledge gaps emerged during the engagement undertaken for this report. Addressing these gaps will strengthen Indigenous science leadership and capacity for First Nations, Inuit, and Métis Peoples. In each area, the knowledge gap reflects our understanding of the direct impact of climate change, as well as the impacts of Canadian policies, programs, and regulations responding to climate change:

Food systems and security – Understanding food security in remote and rural regions through hunting, cultivating, harvesting, and access to resources, and, in urban contexts, the risks to supply chains, access, and storage of food.

Energy security – The implications of transitioning to net-zero and renewable energy solutions for employment and environmental impacts; energy security and impacts on food security, health, and shelter; opportunities for community-level energy solutions and infrastructure; and strategies for transitioning energy systems.

Infrastructure – Understanding how the lack or substandard condition of infrastructure, such as road access and connectivity (multiple routes and connections serving the origins and destinations), in remote and rural Indigenous communities limits the ability to respond to climate change and implement measures to reduce greenhouse gas emissions.

Resilient and sustainable infrastructure and critical services – Understanding community-level risks and opportunities to create net-zero and resilient communities.

Health and well-being – Understanding climate change impacts on access to medical care (for both physical and mental health); resilience of health services systems; risks of vector-borne disease and invasive species; access to freshwater; food security and safety; physical dangers; as well as search and rescue implications of a changing climate.

Climate extremes and extreme weather events – Understanding how changing climate affects livelihoods and well-being through research on extreme weather events, particularly wildfires and flooding, that is oriented to the community and aligned with the culture, to reduce disaster risk, improve response, and plan for evacuations.

Ecosystem resilience – Understanding healthy ecosystems,[11] carbon storage and conservation, and protection of biodiversity as pathways to climate resilience, and considering land, water, snow, and ice as critical natural infrastructure for Indigenous Peoples.

[11] Graeme Reed, Nicolas D. Brunet, Deborah McGregor, Curtis Scurr, Tonio Sadik, Jamie Lavigne & Sheri Longboat (2022) Toward Indigenous visions of nature-based solutions: an exploration into Canadian federal climate policy, *Climate Policy*, 22:4, 514-533, DOI: 10.1080/14693062.2022.2047585

3.5. Looking Forward

To advance climate change science and knowledge in a way that incorporates Indigenous Peoples and serves their interests, there is a need to create or expand research centres and fund programs sufficiently over the long term so that they are accessible, flexible, equitable, and integrative. Centres and programs must also be wholistic, bringing together related areas such as energy, infrastructure, food, water, and health. Regional or local research authorities and centres, and creation and access to data must respect data sovereignty and Indigenous knowledge while building Indigenous science capacity. This support should allow for the reciprocal recognition of Indigenous science and knowledge systems, creating informed rather than prescriptive spaces for the exchange of knowledge between Indigenous and non-Indigenous scientists.

A strengthened Canadian climate change science system should enhance our understanding of people and natural and managed ecosystems. It should guide our relationship with the land, oceans, and waterways to build ecosystem resilience. It should inform efforts to protect biodiversity and people. Self-determination and place-based approaches should be highlighted and respected in identifying priorities for research. Specific co-development policies, such as the 2022 *Inuit-Crown Co-development Principles* and the *Inuit Nunangat Policy* endorsed by the Inuit Crown Partnership Committee, guide this work. Leadership in First Nations, Inuit, and Métis science and knowledge systems is key to informing the novel and transformative change needed for a resilient, net-zero Canada.

Chapter 4. Theme Priorities

Summary

This chapter identifies science priorities according to five themes that contribute to successful mitigation and adaptation action. The priorities reflect the scale of climate change and the urgency of action required. Taking action in these areas will inform the development of mitigation and adaptation measures that are coordinated and complementary.

Healthy and Resilient Canadians

To address the knowledge gaps on climate change and health, collaboration is required across all levels of government and all sectors important to health. Governments and health sectors need to look at how Canadians' physical and mental health is affected by rising temperatures and catastrophic extreme events. They also need to address indirect effects, particularly on food security. Health systems are critical in protecting Canadians from climate change, and, like built infrastructure and critical services, they are vulnerable to extreme events. There are also opportunities to reduce emissions within the health sector on the pathway to net-zero.

The research priorities focus on:

- understanding climate change impacts on health and health systems to find feasible ways to adapt;
- conducting research to create low-carbon, sustainable health systems; and
- understanding policies, programs, measures, and technologies to develop sustainable health systems.

The knowledge synthesis and mobilization priorities emphasize:

- assessing the latest scientific information on climate change and health;
- sharing knowledge about health adaptation within the health services sector; and
- changing behaviour by communicating the health risks of climate change and the adaptation options.

Resilient, Net-Zero Communities and Built Environment

Most of Canada's buildings and infrastructure (transportation, food and water supply, energy, shelter, safety, health care, telecommunications) were not designed or built with a changing climate in mind. During and after extreme weather events, Canadians may lose transportation links, water supply, and other vital services.

Research is needed to:

- improve climate change data products, predictions, and projections to support decision making, infrastructure investments, and reduced risks from extreme events;
- inform mapping of multiple hazards, reflecting interdependencies and potential cascading infrastructure risks and failures;
- expand the use of performance-based design for construction and operations;
- develop an equity-based lens to better inform climate action;
- inform a transition to low-carbon, resilient buildings, transport, and infrastructure; and
- understand how to use nature-based solutions in the built environment.

The knowledge synthesis and mobilization priorities include:

- understanding governance to guide effective coordination and implementation of adaptation and mitigation for infrastructure;
- translating research results for practitioners;
- fostering effective climate action through an understanding of behavioural science and socio-economic context; and
- advancing methods, tools, and technology to benchmark community resilience and improve it.

Resilient Aquatic and Terrestrial Ecosystems

Natural ecosystems are facing multiple stresses—including climate change—that combine to influence their resilience and integrity. These combined stresses can jeopardize many ecosystems' ability to sustain themselves and to provide a diversity of services, values, and benefits, including those for nature, health, the economy, and society. Understanding the spectrum of different ecosystems' responses to climate change will inform actions to sustain and restore these ecosystems, for biodiversity and ecosystem services.

Research priorities include:

- understanding how climate change and extreme weather events affect ecosystems and biodiversity;
- examining the effectiveness and permanence of nature-based solutions; and
- identifying adaptation solutions that promote resilient ecosystems.

The knowledge mobilization priority involves:

- producing regular reports on status and trends in biodiversity and ecosystems to improve adaptive management and evidence-based decision making.

Sustainable Natural Resources

Climate change continues to impact the forestry, agriculture, fisheries, mineral, and energy sectors. As a result, there is a growing emphasis on developing capacity for responses that integrate both emissions mitigation and adaptation. Each sector experiences different impacts. However, research that informs cross-sectoral solutions and system-level transitions to net-zero and resilience is critical. This research will enable natural resource sectors to explore opportunities and develop decision-support tools in the circular bioeconomy as well as "climate-smart" technologies and practices.

The research priorities are to:

- understand emerging risks and vulnerabilities to Canada's natural resource sectors;
- accelerate the contribution of natural resource sectors to climate action;
- develop and track indicators of resilience to support natural resource sectors; and
- explore mitigation and adaptation actions across sectors through collaborative and transdisciplinary approaches, including greater inclusion of social sciences.

Knowledge mobilization activities include:

- developing relevant tools to inform evidence-based policy and decision making; and
- incorporating behavioural and social science to inform more effective decision making and communication.

Informing Progress Towards Net-Zero Greenhouse Gas Emissions

To measure progress toward net-zero GHG emissions, emissions and removals from the atmosphere must be estimated and reported using multiple methods. The research priorities allow us to use new data on source activity as well as emerging surface and satellite-based observations to improve the accuracy and timeliness of reported emissions.

Research is needed to:

- develop integrated monitoring systems for atmospheric GHGs and reconcile different methods to estimate anthropogenic GHG emissions;
- improve quantification of ecosystem carbon stocks and natural GHG fluxes;
- better understand and monitor how land use change and management practices impact carbon fluxes and progress towards net-zero; and
- examine the trade-offs and societal impacts of policies involving GHG emissions reductions and carbon-dioxide removal technologies.

The knowledge synthesis and mobilization priorities emphasize:

- reconciling publicly available emissions data, information, and knowledge; and
- comparing and improving ecosystem models to understand natural carbon fluxes and how humans are driving changes in terrestrial carbon storage.

Climate Science 2050: Advancing Science and Knowledge on Climate Change (CS2050), published in December 2020, identified four science and knowledge outcomes—and a fifth area of foundational research—that contribute to successful mitigation and adaptation action. This chapter provides science priorities under these five themes. The priorities must unfold in parallel across themes, to inform climate action underway across all sectors and communities, and to reflect the scale of climate change and urgency of action required.

The priorities for **research** and **knowledge synthesis and mobilization** are of equal importance. Ongoing research adds knowledge and identifies opportunities for action, while knowledge synthesis and mobilization help translate the research investments into action.

As an example, the priorities in this chapter advocate for more frequent, more accurate, and higher-resolution information concerning weather, climate, and greenhouse gas fluxes. Such information informs climate change adaptation, risk assessment, communication, and climate literacy, and is needed to evaluate the progress of climate policy and action.

For all priorities involving data, open-access datasets that uphold the FAIR principles (findable, accessible, interoperable, and reusable) need to be developed to improve our capacity to identify, predict, monitor, and evaluate climate change and its impacts. Such datasets are needed to understand drivers, develop indicators, and evaluate the effectiveness of management actions under a range of future scenarios.

All climate change research should support and create space for First Nations, Inuit, and Métis Peoples and communities. Researchers should learn from, and partner with, Indigenous Peoples and communities. As discussed in Chapter 3, local knowledge and the science and knowledge systems of the First Nations, Inuit, and Métis Peoples should be integral to research. Research should further take into account the impacts of climate change on First Nations, Inuit, and Métis Peoples and their distinct and diverse traditional practices. Some Indigenous Peoples and communities may be more seriously impacted by climate change and experience greater barriers to adaptation. Regardless of the specific impact of climate change, Indigenous Peoples and communities should be involved in monitoring indicators and in defining and evaluating resilience for their communities, in ways relevant to their culture.

4.1. Healthy and Resilient Canadians

Climate change risks to human health continue to increase. These risks include impacts on the physical and mental health of Canadians, on Canada's health systems, and on those disproportionately affected and vulnerable. Human health cannot be protected from climate change impacts without robust knowledge of risks to Canadians and their health systems, economic costs of health impacts, and effective adaptation measures. This includes new approaches to communicating climate change that support behavioural change. The Public Health Agency of Canada Chief Public Health Officer's Report in 2022 focused on mobilizing public health action on climate change through current public health functions (e.g., emergency preparedness). Indigenous-led research is highlighting the interplay between the health impacts of climate hazards and underlying drivers of vulnerability (e.g., racism, current and historical colonization, social determinants of health). This research also highlights culturally meaningful approaches to protect health (see Box 4.1 Climate Change Poses Serious Risks Across the Métis Nation). However, knowledge gaps continue to hinder health-adaptation efforts. Knowledge gaps also limit efforts to design and implement net-zero transitions in ways that support livelihoods, benefits health, and develops environmentally sustainable health systems.

Box 4.1. Climate Change Poses Serious Risks Across the Métis Nation

Métis Nation citizens living in western Canada are uniquely sensitive to the impacts of climate change because they depend on the land for their identity, culture, livelihoods, and resource economies. Over many generations, Métis People have found innovative ways to live in their environment despite diminished access to land and waters. This resilience to change, built over generations, and Métis environmental knowledge can support adaptation solutions for Indigenous and non-Indigenous populations. In 2020, the Métis National Council released its Métis Nation Climate Change & Health Vulnerability Assessment Report, to explore the risks and current gaps for the Métis Nation and identify supports needed to develop a path forward to climate change resilience.

Addressing the science priorities (below) requires a commitment to multi-sectoral, transdisciplinary, and "systems thinking" approaches. Such approaches include "Health in All Policies" and "One Health." "Health in All Policies" involves collaboration, horizontally and vertically, among all levels of government and across sectors important to health (e.g., energy, transportation, agriculture, forestry, fisheries, water, urban planning, conservation). In this approach, those involved recognize and exercise their role in influencing key determinants of health and drivers of health outcomes. The "One Health" approach recognizes that the health of humans, domestic and wild animals, plants, and the wider environment (including ecosystems) are interdependent (see Chapter 5.5 One Health and Climate Change Nexus Science).

The following research priorities support efforts to protect the health and resilience of Canadians and prepare health systems for a changing climate.

R1 (HRC). Understand the impacts of climate change on health and health systems, to advance effective, equitable, and feasible measures for health adaptation. Research is needed to understand the current impacts and projected health risks to Canadians related to climate change. These include risks affecting air quality, food security and safety (see Box 4.2 Food Security in an Uncertain Future Climate), as well as infectious or chronic diseases, mental health, water quality and security, and natural hazards (see Box 4.3. Reducing Risks to the Health of Canadians From Severe Weather Events). Many of these impacts threaten livelihoods and hunting and fishery traditions, as well as potentially displacing First Nations, Inuit, and Métis People. Research is also needed on how underlying social and environmental factors, such as low income or socio-economic status, inadequate housing, racism, and colonization may increase these risks.

Box 4.2. Food Security in an Uncertain Future Climate

Food security is when all people, at all times, have physical and economic access to sufficient safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life. Climate change is already affecting Canadian food systems and is contributing to food insecurity. For example, Canada's Food Price Report 2022 found that climate change has contributed to rising food prices. Increasing globalization has resulted in a global food system in which Canada participates, importing and exporting raw and prepared foods. Thus, factors disrupting global food systems, such as acute and chronic climate change impacts and political instability, can also affect food security and disrupt food systems in Canada. Chapter 8 of the report Health of Canadians in a Changing Climate (published in 2022) reviews evidence on the impacts of climate change on health through effects on food safety and security, and existing knowledge gaps.

New and innovative methods, tools, and indicators are needed to understand, measure and model health risks, climate stressors, and vulnerabilities (e.g., monitoring indoor heat, using artificial intelligence applications and molecular tools for tracking climate-sensitive pathogens and antimicrobial resistance in food, soil, water, animals, and plants). This includes monitoring the state of resilience of health systems. The costs of the health impacts and risks of climate change on people living in Canada, on health systems, and on the economy must also be analyzed.

Effective, equitable, and feasible measures for climate change adaptation and mitigation actions related to health must be developed to increase the climate resilience of Canadians and their health systems. Research is needed to better understand the co-benefits and possible risks of these measures on human health, as well as to analyze their economic costs and effectiveness. This research should examine ways to avoid "maladaptation," an adaptation action that does not succeed in reducing risks but increases them instead. This requires improved understanding of the impacts of adaptation and mitigation measures, taken both within and outside of the health sector, on human health. This will inform how to minimize risks and health inequities at regional levels and over varying time scales. Research is also needed to better understand the governance mechanisms, institutional and regulatory capacity, leadership approaches, and networking and collaboration opportunities to reduce health risks from climate change.

Box 4.3. Reducing Risks to the Health of Canadians From Extreme Weather Events

Canada is experiencing more extreme weather events and hazards (e.g., heatwaves, floods, and wildfires), and these can have catastrophic impacts on human health. For example, the unprecedented heat event that affected British Columbia in June 2021 led to 619 deaths and to disastrous wildfires in a number of communities. Climate change is increasing the risk of compounding or cascading events that can overwhelm health and social services' capacity to respond. This can affect the availability or quality of care. This can be particularly acute when such events occur at the same time as other societal shocks and stressors.

Chapter 3 of the report Health of Canadians in a Changing Climate (published in 2022) reviews evidence of the physical and mental health impacts of natural hazards related to climate change and key knowledge gaps.

Assessing the health system's capacity to adapt to climate-related hazards is critical to avoid disruption of services and severe impacts on patients and staff due to climate hazards, such as extreme events. More research is needed on climate-related impacts and risks, vulnerabilities, and costs to health systems and facilities from immediate hazards (e.g., flood) or longer-term events (e.g., droughts, infectious diseases, storm disruptions to transportation and critical services). This includes impacts on health policies, programs, services, infrastructure, human resources, and supply chains (e.g., drugs, medical equipment), especially for rural, remote, and Northern health systems and those serving First Nations, Inuit, and Métis Peoples. These health systems are often more vulnerable, and gaps in health outcomes between First Nations, Inuit, and Métis Peoples, on the one hand, and non-Indigenous Canadians, on the other, remain.

R2 (HRC). Conduct research to support the transition to a sustainable, low-carbon health system. Health systems and services play a critical role in protecting Canadians from the current impacts and future risks of climate change. They also present opportunities to reduce greenhouse gases within this sector as they account for approximately 5% of Canada's annual emissions. Climate-resilient and sustainable low-carbon health systems offer a triple dividend of better health and safety for individuals, reduced costs of operations and services, and substantial GHG emissions reductions. The Government of Canada expressed its support for the United Nations Framework Convention on Climate Change COP26 Health Programme, committing to developing climate-resilient and sustainable low-carbon health systems.

Research is needed to support the development of low-carbon health systems. Information and methods are needed to more accurately measure and monitor GHG emissions from health sector activities. These include direct emissions from health care facility operations (e.g., on-site boilers and medical gases) and indirect emissions through purchased electricity and the supply chain.

R3 (HRC). Improve understanding of policies, programs, measures, and new technologies available to health authorities and their partners to develop low-carbon and sustainable health systems. Methods are also needed to measure other non-climatic factors impacting health system emissions, such as population changes, health care demand and utilization, and new technology development. Research can contribute to developing best practices and cost-effective new technologies to manage the health sector's carbon footprint through, for example, retrofits of existing health care facilities, reusable medical supplies, remote medical care technologies, and lower GHG-emitting transportation in supply chains. Additionally, evaluation of current purchasing practices in the Canadian health system and innovative finance-based mechanisms, such as green revolving funds and green bonds, is needed. Last, how measures that support climate resilience, adaptation, and the reduction of GHGs can reduce the costs of climate actions for the health services sector needs to be understood.

Knowledge synthesis and mobilization priorities include:

KM1 (HRC). Conduct regular national, regional, and local-scale assessments of climate change and health. Assessments should summarize the latest information on impacts on human health, health systems, and health equity; variations in vulnerabilities and risks to health; and options for adaptation and for sustainable low-carbon health systems.

KM2 (HRC). Develop innovative strategies and approaches for knowledge exchange among health professionals, practitioners, and administrators. These strategies and approaches should include education and training materials and tools tailored to the specific partners involved, to meet the health-adaptation needs of diverse audiences.

KM3 (HRC). Effect behavioural change among decision makers, stakeholders, and the public by improving strategies for effective communication of the health risks of climate change, adaptation options, and the health benefits of proactive action. This priority includes applying insights from behavioural science, relatable narratives, and participatory approaches, including diverse voices. This includes learning from, and partnering with, First Nations, Inuit, and Métis Peoples and other communities and individuals who may be more seriously impacted by climate change and experience greater barriers to adaptation.

4.2. Resilient, Net-Zero Communities and Built Environment

Most Canadian communities were not designed and constructed with a changing climate in mind. As a result, the infrastructure systems we rely on to meet basic needs—such as food and water supply, energy, shelter, safety, and access to health care—are increasingly vulnerable to climate extremes and extreme weather events. As hazards—such as heavy precipitation, heatwaves, wildfires, and flooding—become more extreme, these systems face increased risks of compound hazards and cascading failures. The infrastructure sector is also a contributor to climate change, with transport and buildings representing the sectors with the second- and third-highest emissions in Canada. Long-term assets, buildings, and infrastructure constructed or retrofitted today are anticipated to have lifespans of several decades. Careful design and planning of our built environment can avoid locked-in emissions and contribute to carbon uptake (through use of innovative carbon-capturing products, bio-based products, and nature-based infrastructure solutions, as examples).

Box 4.4. The Intersection of Adaptation and Mitigation in the Built Environment

Actions to adapt to climate change and reduce GHG emissions are inextricably linked and should be considered together to maximize co-benefits. Examples of these linkages include:

- **Lifecycle environmental performance:** Increased climate resilience can reduce lifecycle carbon emissions by extending service life and lowering maintenance needs.
- **Natural infrastructure solutions:** Natural carbon sinks can complement or replace conventional engineered high-carbon infrastructure to mitigate impacts of flooding, reduce urban heat islands, and lower energy loads to cool buildings.
- **Resilient low-carbon, zero-emission solutions:** In building and transportation system retrofits and maintenance, integrating resilience to climate change and extreme weather events can increase overall community resilience, reduce emissions, and achieve public health outcomes.

Adapting to climate change requires meaningful and profound rethinking of where and how our communities are planned, built, and maintained, from their overall design to individual homes. There is a need to understand where adaptation and mitigation actions will have the biggest impact, and where resilience and mitigation goals reinforce each other or where there are diverging goals (see Box 4.4. The Intersection of Adaptation and Mitigation in the Built Environment). Vulnerabilities and risks are not distributed uniformly across regions or across social, cultural, and economic groups. This needs to be taken into account in determining priorities and solutions.

The research priorities for the built environment span the information needs of all orders of government and economic sectors that must integrate adaptation and low- or net-zero-GHG–emission considerations into decision making for public safety, critical services and infrastructure, livelihoods, and the livability of our communities.

R1 (RNCBE). Generate climate data, predictions, and projections to inform risk assessment, adaptation, and actions to reduce GHG emissions for the built environment. Climate observations, predictions, and projections at relevant spatial and temporal scales are needed, as well as a better understanding of the impacts of climate change on the built environment. This information is critical to shifting to low- and net-zero carbon, resilient buildings, transport, energy, and infrastructure systems (e.g., housing, transit, energy, drinking water, telecommunications). The data should be suitable for estimating emissions and characterizing hazards—such as extreme precipitation, heatwaves and cold snaps, wildfires and smoke, dust storms, ice accretion, extreme winds, high lake and ocean waves, storm surges, flooding, and overland floods—as well as slower-onset disruptions—such as sea-level rise; severe shifts in drought cycles; permafrost thaw; and thinning river, lake, and sea ice.

R2 (RNCBE). Create maps of multiple hazards to identify and prioritize high-risk areas, manage interdependencies, and address potential cascading risks to infrastructure systems. Advances are needed to enable multi-layer geospatial mapping that integrates multiple and compound climate hazards and provides information for decision makers, such as:

- infrastructure system details (location, jurisdiction, type, age, condition);
- critical systems (health care, water treatment plants, emergency response, power, communications, bridges, escape routes, security services, community refuges, and district heating plants);
- social infrastructure (e.g., government buildings, schools, universities, churches, heritage buildings, and libraries);
- natural systems (air quality, parks, water, soils, minerals, wildfire fuel load, forest insects, and pathogens);
- population vulnerabilities (e.g., seniors, children, people with chronic illnesses, socially disadvantaged groups); and
- hazards (e.g., floods, droughts, wildfires, heatwaves).

This research must address current challenges to integrating map layers, which would allow novel ways of combining data and understanding their relationships. These challenges include:

- unavailability or lack of homogeneity in the data structures, limiting concurrent use at common space and time scales;
- uncertainty in climate projections, including those due to different global emission scenarios; and
- integration of real-time or near-real-time data.

This work must also include integrated mapping tools to identify, assess, and rank risks, system interdependencies, and potential cascading failures (e.g., floods impacting energy distribution, food supply, and telecommunications).

R3 (RNCBE). Expand the use of performance-based design to find innovative construction and operating solutions. Research is needed to help move from “prescriptive-based” to “performance-based” design, a goal-oriented design approach that addresses criteria for the performance of the building or infrastructure, such as energy use, operating cost, and occupant comfort, among others. Performance-based national codes and standards will foster innovation and flexibility in how regulations are met. They will ultimately make it easier to attain low-carbon and resilient-performance targets. Research should identify ways to evaluate the performance of materials and systems, and set acceptable performance levels (e.g., for whole-asset life-cycle carbon, material durability, building comfort, wildfire resilience, accessibility). Clear performance-based design requirements level the playing field for a variety of technologies, including bio-based products and nature-based solutions.

R4 (RNCBE). Develop and apply an equity-based lens to better inform climate change adaptation and GHG emission mitigation actions. Research is needed to develop socio-economic and geographic (or place-based) datasets and metrics to characterize the various dimensions of vulnerability. This information can be used to inform the design and management of net-zero infrastructure and built environments in vulnerable communities. Knowledge gaps include understanding the cumulative effects of climate change; how they interact with existing vulnerabilities (e.g., poverty, lack of drinking water, transit, housing, or energy); and how they may amplify systemic or societal inequities and affect lived experiences.

R5 (RNCBE). Inform the transition to low-carbon buildings, transport, and infrastructure. Research is needed to develop methods, technologies, best practices, and guidance to support transition to low-carbon built environments and a zero-waste circular economy (see Box 4.7. Cross-Sectoral and Transdisciplinary Approaches for the Circular Bioeconomy). This research needs to help us move from conventional prescriptive planning and design approaches toward life-cycle–based approaches, which identify opportunities and risks throughout the life cycle, from raw materials to disposal. Further research is needed to advance life-cycle cost and environmental assessment, low-carbon supply chain systems, and low-cost and rapid construction methods. Technical solutions for construction materials and systems will need to be developed, de-risked, and demonstrated.

R6 (RNCBE). Improve understanding of nature-based solutions for use in the built environment. Regional studies, pilot projects, modelling, and sustained monitoring of the performance of nature-based solutions are needed. This research will determine where natural solutions, alone or in combination with conventional human-made solutions, can help manage the risks associated with climate change, extreme events, and associated natural hazards. These risks include urban, riverine, and coastal flooding; urban heat islands; erosion; and permafrost thaw. Research can show how natural solutions can contribute to carbon uptake (e.g., by retaining soil carbon in both natural and managed landscapes). Research is also needed to identify the conditions of regions or sites that affect the viability of nature-based solutions. Such research can help assess the value (including economic value) of ecosystems and nature-based solutions in the built environment, including contributions to carbon sequestration, risk reduction (avoided losses), ecosystem services, and other co-benefits (aesthetic, cultural, health and well-being, recreational value). This priority is closely aligned with science priorities for ecosystems (see Chapter 4.3. Resilient Aquatic and Terrestrial Ecosystems).

The priorities for knowledge synthesis and mobilization include the following:

KM1 (RNCBE). Develop guidance for effective governance, coordination, and implementation of adaptation and mitigation measures at various levels of government and at various phases of infrastructure life cycles. Governance both enables and challenges effective action to mitigate GHG emissions and improve the resilience of communities and their associated built environments. Effective coordination and implementation involve understanding the complex web of relationships, jurisdictions, and key players to inform effective governance of adaptation and mitigation. Research and guidance for effective climate action in our communities and built environments are needed at various phases of infrastructure life cycles, such as pre-planning, planning, and project monitoring, evaluation, and learning.

KM2 (RNCBE). Translate research results into guidance, protocols, and tools for practitioners to help them develop low-carbon, resilient built environments. To bring scientific capacity and awareness to the community level, results must be translated into accessible, locally relevant, and easy-to-use guides, policies, and information to inform decision making. Tools, standards, guidance, data, and other knowledge synthesis products should be targeted and strongly aligned with the intended users. The tools developed, and the information they provide, should be used to inform relevant decision making. Specifically, they should include risk analysis to prioritize built environments most at risk, which helps maximize the value of climate action.

KM3 (RNCBE). Incorporate behavioural science and understanding of the socio-economic contexts to foster climate action in the building, transport, and infrastructure sectors. To facilitate the uptake of technology and policies, effective evidence-based strategies that consider behavioural science and socio-economic factors should be used. An analysis of regulatory, cultural, social, and economic methods for change (including codes, standards, and assessment tools) is needed to identify the most effective ways to realize performance targets. However, a range of methods will be needed to meet a variety of desired benefits, depending on context and goals.

KM4 (RNCBE). Advance methods, tools, and technology to benchmark and increase community resilience, including investments in climate action. Substantial advances are needed in methods, tools, and technology to benchmark and increase community resilience to climate and extreme weather events. Innovative methods are needed to rapidly and reliably assess the capacity of existing buildings, infrastructure, energy, and transport systems to withstand climate risks, and to identify requirements and timelines for maintenance and retrofits. Decision making should inform proactive strategic planning and investments, which may include relocation and decommissioning. Strategic planning should avoid continued investment in high-risk areas where climate resilience is no longer possible.

4.3. Resilient Aquatic and Terrestrial Ecosystems

Healthy, biologically diverse ecosystems are more resilient to the adverse effects of climate change and play a vital role in Canada's ability to mitigate GHG emissions and adapt to climate change. Resilient ecosystems can cool cities, sequester carbon, regulate disease, supply food and materials for people and communities, buffer against floods and droughts, and contribute to the economy as well as the health and well-being of Canadians (see Box 4.5. The UN Convention on Biological Diversity).

Climate-resilient ecosystems are not static. They evolve and adapt with a changing climate and continue to provide a diversity of services and multiple values to humans and nature. Some of the ecosystem values, such as intrinsic and relational values (e.g., cultural, spiritual, societal), are unrelated to climate, but climate change may put these values at risk. Considering these multiple values of nature can help to improve the uptake and relevance of ecosystem science for a broad suite of Canadian priorities, including addressing climate change.

Box 4.5. The UN Convention on Biological Diversity

The UN Convention on Biological Diversity calls for scientific co-operation to minimize threats to biodiversity. The December 2022 COP15 meeting in Montreal culminated with the adoption of the Kunming-Montreal Global Biodiversity Framework, which identifies four goals and 23 targets to be achieved by 2030—including urgent actions to conserve biodiversity in a changing climate and meet people's needs through sustainable use and benefit-sharing. Specifically, Targets 8 and 11 underscore the importance of nature-based solutions and ecosystem-based approaches in achieving these actions. These reflect other international agreements in which parties, including Canada, emphasize the role of nature-based solutions in addressing climate change mitigation and adaptation. Such agreements include the UNFCCC Sharm el-Sheikh Implementation Plan 2022 (COP27) and the Ramsar Convention on Wetlands (COP14).

Interdisciplinary science (in which two or more disciplines come together to define the research problem and to design and execute the research project) is key to understanding how non-climate stressors interact with the impacts of climate change. Non-climate stressors include such issues as introduced alien species; pollution; contaminants; habitat loss; habitat degradation; shifts in land, freshwater, and ocean use; and natural variability. These may interact with climate impacts such as ocean acidification, hypoxia, drought, desertification, and changes to species' distribution and productivity. The UN Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (highlights the importance of using interdisciplinary scientific information, Indigenous knowledge, local knowledge, and practical expertise in identifying solutions for ecosystem management and adaptation, such as preservation, protection, creation, and restoration. Research is needed to understand the complex and inter-related ecological, social, and economic challenges of climate change in order to develop and apply a solutions-oriented lens to increase the potential for co-benefits for biodiversity and ecosystems.

Understanding climate change impacts on ecosystems requires linking biodiversity and climate data with information at temporal and spatial scales that are relevant to decision making. Canada can use this knowledge to inform action that will sustain and restore ecosystems and ecosystem services, further protect biodiversity, and benefit human health, the environment, the economy, and society as a whole.

R1 (RATE). Better understand climate change impacts on ecosystems and biodiversity. This priority involves characterizing ecosystem resilience under changing climate conditions to expand our understanding of habitat diversity, natural variability, connectivity, and biodiversity, as well as of climate change impacts on ecosystem function and services. This includes:

- Developing coordinated, collaborative, and cross-sectoral approaches to monitor, predict, assess, and characterize ecosystem risks and vulnerabilities. It is critical to understand climate impacts and drivers, climate extremes, and extreme weather events that affect the integrity of ecosystems. This research is needed to address uncertainty, especially in regions that are poorly monitored and understood, such as the Arctic and coastal areas.
- Integrating data to characterize key drivers of ecosystem and biodiversity change, and to assess status and trends, as well as attributes of climate-resilient ecosystems and ecosystem services. This information can then be used to support and inform a variety of climate actions, including identifying nature-based and hybrid (combined engineered and nature-based) climate solutions (see Box 4.6. Nature-Based Solutions); carrying out adaptive management of ecosystems; recognizing and characterizing climate refugia; and developing indicators of ecosystem health, connectivity, function, and biodiversity.
- Understanding and assessing cumulative impacts of long-term environmental changes, short-term extreme events, and anthropogenic stressors (e.g., resource and infrastructure development). This research provides valuable information to determine how vulnerable an ecosystem is to environmental change and to inform evidence-based decisions.

Box 4.6. Nature-Based Solutions

Nature-based solutions protect, sustainably manage, and restore natural or modified ecosystems to address societal challenges effectively and adaptively, while providing benefits for human well-being and biodiversity (UN IPCC Working Group III). In a broad context, resilient ecosystems play a two-fold role as nature-based solutions for both climate mitigation and adaptation. Resilient ecosystems sequester, store, and release atmospheric carbon through natural processes. They can contribute to long-term climate change **mitigation** through human interventions in the natural carbon cycle (e.g., above- and below-ground biomass, such as that found in soils). Resilient ecosystems and the multiple services and values they deliver also enable climate **adaptation** for humans and nature, by buffering and rebounding from climate change impacts (e.g., slow-onset hazards, catastrophic events). This adaptive capacity of resilient ecosystems protects carbon stocks and sequestration capacity over time. Taken together, the mitigation and adaptation benefits of resilient ecosystems help address the dual biodiversity and climate crises.

R2 (RATE). Advance multidisciplinary science and knowledge to inform climate adaptation solutions that promote resilient ecosystems in a changing climate. These approaches should respect multiple knowledge systems, support net-zero and adaptation goals, maximize co-benefits to humans and nature, and evolve as new knowledge becomes available. This includes:

- Development of innovative approaches to multi-disciplinary and interactive decision support and visualization tools, including leveraging and expanding existing platforms (e.g. GEO.ca, ClimateAtlas.ca) and multiple ways of knowing, to inform preservation, protection, creation, and restoration of ecosystems, habitats, and terrestrial and aquatic protected areas.
- Creating multidisciplinary research and monitoring frameworks to identify, characterize, and measure the multiple values of nature and how they interact. Such frameworks can be used to put a value on ecosystems and ecosystem services that benefit nature, human health, the economy, and society.[12] These frameworks are needed to develop baseline assessments for different ecosystems, social-ecological systems, and regions.
- Understanding the effectiveness, efficacy, and permanence of solutions, including nature-based solutions. Assessments of solutions should take into account benefits, trade-offs, opportunities, scalability, and effectiveness across diverse ecosystems and regions. They should also consider changes to ecosystems and biodiversity under future climate conditions. Carbon-flux models and data mobilization need to be improved to better evaluate the effectiveness of nature-based solutions. Overall, greater understanding is needed to identify solutions, particularly nature-based solutions, that are informed by multiple knowledge systems and transdisciplinary research (i.e., unifying intellectual frameworks, integrating approaches beyond disciplinary perspectives).

Knowledge synthesis and mobilization priorities include:

KM1 (RATE). Synthesize and mobilize knowledge of ecosystem resilience to support and improve adaptive management and evidence-based decision making in a changing climate. Key synthesis products include regular and systematic reports on national biodiversity and ecosystem status, trends, projections, and services. Reports may synthesize information at an ecosystem, watershed, or biome level, including impacts of multiple stressors on ecosystem functioning for aquatic and terrestrial systems. Needed synthesis products include:

- assessments of the effectiveness of regional and national conservation efforts in achieving conservation and climate goals (e.g., Canada's Biodiversity Target 1 Challenge to conserve 25% of lands and ocean by 2025; targeted conservation through the *Species at Risk Act*), including protected areas, other effective area-based conservation measures, and Indigenous Protected and Conserved Areas; and
- assessments to synthesize knowledge and lessons learned from programs across sectors and jurisdictions that promote nature-based solutions.

Current efforts to synthesize and mobilize science outcomes for national, regional, and local decision and policy makers, as well as systems to collate and disseminate data, must be expanded. These include developing innovative approaches to multidisciplinary (involving researchers from different disciplines, each contributing their disciplinary perspective) and interactive decision-support and visualization tools. These tools should build on and expand existing platforms (e.g., GEO.ca, an online platform for open Canadian geospatial information, managed by Natural Resources Canada) and multiple knowledge systems. They will be designed to inform preservation, protection, creation, and restoration of terrestrial and aquatic ecosystems, habitats, and protected areas.

[12] Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (2022). Methodological Assessment Report on the Diverse Values and Valuation of Nature of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. DOI: https://doi.org/10.5281/zenodo.6522522

Box 4.7. Cross-Sectoral and Transdisciplinary Approaches for the Circular Economy

Building a robust circular economy requires more cross-sectoral, interdisciplinary collaborations. The circular economy transitions society from a take-make-waste economic system to the use, reuse, recycling, and reintegration of materials back into the economy and nature. It would see many products made from fossil fuels, such as plastic, replaced by products made from biomass, such as wood fibre, and fossil-fuel energy sources replaced with renewable sources such as wind, solar, tidal, and bioenergy. Developing the circular economy is a meaningful way to reduce waste, mitigate GHG emissions, and protect biodiversity and ecosystem services.

Science and knowledge synthesis and mobilization are required to enable transformative solutions and break down barriers between sectors. Transdisciplinary research is needed to expand opportunities in the circular economy to achieve sustainability. The circular economy cannot be achieved without a concerted, whole-of-society effort, and the right information, insights, connections, and relationships.

Transdisciplinary research frameworks should be used to develop, test, monitor, evaluate, and implement new practices, processes, and technologies to build the circular economy that achieves a net-zero, resilient Canada.

4.4. Sustainable Natural Resources

The science priorities for sustainable natural resources emphasize multi-sectoral, interdisciplinary, and transdisciplinary perspectives, to build capacity for integrated mitigation and adaptation action. This action across natural resource sectors—including fisheries, aquaculture, forestry, agriculture, mining, and energy—informs long-term sustainable solutions and takes into account the connections among Canada's natural resources. The impacts and risks of climate change are experienced differently in each sector but have implications that cross sector operations. Thus, cross-sectoral solutions need to be developed to achieve a resilient, net-zero, and sustainable natural resource economy.

In developing knowledge for these solutions, strategies specific to each geographic region are needed. Taken together, the following priorities enable science-informed decision-support tools, "climate-smart" technologies and practices, and exploration of circular economy opportunities (see Box 4.7. Cross-Sectoral and Transdisciplinary Approaches for the Circular Economy).

The research priorities include:

R1 (SNR). Understand how natural resource sectors in Canada are affected by climate change.
Observations and predictions (of climate, biological, physical, chemical, ecosystem, socio-economic, and health factors) need to be accessible and available to inform risk and vulnerability assessments. These data are key to characterizing the cascading impacts of climate change on the biological and social-ecological systems that make up each sector. They help us understand these risks within Canada and internationally, and how risks and vulnerabilities may change in future climate scenarios, including the impacts of climate extremes and extreme weather events.

To enhance resilience within the natural resource sectors, we must increase knowledge and understanding of the following:

- the impacts and risks from climate extremes and extreme weather events;
- cascading climate change impacts and risks; and
- the cumulative effects of multiple climate and non-climate stressors.

The impact of extreme events and disturbances (including their timing, frequency, and intensity) on natural resource sectors needs further research.

R2 (SNR). Develop and track indicators of social-ecological resilience in natural resource sectors and communities and understand how these sectors contribute to climate action. This priority requires understanding processes and thresholds affecting resilience, in order to design appropriate indicators and to gather relevant data. Indicators should be developed and data collected for managed and unmanaged areas and for social-ecological systems.

Forest sector: Indicators should help inform and evaluate adaptive "climate-smart" management practices. Such practices support healthy and resilient forests, biodiversity, wildlife habitat, safe and resilient communities, forest genetics, future fibre supply, biofuel production, and forest sector infrastructure. Research is also needed on the impact of forest management on carbon stocks in managed forests; this includes measuring forest carbon and determining social-ecological resilience to climate change. This work should be inclusive, engaging with the forest industry, other resource sectors, communities, and other relevant rights holders, stakeholders, and decision makers.

Fisheries and aquaculture sector: Indicators should identify and track risks and vulnerabilities of species, ecosystems, industries, and communities to the impacts of climate change, including extreme events and slow-onset changes, to build resilience in the sector. There is also a need to better understand the impacts on the sector of loss of coastal habitats, changes in species distributions (including invasive species), changing ocean conditions, and resource development (e.g., marine renewable energy, deep-sea mining, offshore oil and gas development).

Agricultural sector: Research is required to improve indicators that will inform decisions and forecast changes in climate conditions (e.g., soil moisture, growing season length), biodiversity, and climate mitigation efforts (e.g., changes to tillage and fertilization practices) at various time and space scales. Research on the long-term impacts of management practices under changing climate conditions—and their connection to soil carbon, water quality/quantity, and biodiversity—is critical for long-term food security (see Box 4.2. Food Security in an Uncertain Future Climate) and emissions reduction in the sector.

Mining and energy sectors: Research is needed on indicators for operational resilience, to reduce climate risks as these sectors evolve. This research should include a better understanding of regulatory gaps, supply and distribution systems in a net-zero world, critical minerals, site access, waste management, managing legacy contaminants (e.g., re-release from sediments due to warming), water supply, and implications or trade-offs for ecosystem restoration, reclamation, conservation, and biodiversity. Research must inform the transition to net-zero, resilient energy systems across all operations and transportation systems, and future scenarios to expand renewable energy sources.

R3 (SNR). Use collaborative research and transdisciplinary approaches to explore mitigation and adaptation actions, trade-offs, and benefits across natural resource sectors. An integrated, systems-based understanding of natural resource sectors, and the natural systems they are a part of, will help to grow the circular bioeconomy and achieve net-zero goals. Transdisciplinary research is required to develop integrated practices and policies that build adaptive capacity across and within sectors, supporting waste reduction, economic diversification, and development of "climate-smart" solutions for infrastructure and equipment. Research is also needed for low-carbon technologies that realize multiple benefits in sustainable resource management, land-use and aquatic-use planning, and food production from national to local scales.

Knowledge synthesis and mobilization priorities include:

KM1 (SNR). Develop relevant tools to enable evidence-based climate actions for all levels of policy and decision making. Integrated, interactive visualization and decision-support tools that consider future climate scenarios need to be developed, used, and promoted. These tools should be spatially, temporally, and culturally relevant to enable policy and management decisions that support environmental, economic, social, and cultural objectives for Canada's resource sectors and resource-dependent communities, while minimizing trade-offs. The effectiveness of these innovative tools needs to be assessed to ensure that they are appropriate, accessible, and relevant to the communities, governments, practitioners, and decision makers that use them.

KM2 (SNR). Incorporate behavioural and social science in decision making and communication strategies specific to each sector. Research is needed to address gaps in knowledge implementation and to determine which factors enable and which pose barriers to climate action in the natural resource sectors. Social sciences, and specifically psychology and behavioural science, are needed to understand:

- challenges related to misinformation and disinformation; and
- how information and knowledge synthesis and mobilization products can be better targeted.

Behavioural science research should explore the impact and effectiveness of current policies and measures, such as incentives for climate-smart practices, and assess how they can more effectively support climate action. This research can also be used to support co-development and co-implementation of solutions with industry leaders in the natural resource sectors.

4.5. Informing Progress Towards Net-Zero Greenhouse Gas Emissions

Accurate and timely monitoring of emissions reductions and removals (see Box 5.4. Carbon Dioxide Removal) is essential to gauge progress toward net-zero GHG emissions. Emissions may be reduced or removed through changes to energy, manufacturing, agricultural, and transportation systems, urban infrastructure, and management of the land base and natural ecosystems. Monitoring and reporting allow us to evaluate the effectiveness of policies and inform decision makers and the public on the progress toward net-zero.

The National Inventory Report is Canada's official inventory of anthropogenic GHG sources and sinks, reporting mainly at annual time scales and provincial spatial scales, with a 16-month time lag. Canada has some of the most advanced emissions reporting methods in the world and continues to improve its reporting. However, reported emissions estimates derived from activity-based methods (i.e., bottom-up methods) can differ from those based on other methods, such as emissions estimates from atmospheric measurements (i.e., top-down methods). Both approaches have inherent uncertainties. New methods present opportunities to improve the quality and quantity of information used to estimate GHG sources and sinks. These include improved models, monitoring networks for specific sources or regions, new technologies, low-cost sensors, and satellite observations. The research priorities to improve GHG flux estimates are as follows:

R1 (IPNZ). Enhance GHG data reporting by making advances in measuring and modelling GHG emissions and reconciling complementary techniques for estimating emissions. Reporting can be made more accurate and transparent, at finer spatial and temporal scales, by integrating complementary estimation methods and data sources and by addressing remaining gaps in observations. Collecting and reporting activity data (e.g., fuel volumes) more frequently (e.g., subannually) can improve understanding of emissions. Systematic field measurements can provide information on these shorter time scales. Such information can help identify opportunities for mitigation, inform bottom-up inventory methods and models, and measure progress for emissions reduction programs for carbon dioxide and methane. Integrating multiple data sources and methods will also improve reporting of emissions and removals across the Canadian landscape. An example is the use of high-resolution remote sensing data with validated, spatially explicit landscape models to track human impacts on GHG fluxes across Canada's land area.

Research on reconciling differences between estimates of sources and sinks obtained with complementary methods (i.e., top-down and bottom-up methods) will increase confidence in GHG data. Greater understanding of the various methods is needed to understand the source of discrepancies (e.g., missed sources, detection limits, incomplete activity data, limitations of reported data, misallocation of emission sources) and to accurately report changes in emissions over time.

Improved quantification of greenhouse gas emissions also requires integrated atmospheric GHG monitoring systems.

Research is required to evaluate and guide methods to observe atmospheric changes and to continuously track emissions, for example differences between in situ versus remote sensing observations, or stationary observations versus mobile platforms (ground- and water-based vehicles, aircraft, drones, and satellites). Research should also consider differences between sectors, GHGs, and spatial and temporal scales. A near-term priority is detection, measurement, and reduction of fugitive methane emissions from oil and gas operations, as outlined in Faster and Further: Canada's Methane Strategy.

R2 (IPNZ). Monitor, analyze, and assess changes in ecosystem carbon stocks. Stocks of carbon stored in Canada's biomass, soils, aquatic, and coastal environments are important on a global scale. Research is needed to better understand the permanence and vulnerability of carbon stocks in managed and unmanaged wetlands, agricultural, coastal, and forest systems. This research should build on existing data sources and analyses, such as provincial forest inventories. Further research is needed to develop methods and data to regularly and more frequently measure natural carbon sinks at different spatial scales. Improved data on carbon sinks can identify their potential to remove carbon from the atmosphere and contribute to national net-zero objectives. This priority is closely aligned with science priorities for nature-based solutions and the carbon cycle (see Chapter 5.2. Carbon Cycle Science).

R3 (IPNZ). Better understand the contribution of land use and land-use change to achieving net-zero by developing land-use monitoring systems with high spatial resolution. Research is needed to improve the network design and methods used to provide fully reconciled and authoritative systems to monitor land use. Models that are continually validated against measured data are needed to assess how land use and land-use change may affect carbon fluxes and contribute to achieving net-zero. Intercomparison studies are needed to inform alignment of monitoring and modelling methods across land-use categories (i.e., forests, croplands, wetlands, and settled lands) and coastal zones. Land-use models should be used in both national inventory reporting and atmospheric observations-based methods as they become available (see Chapter 5.6. Net-Zero Pathway Science).

R4 (IPNZ). Examine trade-offs involving GHG emissions and removals in economic, environmental, policy, health, and social spheres of Canadian society. Integrated analyses are needed to understand trade-offs associated with GHG emissions and removals and support informed climate policies. These analyses should use ecosystem and socio-economic models to consider the impacts of GHG policy directions. Research should also consider economic, technological, and nature-based solutions, including evaluating the potential benefits, costs, and risks of solutions, and uncertainty associated with them. For example, research and/or modelling should compare carbon dioxide removal methods, such as technologically-based versus nature-based carbon sequestration for multiple climate scenarios, including in the context of extreme events.

The priorities for knowledge synthesis and mobilization are designed to make knowledge and data more useful and accessible. They include:

KM1 (IPNZ). Reconcile publicly available data, information, and knowledge needed to inform calculation of emissions. Comprehensive, authoritative and accessible data is needed for emissions modelling and integrated analyses. Existing data infrastructure should be coordinated and linked. New data and knowledge management infrastructure must be promoted to enable a broader range of academic, stakeholder, and public contributions to the analysis of GHG mitigation opportunities and progress. Remote sensing products also need to be aligned and integrated with data from various sources, including other survey-based data sources. Technology should be developed to integrate datasets, validate models, and allow the free flow of data and knowledge products among governments at all levels, academia, and the public.

KM2 (IPNZ). Conduct intercomparisons and make improvements to ecosystem models to understand anthropogenic drivers of carbon change in the land sector. To improve accuracy and reduce uncertainty in estimates of emissions and removals, research is needed to validate ecosystem models against existing historical datasets and capture how human activities modify emissions and removals in managed ecosystems. A coordinated study comparing models is required to establish the strengths and weakness of various modelling platforms and to assure that functional elements of ecosystems affecting carbon and nitrogen cycles are adequately simulated and consistent across scales. Innovative approaches to combining and refining model function should be explored. These models, which project the impacts of climate change on the Canadian landscape, should play a role in integrated socio-economic analyses of mitigation strategies (see also Chapter 5.2. Carbon Cycle Science and Chapter 5.6. Net-Zero Pathway Science).

These priorities for research and knowledge synthesis and mobilization would improve understanding of Canada's GHG emissions and trends, as well as enable Canada to contribute to international GHG monitoring efforts, such as the International Methane Emissions Observatory initiative of the UN Environment Programme and the global stocktake process of the Paris Agreement. As well, the priorities help us make continued progress toward meeting Canada's nationally determined contributions.

Chapter 5. Convergence Research Topics

Summary

The far-reaching impacts of climate change, and the complexity of the relationships among our environment, economy, and well-being, mean that research needs to work across all disciplines (“convergence research,” see Box 2.2. Research Paradigms for Transformative Science). Frameworks for transdisciplinary research are needed to inform how society responds to climate change and other simultaneous challenges. Knowledge synthesis and dissemination ensures that information on these topics is available to a broad range of policy and decision makers. Using this information will enable us to more effectively transform social and economic systems to address climate change while achieving adaptation and mitigation goals.

Predicting and Projecting Climate Extremes and Extreme Events

Accurate predictions and projections of how the climate will change are essential to characterize risk and plan adaptation responses. They are also critical to inform climate strategies that reduce GHG emissions and will continue to be effective in the face of extreme events and ongoing climate change. Predictions need to go beyond temperature and precipitation extremes. They must provide insights into how frequent and how severe extreme events will become and how they may unfold simultaneously or sequentially, increasing risks to Canadian communities, human and ecosystem health and well-being, and the economy. The science priorities include developing climate predictions on seasonal to annual and decadal time scales, and on kilometric spatial scales. The Arctic region, in particular, would benefit from improved climate monitoring and data to predict climate extremes. Partnering with communities to monitor and predict regional-scale climate change is key to supporting climate action.

Carbon Cycle Science

Carbon cycle science involves understanding how carbon flows through ecosystems, the atmosphere, communities, and industrial and natural resource sectors. This informs mitigation opportunities, as well as adaptation strategies. For example, nature-based solutions can conserve and enhance natural carbon sinks while also supporting climate adaptation (e.g., through natural cooling influences in urban environments). The efficacy of nature-based solutions is dependent on how the carbon cycle will respond to further climate change. Carbon cycle research is needed to inform how we integrate nature-based solutions, as well as technologies that remove carbon dioxide, into plans for net-zero pathways. Effective deployment of and reporting on natural carbon sinks requires strengthened collaborative research to include consideration of the carbon cycle within climate models. Research is also needed to track changes in carbon stocks (both in land and sea) and to understand their response to changing climate conditions and disturbances (natural or human-caused). Complementing this is the need for regular science assessments to track trends and inform integrated methods to measure and calculate carbon. Assessments can also inform reporting on co-benefits of nature-based solutions for biodiversity and health.

Water–Climate Nexus Science

Advancing this nexus science (in which disciplines intersect) will inform interventions to protect human health, safety, and well-being as well as to sustain healthy aquatic and terrestrial ecosystems that, in turn, are integral to human well-being. The science priorities include developing tools to predict water supply and water quality for communities and for natural resource sectors, including hydroelectric facilities. These tools will inform planning to reduce risks from climate extremes and extreme weather events. The science priorities include understanding the sustainability of the water-supply; predicting water-related extremes and their impacts on built infrastructure and critical services; predicting water-related risks to human and ecosystem health; and developing communications about water and climate to improve climate literacy.

Arctic Climate Change Science

Climate change science priorities for the Arctic are cross-cutting. Rapid warming is underway in northern Canada, with deep societal, environmental, and ecological impacts. Global implications of these changes present an opportunity for Canadian scientific leadership and participation. Inuit, First Nations, and Métis organizations must be actively engaged as partners in setting and addressing research priorities across Canada, especially in northern Canada, where *how* research is conducted is as important as *what* research is done. Community-led initiatives are needed to improve environmental monitoring, increase northern research capacity, and analyze future climate change scenarios and their implications to food and water security, transportation, infrastructure, and traditional livelihoods. The five themes of the National Inuit Climate Change Strategy provide a strong foundation for research and capacity needs. Critical science and knowledge priorities in the Arctic include developing monitoring strategies that better integrate surface observations and satellite data, and improved representation of Arctic processes (e.g., the cryosphere) within Earth system models.

One Health and Climate Change Nexus Science

One Health is a collaborative, multi-sectoral, and transdisciplinary approach to achieve optimal health outcomes by recognizing the interconnection among people, animals, plants, and their shared environment (including terrestrial and aquatic ecosystems). Research is needed to strengthen our understanding of the risks and drivers of climate change and how these can have synergistic (also called "complex integrated") health impacts, in which many stressors combine to affect health. This research will help us characterize, and respond to, health risks exacerbated by climate change, such as vector-borne and infectious diseases, invasive species, and pathogens. It will also help us understand associated risks from other threats and stressors influenced by climate change, including environmental contaminants, ecosystem loss and degradation, and loss of biodiversity.

Net-Zero Pathway Science

Net-zero emissions mean that human-caused emissions of GHGs into the atmosphere are balanced by human removals of GHGs (over a specified period). Net-zero pathway science seeks to understand the elements required to achieve net-zero emissions while responding to societal needs. It includes the interconnected biophysical, technological, and socio-economic processes affecting efforts to achieve decarbonization. This research informs planning for a carbon-constrained future, by understanding the drivers and needed shifts in a wide range of natural and socio-economic factors. Science priorities include building datasets and understanding trends in emissions, to inform scenarios of transformational change in Canada. It is also important to better represent social, political, attitudinal, and behavioural processes, and analyze their impacts on net-zero pathways. It is necessary to integrate climate projections, including climate extremes, with models of ecosystems and social and economic trends, as part of the analysis of possible pathways. To nurture these science activities and to build capacity, Canada needs a national modelling strategy for net-zero pathways.

Climate Change and Sustainable Development

Climate change research and climate action are essential to sustainable development and to efforts to reduce vulnerability to climate change and the associated risk. However, there is limited research on the relationship between climate action and sustainable development in Canada. Research on this topic can help to show whether, and to what extent, climate actions have advanced or hindered social, economic, and environmental dimensions of sustainable development.

Climate Change and Security

Climate change is impacting many aspects of people's well-being, safety, and security. Research is needed to better understand the potential implications of climate change on well-being and security, conflict, national defence, and social and geopolitical stability. Such research should analyze intersecting stressors (related and unrelated to climate), environmental risks, and social impacts and issues. Applying a lens that considers climate change and security factors would improve understanding of how climate change affects future development choices, their distributional aspects, and solutions. This lens would incorporate existing data and knowledge on environmental, socio-economic, and health factors to better inform climate and security solutions. Research must also assess long-term climate, economic, political, and financial changes for Canada, and how these are affected by changes on a global scale. Transdisciplinary research frameworks are essential to evaluate the security implications of climate change policy for geopolitical risks, risks to financial systems and energy supply, humanitarian responses, and foreign policy.

Social Science and Climate Change

Social and behavioural science are critical to helping us understand Canadians' attitudes, beliefs, values, and biases related to climate change. This information can be used to develop targeted communication strategies and translate climate change science in way that connects with different audiences. Effective communication, based on the latest scientific knowledge and delivered clearly and concisely, can contribute to the shifts in attitudes and behaviours needed to drive transformational societal change and achieve net-zero GHG emissions.

Convergence research topics were identified according to shared cross-cutting characteristics, high relevance across multiple climate system components and regions, and broad impacts across communities and socio-economic sectors. They focus on biophysical, socio-economic, and policy interactions, as well as feedbacks (i.e., responses that either intensify or minimize the initial effect). These topics require particular attention and support to build multi- and transdisciplinary scientific approaches, looking beyond cause and effect to reflect increasingly complex and difficult-to-manage responses to climate change.

Taken together, these topics reflect knowledge needed to guide integrated approaches to mitigating GHG emissions and adapting to climate change. Such initiatives can transform social and economic systems, promote the health of Canadians and the environment, and conserve natural ecosystems and biodiversity.

5.1. Predicting and Projecting Climate Extremes and Extreme Events

Research is needed to improve prediction (in the near term) and projection (over the long term in response to GHG emissions) of climate extremes and extreme weather events (see Box 5.1. Climate Extremes and Extreme Weather Events). Stakeholders and experts have emphasized that this research is fundamental to advancing a wide range of climate change science and knowledge. It is also critical to planning effective adaptation and mitigation actions. Advances in Earth system climate science and modelling of extreme events require a better understanding of how climate change will influence terrestrial, hydrological, oceanographic, biogeochemical, cryospheric, and atmospheric processes (including those associated with clouds, precipitation, and storms).

Box 5.1. Climate Extremes and Extreme Weather Events

Climate extremes and extreme weather events may be short-term (such as storms and heatwaves that occur over hours, days, or weeks) or long-term (such as multi-year droughts). Prediction and projection of their evolving frequency and intensity should encompass extremes on all time and space scales.

Extremes—The far ends (tails) of the distribution of a particular variable (e.g., hottest or coldest temperature).

Extreme event—An event that is rare at a particular place and time of year (e.g., heatwaves, wildfires, floods, droughts, storm surges).

Compound extreme events—Simultaneous or sequential combined extremes or multiple events or hazards (e.g., sea level rise and storm surge; drought coupled with heatwaves and/or wildfires).

Predictions and projections rely on a strong Earth system climate modelling capacity. These models simulate how chemistry, biology, and physical forces work together. Understanding extremes can also contribute to climate literacy, which, in turn, can help build competencies for climate adaptation in the public and private sectors and increase awareness of climate risks among citizens, motivating individual and collective climate action.

Improved predictive capacities should be coupled with risk assessment tools to plan for climate extremes and extreme weather events, especially for compound extreme events (see Box 5.1. Climate Extremes and Extreme Weather Events). Compound events may be more likely than individual events to push natural resource sectors, infrastructure, and public safety, beyond their resilience thresholds. A further step in understanding the consequences of compound extreme events is considering concurrent socio-economic conditions, such as economic recession, which may exacerbate or create additional vulnerabilities and challenges to recovery (see Box 5.2. Responding to Climate and Weather Emergencies).

Box 5.2. Responding to Climate and Weather Emergencies

For Métis Nation BC (MNBC), the challenges posed by climate change, such as more intense storms, frequent heavy rain and snow, heatwaves, drought, extreme flooding, and higher sea levels, could significantly alter the types and magnitudes of hazards faced by communities and the teams of emergency management professionals serving them. This is reflected in the **Emergency Support Framework Phase 1** project started in 2020 to help MNBC support MNBC Chartered Communities and Métis Citizens in emergency preparedness and readiness in case of future disasters. The project included an assessment of existing conditions, emergency response capabilities, program status, and identification of challenges for Métis Citizens regarding emergency operations. This critical preliminary assessment will help deliver effective emergency support for the MNBC to supplement existing systems managed by the local, regional, and provincial government. For more information: Climate Preparedness Workshop Series Final Report Released | MNBC

Ongoing research and investment are needed to improve climate predictions. Within the following priorities, progress may be accelerated through a more coordinated national approach, closer integration with the community or stakeholders, and/or interdisciplinary approaches that include social and health sciences. The science priorities are:

> **R1 (PPCEE). Improve predictions and projections of extremes, on time scales of seasons to decades, and on kilometric spatial scales.** Develop and improve predictions on seasonal to interannual time scales, projections on decadal to century time scales, and parameters (measures of specific aspects of climate or weather) relevant to users in Canada. These include extremes and conditions conducive to extreme events, air quality, ocean conditions and sea level, and hydro-climate parameters related to freshwater security. These parameters should be “downscaled” from large-scale models or observations to kilometre scales for use in models (e.g., hydrological, oceanographic, vector-borne disease, wildfire, and coastal erosion models).

Improved projections of climate extremes will inform climate metrics and design codes for specific sectors, disaster risk reduction and emergency preparedness, public health and security, food security, and other applications of climate risk management.

Larger-scale models provide information that becomes input into smaller-scale receptor models useful for planning at the regional and local level. This “modelling chain” of global to high-resolution regional Earth system models needs to be improved to better represent conditions (e.g., soil moisture, permafrost, ocean temperature) and atmospheric processes (e.g., convective instabilities, extreme winds, storm tracks), and predict climate and climate extremes. The modelling chain of Earth system models must output data at high resolution so that the data can be used in regional or local receptor models. Interdisciplinary research is required to expand the range of variables and parameters that are predicted and projected to include those relevant to impacts and risks for Canadian users (discussed above). This will allow models to better inform health and safety, infrastructure, disaster preparedness, and other economic and societal outcomes. For example, data from models can be incorporated into climate services to help governments and communities prepare for and react to extreme weather events.

Currently, capacity in seasonal, interannual, and decadal predictions is limited. Advances are possible in seasonal prediction systems and in the quality of observations and reanalyses used to initialize simulations. To expand the range of variables and parameters, research is needed on how machine learning and artificial intelligence could build on existing Canadian capacity for seasonal predictions. Improved models would be valuable for environmental prediction (e.g., of floods, storm surges, and fires) as well as for socio-economic applications, such as agricultural practices and management of natural resources (e.g., water, forestry, fisheries).

R2 (PPCEE). Improve monitoring, data collection, and accessibility. Accessible, integrated, and interoperable datasets of climate and Earth system observations are essential to inform Earth system modelling and prediction of extremes, help us understand long-term evolution of extremes, and inform adaptation and infrastructure investments. Such datasets should also be updated on a regular basis. Climate monitoring (both land surface and ocean) must be improved and better aligned with user-defined climate indices (used to characterize an aspect of a system, such as a circulation pattern), especially for extreme events, precipitation, wind and cryosphere changes. Specifically, sparsely observed regions, such as the Arctic, need to be better covered (see Box 5.3. Filling the Gaps in Atmospheric Arctic Observations), and monitoring systems (i.e., siting and technology) must be maintained over the long term. At the same time, investments are needed in new technology to sustain and extend monitoring capacity and provide products at higher resolution. This technology includes autonomous systems, space-based Earth observation products and their calibration, and blended in situ and remote sensing products.

Box 5.3. Filling the Gaps in Atmospheric Arctic Observations

Temperatures in the Canadian Arctic are increasing at a rate of two to three times the global average, yet a significant gap still exists in atmospheric Arctic observations compared to the rest of the world. There are only a small number of ground-based atmospheric measurement stations (that gather data on weather and climate variables as well as GHGs) in Canada's northern regions, which limits our ability to track changes in vulnerable northern ecosystems and feedbacks due to the more rapid rate of warming in these regions. As a result, studies to predict future climate conditions may not be accurate enough to inform adaptation efforts and to assess progress toward stabilizing global temperatures. Although planned satellites to monitor carbon dioxide and methane will increase global observational coverage, Canada's northern latitudes will continue to be under-observed. The Government of Canada is proposing the Terrestrial Snow Mass Mission and the Arctic Observing Mission, which could observe the Arctic like never before. These missions being developed in partnership between Environment and Climate Change Canada, the Canadian Space Agency and Natural Resources Canada, working with domestic academic institutions and international scientific experts, would have unprecedented capabilities for observing climate change impacts, improving emergency preparedness to extreme weather events and supporting resilient adaptation in the North. This is an opportunity for Canada to take international leadership to advance progress in satellite Earth observation capacity, focused on the North.

R3 (PPCEE). Co-develop approaches to monitoring, conducting research, and predicting climate change with affected communities. For prediction of extremes and climate change monitoring, partners include First Nations, Inuit, and Métis communities, municipalities, provinces and territories, and other involved groups. Existing science activities need to move beyond an expert role and instead co-create knowledge directly with affected communities, in order to provide relevant climate information that supports climate mitigation and adaptation. There are opportunities to form or strengthen partnerships for observational and process studies as well as long-term monitoring and modelling efforts. Community partnerships can also build local and regional capacity, strengthening understanding of climate change and the engagement of citizens, organizations and communities in climate mitigation and adaptation.

For this convergence research topic, there is a priority for knowledge synthesis and mobilization:

KM1 (PPCEE). Synthesize and mobilize existing knowledge on the physical science of climate change, including extremes. Knowledge should be synthesized and mobilized through many avenues (see Chapter 6. Moving the Climate Change Science Agenda Forward).

In regard to extreme weather events specifically, work is underway to develop rapid "event-attribution systems" that would evaluate and communicate the contribution of climate change to such events. A new federal program is using the growing field of "attribution science" to promptly establish to what extent a certain extreme event (for example, a flood in British Columbia or wildfire in Quebec) is due to climate change.

Tools, guidance, and training continue to be required to build competencies in taking action on climate change in all levels of government and private sector. This will allow decision makers to incorporate climate change considerations in policy development and infrastructure projects, to improve the resilience of projects climate extremes and extreme events.

5.2. Carbon Cycle Science

Carbon cycle science involves understanding how carbon flows through communities, industrial and natural resource sectors, ecosystems, and the atmosphere. Carbon cycle science that reflects ecosystem responses to deliberate human actions and removal of carbon dioxide from the atmosphere is incorporated in national inventories of GHG sources and sinks, and in Earth system climate models, to varying degrees. This understanding informs mitigation opportunities, including enhancing natural sequestration and in situ conservation of carbon, as well as adaptation strategies that build on nature-based or hybrid solutions.[13] Overall, the mitigation potential of nature-based solutions that aim to preserve or enhance carbon storage has not been well calculated over space and time. Furthermore, the variables influencing these calculations are not used consistently, and various estimates of carbon sinks are not directly comparable.

The potential contribution of carbon dioxide removal to national emissions-reduction objectives requires ongoing research. Research is needed to improve calculation of removals and to understand the effects of ongoing warming on large-scale efforts to sequester carbon (see Box 5.4. Carbon Dioxide Removal). New research should build on atmospheric observations and model-based methods to estimate carbon fluxes, which can complement National Inventory Reporting. Broadly, this research contributes to:

- improving mitigation strategies;
- validating and refining reporting methods for carbon dioxide removal technologies and for natural carbon sequestration;
- understanding potential contributions to emissions reductions; and
- achieving and sustaining net-zero emissions.

Nature-based solutions are an important element of mitigation strategies. However, uncertainties and gaps limit our understanding of their current and potential capacity to sequester and store carbon in managed and unmanaged areas (e.g., wetlands including peatlands, agricultural and forest systems, harvested wood, and coastal ecosystems). Research on the permanence of natural sequestration must take into account the impacts of future warming and changing precipitation on how ecosystems function. This includes the potential release of carbon dioxide and methane (e.g., from permafrost and soils) in response to warming, disturbances from extreme events or human activity, and hydrological changes (e.g., in wetlands and coastal areas) as well as related climate feedbacks in the Earth system that amplify climate change.

[13] For more in depth review of natural carbon sink potential and knowledge gaps, see Council of Canadian Academies (2022) *Nature-Based Climate Solutions*.

Box 5.4. Carbon Dioxide Removal

Carbon dioxide removal (CDR) involves removing carbon dioxide from the atmosphere and storing it durably in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential human improvements to biological or geochemical carbon dioxide sinks and direct air carbon dioxide capture and storage (DACCS), but excludes natural carbon dioxide uptake not directly caused by human activities (see IPCC AR6 WGIII Glossary).

The need for more science on CDR is pressing because of Canada's commitment to reaching net-zero GHG emissions by 2050, which will require CDR to offset remaining GHG emissions that prove hard to mitigate. These science needs are also underscored by the prominence of CDR in recent scenarios limiting global warming to 2°C or less as well as by announcements of large private and public funding commitments for CDR projects around the world.

In the Canadian context, science needs for CDR can be grouped into five categories covering physical, economic, and social sciences. Key CDR methods to focus on include: DACCS, bioenergy with carbon capture and storage, biochar, and nature-based solutions.

1. **Risks, trade-offs, and co-benefits** – Identify the major risks, trade-offs, and co-benefits from deploying CDR methods in Canada.
2. **Feasibility and economic impacts** – For various levels of deployment of CDR (megatonnes of carbon dioxide per year, see item 5), determine the life-cycle energy and material requirements, estimate costs (including those for the enabling infrastructure) and potential impacts on the job market, reflect the need for both direct decarbonization and CDR to reach net-zero GHG emissions, project technical and economic improvements over the coming decades, estimate the potential synergies among CDR methods, and optimize their deployment across the country and over time.
3. **Governance** – Assess regulatory and governance frameworks for real-world research and large-scale deployment of CDR in Canada; develop protocols for monitoring, reporting, and verification of CDR; assess implications of CDR deployment for GHG reporting and accounting; and study the social and political implications of various governance approaches for CDR.
4. **Stakeholder engagement** – Assess public acceptability and develop strategies to constructively engage stakeholders on the potential deployment of CDR.
5. **Level of deployment** – Estimate the level of deployment (megatonnes of carbon dioxide per year) Canada needs to and can achieve to contribute to net-zero GHG emission targets by 2050, for CDR as a whole and for specific CDR methods.

Research activities under these categories should assess whether existing scientific studies are directly applicable to Canada and should use the national climate change research infrastructure (e.g., federal laboratories, observation network, and high-performance computing) in moving forward.

There is an increasing need to predict, measure, and validate direct interventions to divert carbon through carbon capture, utilization, and storage, including through direct air capture technologies. Emerging opportunities in the circular bioeconomy (an economy powered by nature, emphasizing renewables and minimizing waste) and bioenergy (fuels from biomass), including low-carbon and hybrid engineering solutions for infrastructure, represent further interventions to sequester carbon, diverting or delaying carbon flows back to natural ecosystems. The impact of these interventions on ecosystem function and biodiversity is poorly understood. Nature-based and hybrid approaches to managing flood and wildfire risks, creation of greenspace and parks within and beyond urban areas, and Canada's Nature Legacy Agenda (conserving 30% of our land and ocean by 2030) all have implications for ecosystem function and biodiversity as well as long-term carbon sequestration.

The priorities for carbon cycle science (below) include improved, process-based understanding of vegetation and soil-related carbon sources and sinks across the Canadian landscape, spanning agricultural, forest, wetland, coastal, and tundra environments.

To track how nature-based solutions affect the carbon cycle, we need a comprehensive understanding of current natural carbon stocks and fluxes (i.e., baseline conditions).

Building coordinated, national capacity for carbon cycle science in Canada is critical. This includes participating in international efforts and organizations in Earth system and carbon science and building on that knowledge to advance Canada's interests and climate objectives. The science priorities are to:

R1 (CC). Conduct collaborative research in Earth system modelling and in understanding the carbon cycle. This priority includes developing national government and academic strategies and collaborative partnerships in (1) developing and evaluating Earth system climate models and (2) conducting research and monitoring of the carbon cycle. Research in this area should include a broad range of observational data and process studies to help develop and validate models.

Research requires a multidisciplinary, Earth system approach. In several regions of Canada, ecosystems and climate processes have substantial impacts on the global carbon cycle, yet there are uncertainties concerning associated feedbacks. These regions include boreal forests, wetlands, wildfire-prone areas, permafrost, and coastal ocean regions. Climate, soil processes, vegetation, hydrology, and the cryosphere are all linked. This has important impacts on biogeochemical cycles, including the sequestration and potential release of stored carbon (in the form of carbon dioxide, methane, or other GHGs) and nitrogen.

R2 (CC). Monitor carbon stocks to understand their responses to changing climate conditions and disturbances. Long-term monitoring of biological, chemical, and physical aspects of ecosystems will allow us to track changes in both land- and marine-based carbon stocks over time and relate them to changes in environmental conditions and disturbances, both natural and human-caused. Research is needed to understand the role of wetlands (including peatlands) and permafrost areas in climate warming. Research is also needed to understand the effect of increasing frequency and severity of natural disturbances, such as wildfires, on forest carbon. These should be considered together with the effect of forest management practices and the transfer of carbon to harvested wood products. Research should also focus on the role of lakes and rivers in storing and transporting carbon between terrestrial and marine environments, and the potential for carbon sequestration in coastal sea grasses and wetlands, salt marshes, and kelp beds, to inform coastal management and the protection of these marine ecosystems (see Chapter 4.5. Informing Progress Towards Net-Zero Greenhouse Gas Emissions).

Research is needed to evaluate and guide observation-based methods (involving data from ground stations and satellites) to estimate emissions, and long-term field experiments to estimate regional- and national-scale carbon stocks and carbon fluxes. While both natural and human-caused carbon fluxes should be estimated, the techniques and implementation considerations differ between the two, in terms of precision, accuracy, spatial and temporal coverage, frequency, and measurement.

R3 (CC). Improve, compare, and apply ecosystem models to estimate carbon fluxes on a national scale. It is important to validate the main models used to simulate carbon emissions and removals across Canadian ecosystems against existing historical datasets. Validation ensures their accuracy and helps us better understand the uncertainty in the model simulations. There is a wide range of ecosystem models that can inform the understanding of carbon and nitrogen cycles. These models function on a number of scales, ranging from models specific to a single site to watershed, landscape, and global-scale models.

As a part of validation, a coordinated model intercomparison study could establish the strengths and weaknesses of various models. The study would also determine whether models at the landscape, watershed, regional, or global scales are consistent with finer-scale models and examine whether key functional elements of ecosystems are adequately simulated and consistent across scales. Validated ecosystem models should play a key role in analyzing mitigation strategies, involving nature-based solutions, projecting the impacts of climate change on the Canadian landscape, and monitoring and reporting emissions and removals of GHGs from the managed and unmanaged landscape.

There is one priority for knowledge synthesis and mobilization:

KM1 (CC). Undertake regular science assessments of the carbon cycle and the potential for increased carbon uptake in Canada. Regular science assessments are needed to inform integrated methods for carbon accounting and tracking over time, including long-term tracking (beyond 2050). Such assessments of carbon stores and stocks should be national (with regional resolution) and conducted regularly (approximately every five years). They should also consider interannual variability and vulnerability to future warming and extreme events.

5.3. Water–Climate Nexus Science

Water responds to increasing temperatures throughout the Earth system, with impacts on water quantity, quality, and chemistry, as well as biodiversity and ecosystems. Warming temperatures affect the physical state of water in the atmosphere (rain, snow, ice) and on the surface, which has cascading impacts on human health, ecosystem health and services, biodiversity, community infrastructure and services, culture, and sustainability of natural resource sectors. Water is involved in substantial climate feedbacks. Climate change results in increases in hydrological variability and extreme events (such as floods and droughts), ocean warming and acidification, a changing cryosphere, and shifting species distributions. However, how aquatic, terrestrial, cryospheric, estuarine, and marine environments respond to climate change, water management, and GHG mitigation actions is not fully understood.

The effects of increased atmospheric GHGs on aquatic ecosystems are often manifested in changes in water quality in both freshwater and marine environments. Warmer water temperatures, changes in water chemistry, sea-level rise, eutrophication, salination of coastal freshwater environments, droughts, and flooding are just some examples of change that can have a negative impact on water quality and the ecologically sensitive species that inhabit these environments. Coastal and Arctic environments are particularly vulnerable during the spring, as increased precipitation and snow/ice melt can lead to greater freshwater and nutrient influx. These changes can impact the quality of water for the people and organisms that rely on it.

Risks to human and ecosystem health related to the water–climate nexus include the following:

- effects on drinking, agricultural, and recreational water quality;
- threats to freshwater supply through climate-driven changes to essential sources (melt water from seasonal snow and glaciers, changes to regional precipitation patterns);
- water-borne diseases;
- impacts on biodiversity;
- physical injuries and mental health impacts due to extreme flooding events and their effects on local or regional infrastructure and services; and
- impacts on water and food security.

Science on the water–climate nexus informs interventions to sustain healthy aquatic and terrestrial ecosystems. It improves confidence in tools that predict freshwater supply and improve or maintain water quality for communities and for natural resource sectors. This science also informs planning to reduce risks from hydro-climate extremes and extreme events, particularly floods, storms, wildfires, drought, and harmful algal blooms. These challenges require mobilization of Western and Indigenous science and partnerships with First Nations, Inuit, and Métis Peoples and communities, who are stewards of water in large areas of Canada.

Building the scientific evidence to manage water resources effectively is complex and needed to ensure that decision makers and end-users have clear and understandable information and tools to make decisions and take appropriate action. The science priorities are to:

R1 (WCN). Understand future water sustainability, including supply, demand, quality, and effects on human and ecosystem health. Transdisciplinary science efforts are required to understand freshwater sustainability in the coming decades. Sustainability means a balance of water resource use with ecosystem health, functions, and services. This understanding includes how vulnerable freshwater supply is to climate change, and whether water supply will meet the expected increase in demand by humans and ecosystems. This underpins research in the topics below and is essential to determine where, and in which seasons, future warming threatens water supply and quality. Sustainable integrated management and decision making, should address:

- climate impacts on freshwater use and impacts on water users, such as agricultural and urban communities;
- contaminant and nutrient pollution;
- aquatic habitat health, including the impacts of invasive species; and
- projected changes in extreme events (i.e., floods, droughts), their societal impacts and implications for water resource infrastructure.

Freshwater sustainability involves integrating requirements for specific communities and for public health with protection of ecosystems and their services, such as the sustainable operations of natural resource sectors (see Chapter 4.4. Sustainable Natural Resources). Hydroelectric power generation continues to be an integral component of renewable energy in many regions. Research is needed to understand the impact of climate-induced changes in streamflow regimes on hydroelectric power capacity and resilience. Better understanding can help inform monitoring and management of freshwater resources, at the national and regional levels.

An understanding of long-term freshwater supply and demand across Canada is needed to develop methods and models to predict the timing and severity of supply stresses in freshwater systems. These methods and models can also help meet household, agricultural, and industrial water demands, especially during extreme heat events and droughts. This research requires collaborative efforts to forecast (seasonally, on a local to regional scale) and project (long-term) freshwater carrying capacity for key watersheds. This will become particularly important as changes to snowpack and glaciers impact the timing and quantity of meltwater runoff to hydrological systems. Such forecasts and projections can inform planning for freshwater supply and infrastructure.

Scientific information that is multi-scale (e.g., local or urban, regional, ecosystem, watershed) is essential to support integrated freshwater management and stewardship.

R2 (WCN). Model water-related risks to the health of humans and ecosystems as well as burden of disease (illness and death) due to further warming. Climate-driven changes to water quality and quantity have consequences for both natural ecosystems and freshwater availability and safety for human consumption. Impacts differ by region and include warmer waters, increased sediments associated with thawing permafrost, sea-level changes, flooding, drought, changes in precipitation patterns, and greater land-based runoff. Other impacts may also disrupt the health of aquatic ecosystems and degrade their ability to provide ecosystem services, including food and water security for Canadians. Research is needed to develop new and strengthened monitoring approaches and analytical methods for detecting new or previously rare health risks. These approaches and methods can be used to develop effective measures to protect the health of humans and aquatic ecosystems. An increase in the frequency and intensity of extreme events, including wildfires, heatwaves, droughts, and floods, can result in freshwater contamination, shortages, freshwater runoff, eutrophication, and other issues. Changes in water quality and quantity may have cascading effects for the health and well-being of communities and individuals, and may exacerbate existing social inequities. Climate-driven changes to water resources may also impact health and well-being by impeding access to traditional foods, affecting agriculture and tourism, and hindering safe travel and supply lines (e.g., ice roads) in some communities (e.g., coastal, Arctic, and northern communities).

To take action on the modelled risks, research should advance source water protection and public health interventions in equitable and effective ways, through transdisciplinary science frameworks and programs to acquire needed data. These data can be used to develop mechanistic understanding, new technologies, and models to assess the burden of illness due to climate change impacts on water quality and quantity. Efforts to protect health from these impacts should be informed by an understanding of the needs of those most at risk, co-developed with communities and groups affected, where possible.

5.4. Arctic Climate Change Science

Over recent decades, the temperature in the Arctic has increased at three to four times the global average, as a result of climate feedbacks that amplify climate change. The impacts of this warming are significant because of the close cultural connection that First Nations, Inuit, Métis, and other northern residents in the Arctic have with the natural environment (see Box 5.5. Our Arctic Science Context). Climate-induced changes to the Arctic also have global consequences. These include:

- reduced albedo (reflection of sunlight back into space) from reduced Arctic snow and ice cover, which amplifies warming;
- significant carbon emissions from thawing permafrost;
- changes to the behaviour of the jet stream (driven by amplified Arctic warming and reduced sea ice); and
- global sea-level rise associated with glacier and ice sheet melt (mainly from Arctic Canada and Greenland at this time).

These global effects also have implications for every region of Canada. Since the Arctic affects climate change and is affected by climate change, Arctic research priorities are relevant across all themes and topics in this report.

Box 5.5. Our Arctic Science Context

Inuit Nunangat, the Inuit homeland and settled land claim areas, reaches across the entire Canadian Arctic, which accounts for 40% of Canada's land mass. Other Indigenous groups, including First Nations and Métis, also reside in the region on unceded territories. As a result, Canada must collaborate in global science communities on *what* research is conducted in the Arctic, and *how* Arctic science is planned, led, implemented, and reported. This includes considerations for Arctic science capacity, infrastructure, knowledge dissemination, and partnerships, including co-development and leadership of research initiatives with Indigenous communities.

The Arctic of the future will be significantly different from the Arctic of today. Climate science is essential to inform effective, evidence-based adaptation and mitigation activities across Arctic and sub-Arctic Canada.

How Arctic research is planned, conducted, and delivered in Canada is just as crucial as *what* Arctic science is prioritized. Governments and the research community must actively engage First Nations, Inuit, and Métis organizations as partners in addressing science and knowledge priorities across northern Canada. Community-led initiatives are needed as part of self-determination in environmental monitoring, enabled by increased northern capacity. Climate change is the key driver of Arctic environmental change, and climate research must be grounded in Indigenous knowledge systems. These knowledge systems should be more integrated in research design and monitoring of environmental conditions that affect social, cultural, and health considerations in northern communities.

Knowledge co-production, information-sharing, and evidence-based decision making are foundational principles for research and knowledge synthesis and mobilization activities in northern Canada. Current Arctic research capacity is loosely coordinated across a range of institutions, stakeholders and rights holders, and programs (e.g., federal and territorial government departments, and university-led networks such as ArcticNet and PermafrostNet). There is an opportunity to increase co-development, co-management, and coordination in these areas.

A Canadian Arctic climate science and knowledge system needs to be established to support climate information needs across northern regions and communities. A rights-based approach is required, premised on partnerships with First Nations, Inuit, and Métis representatives and respect for multiple knowledge systems.

Increased northern scientific capacity should include community-based monitoring as well as participatory scenario analysis, planning, and governance. These scientific approaches are key to resilience-based ecosystem stewardship and adaptive governance. They can also help preserve livelihoods and well-being as environmental conditions change. Northern-based training opportunities and research facilities (e.g., laboratory capacity) must continue to be developed. Communication and coordination between southern and northern science networks can be enhanced through increased capacity of community-based knowledge brokers and mediators.

The Inuit Tapiriit Kanatami (ITK) National Inuit Climate Change Strategy provides a strong foundation for establishing Arctic science priorities. The five thematic areas identified by the ITK (knowledge and capacity; health, well-being, and the environment; food systems; infrastructure; and energy) align with science priorities in this report. These priorities for Arctic climate research form part of a framework that can be revised to include additional and changing perspectives.

The first four research priorities are aligned with thematic areas identified by the ITK (R1—health, well-being and the environment; R2—food systems; R3—infrastructure; and R4—energy):

R1 (ACC). Understand climate change influences on traditional and cultural activities.
Research is required to:

- implement innovative and collaborative monitoring programs for terrestrial, cryosphere, freshwater, and marine environments;
- understand changing Arctic Ocean and sea ice conditions; and
- enhance Earth system modelling and weather, ice, hydrological, and oceanographic forecasting.

This work will inform the development of approaches to reduce climate change impacts on traditional practices, cultural activities, public health and safety, mobility, and food security for northern Canadians.

R2 (ACC). Conduct research to support secure and sustainable food systems, along with surveillance of the exposure of northerners to emerging food- and water-borne infectious diseases, contaminants, and parasites. Climate change is strongly influencing risk for food systems. Research priorities include improved understanding of the intersection of climate and ecosystem changes, including impacts on human health and threats to food and water security. In the North, food systems include traditional harvest of wild plants and animals and market food. Research is needed to assess the risk climate change poses to traditional and market food access. Monitoring is also needed to assess the exposure of northerners to food- and water-borne infectious diseases, contaminants, and parasites. This includes evaluating community resilience to these risks.

R3 (ACC). Conduct hazard mapping and vulnerability assessments to inform adaptation planning for built infrastructure in northern communities. Knowledge of hazards and vulnerability will inform research to determine adaptation needed for infrastructure (roads, airstrips, buildings, wharves) and transportation (vehicles, air, shipping), including improved understanding of future ice conditions and landscape disturbance from permafrost thaw and coastal erosion. The key outcomes will guide the construction of infrastructure that is climate-resilient and sustainable, while meeting cultural needs and preferences.

R4 (ACC). Design monitoring programs that integrate surface observations and satellite data (existing and planned missions) to track key climate indicators and determine risks from changes in disturbances (such as wildfires and melting sea ice). New satellite missions are needed to address gaps in national observations (see Box 5.3. Filling the Gaps in Atmospheric Arctic Observations). These missions will help us understand and measure cryospheric change (e.g., snow water equivalent; snow depth on sea ice; river, lake, and sea ice conditions) and landscape-scale GHG fluxes. We need a nationally coordinated approach to deploying and maintaining instruments and sustaining observation networks. This approach must be supported by enhanced scientific infrastructure (e.g., improved telecommunications capacity for affordable, near-real-time data transmission).

R5 (ACC). Advance and evaluate Earth system models to better represent the atmospheric, cryosphere, hydrological, oceanographic, ecological, and carbon cycle processes in northern regions. Improved understanding and representation of the carbon cycle is a high priority to assess future carbon fluxes (both sources and sinks) from thawing permafrost, the changing boreal forest (including increased wildfire), expanding tundra vegetation, and the warming Arctic Ocean. Understanding the changing freshwater and sea ice conditions in the Arctic Ocean will inform projections of Arctic Ocean stratification and acidification, and impacts on ecosystems, fisheries, food security, and carbon uptake. Weather-prediction capabilities need to be improved to better forecast extreme events that are common across northern Canada (e.g., fog, freezing rain, blizzards). Advances are needed in river, lake, ocean, and sea ice forecasts across operational (near-real-time), seasonal, and decadal time scales for safety, navigation, and commerce. Research is also needed to better understand:

- climate forcing and feedbacks from changing Arctic clouds and aerosols;
- the impact of climate change on contaminants (including black carbon deposition on snow and ice, as well as changes to mercury in terrestrial, aquatic, and marine environments);
- the ecological impacts of ice crusts resulting from winter rain events;
- changing Arctic Ocean conditions; and
- implications for Arctic marine ecosystems, shipping, security, and economic development.

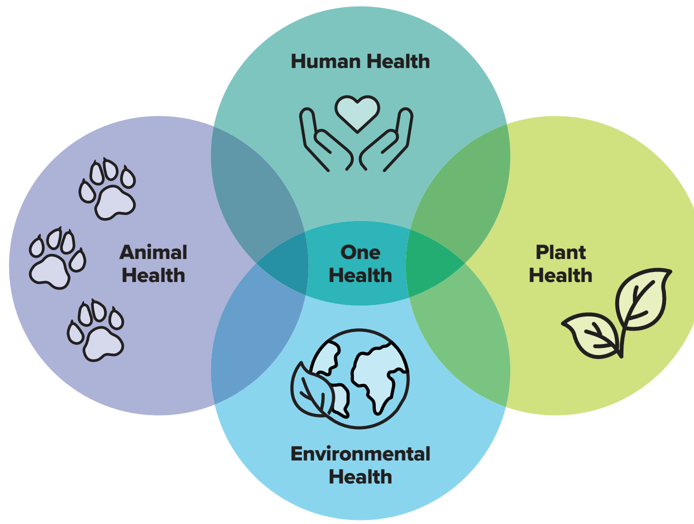
The physical and ecosystem changes occurring across the Canadian Arctic cannot be viewed through the lens of individual disciplines. Interconnected climate and environmental changes across the Arctic create cascading impacts and risks. A holistic and transdisciplinary understanding is necessary to determine the efficacy and limits of strategies to reduce climate risks and strengthen resilience and sustainability for Arctic ecosystems and people.

The knowledge mobilization priority aligns with ITK's knowledge and capacity theme.

KM1 (ACC). Co-develop a distributed approach to delivering climate services for northern communities to inform evidence-based decision making. This priority is to ensure that place-based climate information is available to northern communities. Climate services organizations can help better understand current climate vulnerabilities, risks, and opportunities. They can support planning and decision making to allow northerners to become more resilient to the expected impacts of future climate change.

5.5. One Health and Climate Change Nexus Science

Climate change risks are complex and interconnected, and impacts can propagate through natural and human systems in ways that are difficult to anticipate. Investigating those interconnections through the lens of a One Health and climate change nexus supports science-based adaptation. One Health is a collaborative, multi-sectoral, and transdisciplinary approach to achieve optimal health outcomes by recognizing the interconnection among people, animals, plants, and their shared environment (including terrestrial and aquatic ecosystems; see Box 5.6. One Health). By taking a One Health approach to tackle climate change, we can:



- better understand the impacts of climate change on health equity, and on the health of Canadians, animals, plants, and the environment;
- find collaborative, effective, and economically advantageous approaches to adaptation and mitigation (e.g., surveillance, prevention, and risk management along with guidance to support regulatory decision making); and
- avoid siloed adaptation and responses that have limited benefits or negative impacts outside the targeted sector.

Box 5.6. One Health

One Health, as defined by the World Health Organization, is an integrated, unifying approach that aims to sustainably balance and optimize the health of people, animals, and ecosystems. It recognizes that the health of humans, domesticated and wild animals, plants, and the wider environment (including ecosystems) are closely linked and interdependent. The approach mobilizes multiple sectors, disciplines, and communities at varying levels of society to work together to foster well-being and tackle threats to health and ecosystems. At the same time, these sectors, disciplines, and communities can address the collective need for:

- clean water, energy, and air;
- safe and nutritious food; and
- action on climate change.

Substantial knowledge gaps and issues in data accessibility, sharing, and interoperability currently limit our understanding of the interconnected impacts of climate change on health. To address those gaps, advance collaboration, and identify transdisciplinary opportunities for adaptation, the activities for research and knowledge synthesis outlined below are needed.

R1 (OHCC). Strengthen understanding of risks and drivers of change across the human, animal, plant, and environment interfaces. Climate change continues to create synergistic (also called “complex integrated”) health impacts in which many stressors combine to affect the health of Canadians, animals, plants, and their shared environment. These impacts are due to extreme events and slow-onset changes, along with unprecedented environmental degradation, societal inequities, and changes in biodiversity, land use, and demographics. These impacts may emerge unexpectedly because there is a lack of understanding of the scope and scale of ecosystem changes, how these changes may intersect, and what the impacts will be on health (with “health” defined in this section as the health of Canadians, animals, plants, and their shared environment). There is a need to better understand and detect current, emerging, and often converging trends through greater foresight, modelling, risk assessment, surveillance, and laboratory diagnostic capabilities, including:

- examining the sensitivity to climate change of pathogens, pests, and populations of concern (e.g., invasive species, disease vectors), to determine where and when these may emerge or re-emerge in Canada;
- predicting future shifts in ecological and species ranges (e.g., plants, wildlife, invasive species, disease vectors) due to climate change and how human interaction, exposure, and socio-economic factors may interact with these changes; and
- understanding how health inequities and the social determinants of health influence climate change vulnerability, putting some populations at greater risk of health hazards due to climate change and creating barriers and challenges to protective adaptation measures.

R2 (OHCC). Advance transdisciplinary approaches as well as First Nations, Inuit, and Métis ways of knowing in knowledge-sharing, data braiding, and analytics. The complex and interdependent nature of health underscores the need for coordinated, collaborative, and cross-sectoral approaches. Such approaches should enable multiple and diverse disciplines to work better together to understand, assess, collect, synthesize, and analyze cross-cutting issues. The One Health approach aligns well with Indigenous science and knowledge, including a holistic view of health that links the health and well-being of humans, animals, plants, and their shared environment. First Nations, Inuit, and Métis ways of knowing in this research area will introduce novel approaches for collecting, using, sharing, and analyzing socio-economic and environmental data. These approaches will help us to better understand climate impacts, risks, and adaptation solutions. This requires:

- integrated, multi-sectoral approaches for risk intelligence (information-gathering to identify risks) and surveillance systems for early warning, detection, and risk assessment of threats to health;
- development of First Nations, Inuit, and Métis partners’ capacity and bringing together Indigenous science and ways of knowing and Western knowledge to conduct research and monitoring projects on climate change and various health risks, specifically, zoonotic infections and food safety and security;
- innovations in assessing cumulative effects and cross-sectoral risk management capacity, equipping Canada to better protect the health of individuals and communities, ecosystems, and plant and animals; and
- evaluation of existing climate One Health interfaces and frameworks, integrated in the Canadian context.

The priority for knowledge mobilization is the following:

KM1 (OHCC). Develop decision support and visualization tools that are transdisciplinary and interactive, supporting decision making and ecosystem management.

One Health provides an opportunity to integrate data streams that have not traditionally intersected. To ensure that researchers and data users can access the information they need for transdisciplinary research, they will need:

- data infrastructure, including high-performance computing (see Chapter 6. Moving the Climate Change Science Agenda Forward);
- integrated community-based surveillance; and
- appropriate, accessible, and interoperable data streams.

Public health surveillance, artificial intelligence, and big data will be essential to advance progress on the science and knowledge gaps. To mobilize information and enhance collaboration and external partnerships, there is a need for networks, venues, or forums that include First Nations, Inuit, and Métis communities.

Advancing these science priorities will enable:

- One Health objectives;
- a multi-sectoral, transdisciplinary, "systems thinking" approach; and
- integration of First Nations, Inuit, and Métis ways of knowing.

The key outcomes will be better surveillance, prediction, and communication to protect people, economies, food supply, and natural systems against current and future climate risks.

5.6. Net-Zero Pathway Science

This convergence research involves decarbonization pathways, in line with Canada's commitment to reach net-zero GHG emissions by 2050. Pathway science explores the inter-related biophysical, technological, and socio-economic processes involved in decarbonization. The priorities for this topic seek to inform social, institutional, and political considerations, including opportunities for and barriers to successful decarbonization. This theme also embraces multiple approaches, models, and methods. It reflects diverse streams of knowledge and values in order to understand—and ultimately guide—transformational change. The science priorities are based on user needs and open science principles to support decision making, consistent with the *Canadian Net-Zero Emissions Accountability Act*.

Net-zero pathways are far more than lines on a graph. As the UN Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Reports make clear, net-zero pathways necessitate systemic transformations to all parts of society to drive down emissions and to secure outcomes for resilience, adaptation, and, more broadly, sustainable development. This effort charts a course for the future of Canada in a carbon-constrained world, including underlying shifts in technology, infrastructure, policy, institutions, business models, markets, behaviours, labour, culture, and beliefs, along with many other factors. To understand the scope of this change, pathway analysis must integrate social and behavioural shifts, as well as distributional effects and principles of equity and justice.

Net-zero pathway science relies on efforts from multiple disciplines and embraces diverse streams of knowledge, ways of knowing, and values that inform societal responses to climate change.

The conceptual framework for net-zero pathway science—reflecting iterative knowledge development, evaluation, and monitoring processes—is shown in Figure 5.1. Engineering and natural science can contribute understanding of the biophysical and techno-economic dimensions, spanning carbon sinks and cycles as well as technological and nature-based climate solutions. The social sciences and humanities can make critical contributions to socio-political and policy dimensions needed to inform this research and deliver practical results. Transition, innovation, and historical science and technology studies offer insights about the way major systems, such as electricity, transport, and agri-food, have shifted over time. These efforts must also engage with the arts and humanities to envision alternative futures, promote usability, and support learning and attitudinal shifts.

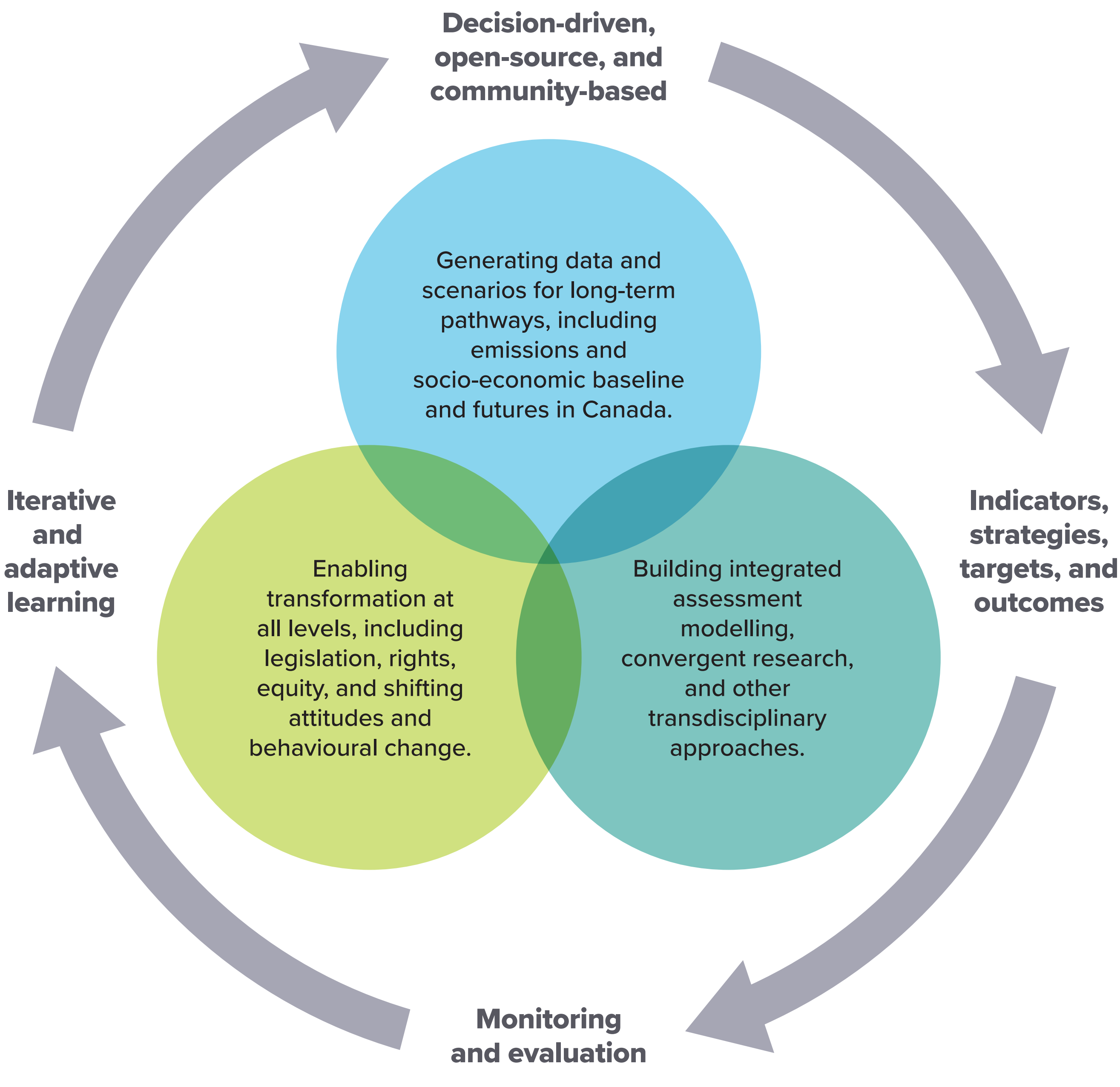


Figure 5.1. Conceptual framework for net-zero pathway science, reflecting iterative knowledge development, evaluation, and monitoring processes.

The research priorities are the following:

R1 (NZP). Build foundational knowledge, including societal and economic considerations, to inform net-zero scenarios for transformational change in Canada.

- Identify trends and socio-economic changes that will drive emissions reductions, through methods such as foresight analysis, futures research, and scenario development (e.g., urbanization, electrification, digitization).
- Conduct economic and integrated assessment modelling that reflects the complexity of the technological, economic, and social spheres, including alternative economic paradigms.
- Analyze and compare pathways through model intercomparison projects (for example, those organized by the World Climate Research Programme or Energy Modelling Forum) and science assessments. In these comparisons, consider environmental objectives unrelated to climate as well as sustainable development.
- Integrate Canadian pathways with regional and global pathways, to understand external influences on Canada's net-zero pathways.

R2 (NZP). Understand socio-political, attitudinal, and behavioural processes in net-zero pathways and improve how these are integrated in modelling and analysis.

- Use attitudinal and behavioural knowledge to understand how Canadians can be empowered to make informed decisions and adopt new practices, for example, through capacity-building and information sharing.
- Bridge social science knowledge with economic, energy, and technology considerations to explore the linkages between regulations and policy, economic incentives, social marketing campaigns, grassroots change, and co-benefits of climate action, to understand their influence on net-zero action.
- Understand the effectiveness of climate policy, incentives, regulations, and jurisdictional governance and responsibilities in order to better tailor net-zero programs so that they resonate with audiences to motivate progress.
- Incorporate diverse forms of knowledge creation and emerging perspectives. These forms include prioritizing new voices that can expand the usability of these approaches as well as Indigenous science and perspectives. Perspectives of youth, gender, and race, and historically and currently marginalized voices are all needed to expand the knowledge base and frames of reference for net-zero futures. This can be achieved through co-producing proposals for changes to the existing systems.

R3 (NZP). Develop a national strategy for modelling net-zero pathways to inform transformational change in Canada.

- Build a community of scientists to work on net-zero pathway models in an open-source, decision-driven research environment. This effort would include integrated assessment modelling and allow transparent model development and intercomparison of models and results. Leveraging international examples and modelling tools, where possible.
- Advance understanding of the potential of concurrent solutions that achieve adaptation, resilience, and sustainable development.
- Better represent socio-economic factors, through systems-based approaches and "futures" research (the study of social and technological advances). As multiple modelling approaches continue to evolve, models should have less uncertainty and respond better to diverse information needs, to inform net-zero planning in various regions and sectors.

- Develop models capable of analyzing net-zero pathways beyond "business as usual" or incremental change as required, in order to reflect the transformative processes for achieving and sustaining net-zero. Current models were designed for a given purpose in a specific context; they must be further developed to explore new scenarios involving radical changes (step changes in technologies but also crises and unexpected developments).

Pathway science capacity in Canada is expanding rapidly, with centres of expertise emerging across society. But greater coordination is needed to make usable and salient information available to guide net-zero pathways. As well, advancing these science priorities requires a vast expansion in systems-based and transdisciplinary approaches. This convergence research topic emphasizes the importance of opening up the pathway development process to multiple disciplinary perspectives and approaches. Pathway development must incorporate open-source data and transparent assumptions, and reflect the range of social, economic, technological, and future climate considerations needed to move Canada rapidly toward its net-zero objective. These approaches will help to establish pathway science capacity in Canada, to build knowledge about the key features of pathways, including technology adoption, uncertainty, norms, culture, politics, equity, and justice. To advance pathway science, the knowledge and capacity in Canada's think tanks; private sector; academic institutions; civil society; arts organizations; First Nations, Inuit, and Métis Peoples and organizations; and governments are all needed. This science will position Canada to envision and move toward a net-zero, resilient future.

5.7. Climate Change Research and Sustainable Development

The Working Group III contribution to the IPCC Sixth Assessment Report finds, with high confidence, that accelerated and equitable climate action is critical to sustainable development, given the strong links among sustainable development, vulnerability, and climate risks. Climate change research and climate action are essential to sustainable development in Canada (see Box 5.7. Sustainable Development). Equitable and meaningful participation of all relevant actors in decision making for mitigation and adaptation is necessary to facilitate the shift toward sustainability.

In Canada, the *Federal Sustainable Development Act* establishes support for sustainable development, with a view to improving the quality of life of Canadians and taking action on climate change. This legislation identifies principles for sustainable development, namely, that it is based on an efficient use of natural, social, and economic resources, and that the Government of Canada needs to integrate environmental, economic, and social factors in making all of its decisions.

Research should focus on understanding how climate action, including mitigation and adaptation, can impact sustainable development. This includes supporting the United Nations sustainable development goals (SDGs), strengthening the science–policy interface, and sharing best practices and experiences in sustainable development.

Box 5.7. Sustainable Development

The meaning of **sustainable development** continues to evolve. In the 1987 Brundtland Report, *Our Common Future*, it was defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." It has been conceptualized as "three pillars" or "nested dependencies," with social, economic, and environmental dimensions. Other concepts of sustainable development also involve substituting technology and skills for benefits traditionally provided by nature or ecosystems.

Among the elements of sustainable development, the **relationships** among social, economic, and environmental elements are integral. Achieving goals in only one dimension is insufficient. Instead, SDGs must be pursued and achieved concurrently. This is why the SDGs are described as **integrated** and **indivisible**.

A **trade-off** refers to an outcome where action on one dimension of sustainable development is observed to *hinder* or *regress* progress toward another dimension of sustainable development.

A **synergy** refers to an outcome where action substantially supports simultaneous progress on multiple dimensions of sustainable development.

A **co-benefit** refers to the positive effects that a policy or measure aimed at one objective might have on other objectives, regardless of its net effect on overall social welfare. Co-benefits (or *ancillary* benefits) are often subject to uncertainty and depend on local circumstances and implementation practices, among other factors.

Despite advances in climate change science and sustainable development, there is a gap in research on how climate actions implemented in Canada either advance or hinder sustainable development, including its social, economic, and environmental dimensions.

The research priority is:

R1 (CCRSD). Examine the relationships between climate action and sustainable development. Research should be specific to the Canadian context and support the SDGs. This includes research to understand how climate action implemented in Canada affects sustainable development, developing equity-based models and analytical frameworks to predict or evaluate the impacts of climate action on sustainable development, and understanding how climate action interacts with socio-economic elements of sustainable development. Gender-based and intersectional (the ways in which systems of inequality intersect) analyses of sustainable development, as well as consideration of interactions between distinctions-based Indigenous science and worldviews are needed to support this research.

5.8. Climate Change and Security

Climate change substantially alters human security, political stability, and security infrastructure (which protects critical systems from threats to their operation). This includes increased frequency of extreme events, impacts on food, water and energy availability, impacts on livelihoods and well-being, increased competition for natural resources, and increased displacement and migration.

Addressing the range of climate change's implications for security is urgent. Without urgent and substantial mitigation and adaptation efforts, climate change will generate increasingly severe, pervasive, and widespread risks for most aspects of natural and human well-being, as well as livelihoods, public safety, and economic performance and resilience. Many climate change impacts have profound implications for safety, vulnerability, and security, as well as for national defence, conflict, and social and geopolitical instability (see Box 5.8. Canada's Defence Operations and Climate Change). Climate solutions to address security considerations need to integrate strategies, policies, and actions to reduce GHG emissions (mitigation). Such solutions should be carried out in tandem with reducing exposure to climate hazards, environmental conservation and protection, and securing well-being for all.[14] Research should inform solutions that are well-timed and align with other economic and environmental policy goals, to avoid exacerbating existing inequities and to favour solutions that enhance equity and justice. Transdisciplinary research is essential to an integrated understanding of the multiple factors that could guide orderly transitions to net-zero and adaptation planning, and sustainable development, while avoiding worsening vulnerabilities.

Box 5.8. Canada's Defence Operations and Climate Change

The growing impacts of a changing climate pose direct and indirect threats to human and national security worldwide. Canada's defence policy, Strong, Secure, Engaged (SSE), recognizes climate change as a security challenge both at home and abroad. In Canada, the effects of climate change are transforming the physical and security landscape, leading to an evolving set of challenges. For example, severe effects such as floods and wildfires are increasingly impacting communities and threatening critical infrastructure.

The Department of National Defence and the Canadian Armed Forces provide critical services for Canada's security, both internationally and nationally. The department plans to better understand demands for military aid during extreme events, such as floods and wildfires, domestically and internationally.

In June 2022, the North Atlantic Treaty Organization (NATO) announced it plans to establish a Climate Change and Security Centre of Excellence (CCASCOE) in Canada, to work cohesively across member nations to develop and promote solutions to climate security challenges by creating new opportunities for collaboration. These solutions include the member countries' shared objectives of mitigating GHG emissions from security activities, as well as adapting and building resilience to climate change.

The science priorities for this nexus topic respond to the top risks identified on a global scale and their impacts in a Canadian context.[15] Research is needed to inform risk assessments on daily to seasonal and decadal scales across Canada, including urgent attention to the more rapidly warming Arctic. Conceptual models, such as those that reflect the risk-multiplier framing, the direct impacts of further climate change in Canada, and the feasibility and effectiveness of mitigation and adaptation actions are needed. This research should enable understanding of security implications as well as collective and co-operative action through analysis of intersecting stressors, related and unrelated to climate. This would include analyses of environmental risks (extreme weather events, biodiversity loss, infectious diseases, and human-caused environmental damage) and social impacts (social cohesion, livelihood crises and coping, natural resource management, food security, energy supply and transition, debt crises, economic and just transition, and gender equity).

Applying a climate change *and* security lens to climate change research could improve our understanding of how climate change affects future development choices, their distributional aspects, and solutions. Such a lens draws on the breadth of environmental, socio-economic, and health data and knowledge that inform Canadian solutions. This research framework can include perspectives outside of Canada's domestic context, to help understand the implications of global responses to climate change for Canada, and inform Canada's contributions to international initiatives (e.g., climate mitigation and adaptation activities, finance, disaster risk management, and foreign aid).[16] This research includes identifying immediate security issues and those anticipated under various future climate scenarios. It involves looking at how these security issues can affect existing geopolitical tensions and the dynamics of violence, conflict, and co-operation. It can also include understanding how safety, health, and humanitarian needs will be identified and met, and how the impacts of climate change can be managed through disaster preparedness and long-term support for

[14] Frequently Asked Questions 6: What is Climate Resilient Development? Climate Change 2022: Impacts, Adaptation and Vulnerability) in IPCC AR6 Working Group II: Impacts, Adaptation and Vulnerability.

[15] World Economic Forum. Global Risks Report 2023.

[16] Government of Canada. Canada's climate finance for developing countries.

sustainable development (for example, in developing countries). There is also a need to assess long-term political, economic, and financial transformations in domestic and global contexts as part of future climate scenarios.

There is limited and fragmented capacity to pursue this research in Canada. Specific science priorities for Canada in this area include the following:

R1 (CCS). Evaluate climate change policy pathways and their security implications. These pathways span multiple future contexts, including those that would result from meeting emissions targets, currently stated Nationally Determined Contributions, or other global emission pathways (see Chapter 5.6. Net-Zero Pathway Science). Evaluating their security implications can better inform decision makers, including implications for geopolitical risks, risks to financial and energy supply systems, humanitarian responses, and Canadian foreign policy. The near-term and longer-term impacts of these pathways on adaptive capacity, ongoing adaptation actions, and resulting resilience need to be understood.

R2 (CCS). Identify the risks and threat-multipliers of climate change for the operations of security institutions and for emergency preparedness and response. Climate change intensifies resource scarcity and worsens existing social, economic, and environmental factors. Research is needed to understand the climate-related impacts on, risks to, and vulnerabilities of the operations of Canada's security institutions and emergency preparedness and response.

R3 (CCS). Develop a suite of security responses to climate change, across relevant contexts and scales. This would include developing collaborative strategies for climate change security that consider interactions between socio-economic factors (e.g., social inequities), and potential alignment with other economic and environmental policy goals.

R4 (CCS). Develop a "system of systems" response to climate change, reflecting the interconnections and cascading responses across social and economic sectors and communities. This includes identifying where climate risks to security may be underestimated ("blind spots") or where impacts may be indirect or difficult to predict. Research needs to consider the Canadian security context as well as broader international considerations to better understand security impacts and inform solutions.

5.9. Social Science and Climate Change

To make a difference, research results must be used—by other researchers, by decision makers involved in setting policies, by practitioners in the public and private sectors, and by members of the public. Behavioural and social science can help identify and study these different audiences and their needs to inform the development of targeted tools, products, and assessments to better communicate and translate climate change science in a way that connects with each group and facilitates climate action.

Social science research results can also inform climate policies, such as regulations, tax measures (disincentives such as carbon pricing and incentives such as tax credits), rebates and similar financial incentives, public health measures, municipal bylaws, and information and promotion programs.

Social science informs effective knowledge mobilization and communication which are critical to bringing research results to decision makers, practitioners, and members of the public. Plans for synthesizing and mobilizing the results of research should be built into every research project, rather than being an afterthought.

To mobilize knowledge, there is a growing role for climate change communication. Best practices, toolkits, and playbooks are emerging to make such communication more effective. Communication strategies draw on social science, particularly behavioural science, to contribute to shifts in attitudes and behaviours across various Canadian audience segments (see Box 5.9. Program of Applied Research on Climate Action in Canada (PARCA Canada)).[17]

However, public opinion research and the UN Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) demonstrate that there is still a need to:

- increase climate literacy;
- address a lack of trust in government and experts;
- respond to misinformation and disinformation; and
- bridge the knowledge gaps between understanding climate impacts and the need for action, in parallel with efforts to motivate that action.

Experts and practitioners have highlighted knowledge gaps in understanding:

- the attitudes and beliefs of Canadian audiences;
- how to reach those audiences effectively; and
- how to evaluate the impact of communication products and delivery on Canadian audiences' attitudes and behaviours toward climate action.

Box 5.9. Program of Applied Research on Climate Action in Canada (PARCA Canada)

Canada's experience and expertise in behavioural science is being applied to climate and environmental action through a multi-year research program, the Program of Applied Research on Climate Action in Canada (PARCA), a collaboration among Environment and Climate Change Canada, Natural Resources Canada, and the Privy Council Office's Impact and Innovation Unit. PARCA is generating evidence about motivations for, and barriers to, climate action. The information will be used to inform policy development, program interventions, and communications.

Communication efforts have a higher chance of success if they are based on the latest scientific knowledge and delivered through clear and coherent communication products. Developing the right message through evidence-based methods, finding appropriate messengers, and choosing the right delivery tool for audience segments are all essential elements of communication strategies.

To mobilize knowledge, climate change communication can draw on social and behavioural science to influence Canadian attitudes and behaviour. Research is still needed to understand Canadian audience segments and develop communication products targeted to them. To build trust with each audience segment, communicators can develop narratives about climate change impacts and action that relate to people's lived experiences and perspectives. Narratives and visuals (illustrations, videos) can help bring complex climate change issues home to Canadians. Misinformation, disinformation, and malinformation about climate change must be countered with a flow of credible information (see Box 5.10. Terms Used in Climate Change Information). Trusted messengers—who may be community members beyond the traditional sources of information—are critical in getting messages out.

[17] For more in-depth discussion, see Council of Canadian Academies. (2023). *Fault Lines: The Expert Panel on the Socioeconomic Impacts of Science and Health Misinformation*.

Box 5.10. Terms Used in Climate Change Information

Misinformation: Information that is false but is created or spread by someone who thinks it is true, without the intention of causing harm (e.g., someone posting an article containing out-of-date information but not realizing it).

Disinformation: Information that is false and deliberately created to deceive or harm (e.g., purposely posting false data with an intent to discredit).

Malinformation: Information based on real information and used to inflict harm on a person, organization, group, or country (e.g., someone using information that is picked selectively and represented out of context to ignite controversy or hatred; or someone responding negatively to a particular ideology, program, or policy).

Science capital: Science-related qualifications, understanding, knowledge (about science and "how it works"), interest, and social contacts (e.g., knowing someone who works in a science-related job).

Audience segmentation: The process of finding strategic subgroups of your target audience, based on shared behaviour, interests, or attributes that indicate how they may respond to marketing.

The "movable middle": Those whose demand for climate action is much lower than their stated concern, representing an overall lack of support for individual and/or collective action.

Knowledge synthesis provides up-to-date research that policy makers can use to inform evidence-based decisions and make progress towards mitigation and adaptation goals. In fact, scientific evidence can motivate action by illustrating the impacts of climate change and therefore the urgent need for climate action.

Knowledge synthesis includes periodic assessments of the state of knowledge, every five to 10 years, with more frequent updates and targeted products as needed. There are existing assessments on a variety of topics, including climate change science, climate change and health, and national and regional climate change impacts and adaptation. New assessments are needed on topics such as carbon cycle science and motivating climate change action. Translation of science is also needed to develop tools, products, and services that are relevant for policy and decision making.

To date, knowledge synthesis has mainly taken the form of reports assessing and summarizing the current science results. These include the federal government's report series *Canada in a Changing Climate: Advancing our Knowledge for Action*, including *Canada's Changing Climate Report*, *National Issues Report*, *Health of Canadians in a Changing Climate*, and reports on regional, national, northern, and Indigenous issues. Many non-governmental organizations (David Suzuki Foundation, Clean Prosperity for Canadians, Pembina Institute, among others) also include research results in their reports, often as the evidence base for their recommendations.

Research priorities for social science, as it relates to climate change, are the following:

R1 (SSCC). Understand Canadian audience segments and develop communication products that target these audiences. Research is needed to understand audience segments in Canada, including attitudes, beliefs, values, and biases in various demographic, regional, socio-economic, and sectoral groups. Segments can be identified from research and statistical analyses of demographic, socio-cultural, contextual, or situational factors. Understanding audience segmentation will help develop communications that target various audiences. It will also inform which communication channels (web sites, traditional news media, social media) and types of media (reports, social media posts, illustrations or infographics, videos) should be used.

To build trust, communicators must also understand what constitutes credible evidence for each audience type. Sectors more affected by government policy and regulation are particularly important to reach, to achieve high levels of policy and regulatory compliance.

R2 (SSCC). Develop narratives about climate change impacts and action to empower Canadians, inspire hope, and accelerate societal transformation. Communicators must develop narratives about climate change impacts and action that empower and inspire the Canadian audience segments identified. Participatory research[18] methods, which involve a systematic inquiry conducted in collaboration with those affected by an issue, can help inform this communication. These approaches—among others—can build a connection between people and their experience of climate change, to understand and inform action. (See Box 5.11. Lessons from Public Health for Effective Climate Change Communication and Box 5.12. The Monitoring and Evaluating Climate Communication and Education (MECCE) Project.)

Narratives[19] or storylines contextualize scientific information so that it relates to people's lived experiences and perspectives. This communication approach is grounded in engagement with target audiences. Narratives can help Canadians make sense of the data on climate variability and change, GHG emissions, and other topics, in terms of current impacts, risks, and future scenarios.

Box 5.11. Lessons From Public Health for Effective Climate Change Communication

The public health community has decades of experience in communicating health risks to Canadians in order to shape behaviour. Climate change communication can draw from this rich experience. A dedicated effort to learn from advances in health and pandemic-related knowledge is needed to translate this experience and its impact on human behaviour to climate action. The health research community mobilized rapidly and worked directly with health policy decision-makers and practitioners in response to COVID-19, for example, which has immediate lessons for climate communication.

Box 5.12. The Monitoring and Evaluating Climate Communication and Education (MECCE) Project

The MECCE Project's goal is to advance global climate literacy and action by improving the quality and quantity of climate change education, training, and public awareness. It is a Canadian-led academic international research partnership of over 80 leading scholars and agencies, based at the University of Saskatchewan. The MECCE Project is supporting transformation through intersecting areas of research and mobilization of action on climate change communication and education, in alignment with the United Nations Framework Convention on Climate Change (UNFCCC) Action for Climate Empowerment commitments.

R3 (SSCC). Understand public trust and information flow to support the communication of credible information, while limiting the spread of incorrect or misleading climate information. Trust is a key factor in how people consume and act on information. The critical role of messengers matters as much as the message itself. Research on effective framing and other approaches from social and psychological sciences would be beneficial to identify a diverse pool of messengers with whom to co-develop climate action narratives. Different audience segments may also require different communication approaches. For some audiences, emphasizing knowledge systems and responding to existing social issues affecting them helps build trust. For many Canadians, visual features, such as illustrations and videos, helps them make sense of complex information.

[18] Vaughn, L. M., & Jacquez, F. (2020). Participatory Research Methods—Choice Points in the Research Process. *Journal of Participatory Research Methods, 1*(1). https://doi.org/10.35844/001c.13244

[19] For an overview of environmental narratives, see Lejano, R., Ingram, M., & Ingram, H. (2013). *The Power of Narrative in Environmental Networks*. MIT Press.

Supporting the flow of credible information is key. Understanding how information spreads; how messengers are perceived as credible; and who spreads misinformation, disinformation, and malinformation is central to understanding information flows. This understanding could also contribute to mitigating the harmful effects of false or misleading information and to co-developing accurate, objective, and empowering climate narratives with trusted members of communities.

Thus, knowledge mobilization is not the final step in research but an ongoing effort involving co-development with the intended audiences. It provides a crucial link between science and climate action by contributing to the shifts in attitudes and behaviours needed to reduce GHG emissions and take adaptation action. In this way, knowledge mobilization makes an important contribution to achieving the United Nations Framework Convention on Climate Change (UNFCCC) Action for Climate Empowerment goal to empower all members of society to engage in climate action.[20]

The knowledge synthesis and mobilization priority is to:

KM1 (SSCC). Conduct regular, substantive science and knowledge assessments (on a five- to 10-year cycle), complemented by shorter, more frequent updates and targeted products. Experts emphasized the importance of updating such reports regularly (such as every five to 10 years), as well as more frequent and shorter updates (see Chapter 4.1. Healthy and Resilient Canadians and Chapter 5.2. Carbon Cycle Science on the importance of such assessments for health and for carbon cycle science, respectively). The assessments discussed included both existing assessments on climate change science and on climate change and health, as well as new assessments on the carbon cycle and motivating climate action.

Experts also stressed the need to conduct science and knowledge assessments of Canada's regions as well as for the country as a whole. Past reports have targeted specific regions of Canada or have included a regional breakdown, as regional assessments are useful to provincial, territorial, and municipal governments, as well as to Indigenous communities. Such regional assessments should consider social, cultural, ecological, and environmental outcomes, as well as climate change impacts on health, food security, and the environment. The Northern Canada chapter of the *Canada in a Changing Climate: Regional Perspectives Report* was released in 2022. Continuing assessments for northern Canada are critical because of the faster rate of warming in the region and the dependence of northern communities on land, oceans, and ice for food, transportation, and culture.

These assessments can also help efforts to build climate literacy among members of the public and climate competencies among professionals and practitioners in many fields who must integrate climate considerations into their work.

There is also a need to create climate data and information products tailored to specific economic and industrial sectors (e.g., health, infrastructure, natural resources), so that the data can be readily accessed and applied to inform policy and decision-making. As well, information streams and products that target urban, rural, coastal, remote, and Indigenous communities can help in local decision making. These should be available on geographic scales and time scales that are relevant to policy and decision making and should cover aspects of climate useful to communities, such as extreme events, health, and water resources.

[20] Action for Climate Empowerment | UNFCCC.

Chapter 6. Moving the Climate Change Science Agenda Forward

Summary

Several overarching considerations were raised during engagements for the development of this report.

Data infrastructure is an important prerequisite to climate change science. Hubs, platforms, and supercomputers are needed for storage, processing, and analysis of large volumes of data. Rapidly advancing technology in this area will help scientists collect more information at greater resolution. This technology includes cloud-based systems that permit secure sharing of large data sets, artificial intelligence, and "big data" technologies. Datasets should cover not only climate, ecosystem, and biodiversity data but also human indicators such as socio-economic and health data. Data platforms should apply international standards, allowing Canadian scientists to contribute to and gain access to international datasets.

"Open science" involves making the whole process of science openly available to all. In this regard, climate change datasets should meet the FAIR principles (findable, accessible, interoperable, and reusable). The Government of Canada has committed to open science for its scientific operations, and specifically for information on the impacts of climate change. However, open science must be balanced with ethical considerations, protecting private data about people and respecting data sovereignty and intellectual property rights. Collection and analysis of data involving First Nations people must follow the First Nations OCAP (ownership, control, access, and possession) principles, and data involving Inuit communities must follow the National Inuit Strategy on Research.

Science in Canada, and climate change science in particular, lacks national coordination. The current fragmented system is difficult to navigate, creates roadblocks to collaboration, and fails to bridge science results with policy making. Science networks have been an effective way to enable transdisciplinary collaborative research in specific areas. Focused efforts to convene and encourage further collaborative research are required.

Canada has benefited from participation in international efforts to understand climate change. Canadian data and knowledge must meet rigorous quality and accuracy standards to be included in these efforts. Among the many international efforts Canada is involved in are global and regional science assessments, global monitoring programs, emissions information initiatives, and transdisciplinary research programs.

The priority science activities that this report recommends will increase the creation, dissemination, and use of climate-related information across Canada. The objective is to advance the tools, services, policies, and programs essential to meeting the challenges ahead in creating a resilient, net-zero Canada.

This report has focused on the priorities for Canadian climate change science most relevant to informing climate action and evaluating progress. All of the priorities identified can help Canada reach its objectives for net-zero GHG emissions and climate change adaptation. While research and development and technological innovations are outside the scope of this report, the science priorities overlap with R&D objectives for clean technology and emissions reductions in various sectors.

The experts who contributed to this report were unanimous in emphasizing the urgency of climate action. They noted that there is already a substantial knowledge base to guide GHG emissions reductions and strengthen adaptation efforts. Continuing scientific research will help climate action to evolve by better characterizing risk, evaluating the effectiveness of mitigation and adaptation approaches, measuring progress, and identifying new opportunities for action.

To advance the agenda set in this report, several overarching issues relevant to many priorities need to be addressed. These issues were raised repeatedly during engagements and underpin the priorities:

- data infrastructure
- open science
- national coordination
- international engagement

6.1. Data Infrastructure

Data infrastructure, including hubs, platforms, and supercomputing resources, enables the storage, processing, and analysis of the large volumes of data produced by climate change science activities. This data is then used to inform further research and modelling efforts, as well as customized information products for activities such as climate services. While governments and other organizations currently operate many data hubs and platforms, rapid technological advances in monitoring approaches (surface, ocean, and space-based), data collection, and analytics present opportunities to collect more information, with greater spatial and temporal resolution.

Fundamental to climate and Earth system modelling is supercomputing infrastructure. Such infrastructure should be collaboration-oriented, including cloud-based systems that permit secure sharing of large datasets. Artificial intelligence and "big data" technologies for automated management of large datasets and integration and validation of models should be prioritized.

Once data has been gathered and analyzed, access to relevant data and to supercomputing infrastructure remains an obstacle for the research community. Datasets also need to be interoperable, so that data from multiple datasets can be analyzed to discover relationships and trends. This is especially important to enable transdisciplinary research, which may use climate data in conjunction with environmental, socio-economic, and health data. Sophisticated data platforms are needed to facilitate contributions from a diverse range of public and private sector sources and observation systems. Analytics must enable access to data from different sources, in various formats. "Data catalogues" should be developed so that users can find integrated and interoperable data.

The data infrastructure science priority is to:

R1 (Data). Create, maintain, and strengthen accessible and interoperable platforms for data on climate, greenhouse gases (GHGs), ecosystems and biodiversity, and related socio-economic, and health indicators. Platforms on climate data (terrestrial, hydrological, ocean, and atmospheric) must provide this data at multiple scales to support research and reporting on regional to national scales. This must include:

- necessary digital space for the platforms, data, and **data analytics** tools;
- **awareness-building and training** so that the platforms can be used by all those involved in climate change science; and
- **national governance** to enable coordination and to support contributions across relevant platforms (federal, provincial, academic, private sector); to sustain and manage contributions; to implement and sustain the technical infrastructure; and to develop user protocols respecting needs of contributors and science users.

> The data platforms must represent a scientific and authoritative source of climate change data. They should include integrated tools for analytics and reporting to better inform research and decision making for both the public and private sectors. The platforms, datasets, and analytics should then be used by climate services to provide operational, near-real-time applications, as well as longer-term reporting (see also Chapter 6.2. Open Science).

Federal government leadership, as well as contributions from Indigenous, provincial, territorial, academic, non-governmental, and private sector organizations, can build on current efforts, such as the following:

- the **Fifth National Action Plan on Open Government—Climate Change and Sustainable Growth Commitment:** the Government of Canada plans to enhance access to timely climate and environmental science, information, and data, working in partnership with other levels of governments, businesses, Indigenous Peoples, and citizens;
- the **Canadian Centre for Climate Services** and regional climate services organizations;
- a **climate data strategy** to support access to the range of climate change data holdings of the federal government;
- the Statistics Canada **Census of Environment**; and
- the emerging **Digital Earth Canada** platform for a networked system based on Earth observations.

Data platforms should apply existing international standards, so that Canadian scientists can contribute and gain access to international datasets. Such standards also ensure that science outcomes are comparable across countries and can be used in international policy making.

6.2. Open Science

Open science involves making science openly available to all—scientists, policy makers, and the public—from design through methods and results. Open science is critical to public dialogue about climate science, helping to improve understanding and public confidence.

A critical component of open science is open-access datasets that uphold the FAIR principles; such datasets should be integral to all aspects of climate change science. Open, interoperable data platforms are particularly important to collaborative and multidisciplinary research that combines datasets from multiple fields (see 6.1. Data Infrastructure).

Canada's commitment to open science was reflected in Canada's 2018–2020 National Action Plan on Open Government, which committed to developing an open science roadmap for the Government of Canada. The resulting Roadmap for Open Science, published in 2020, provides overarching principles and recommendations to guide these activities in Canada. The recommendations are intended for science and research funded by federal government departments and agencies.

In response to the roadmap, federal departments and agencies have designated Chief Scientific Data Officers and published open science action plans. The three federal granting bodies (the Natural Sciences and Engineering Research Council, the Social Sciences and Humanities Research Council, and the Canadian Institutes of Health Research) have policies on open access and research data management intended to improve access to research findings and data funded by these bodies, and to disseminate research results.

The updated 2022–2024 National Action Plan on Open Government went a step further by including a commitment to give people access to the information and tools they need to better understand the impacts of climate change. During consultations on the action plan, Canadians said the Government of Canada needs to better communicate and engage with citizens on its decisions and on its progress on combatting climate change and ensuring sustainable growth. With this in mind, the Government of Canada has committed to enhancing access to timely climate and environmental science, information, and data. The federal government will also help other levels of governments, businesses, Indigenous communities and organizations, and citizens better understand climate change and its impacts on ecosystems.

Open science must be balanced with ethical considerations, mainly involving protection of data. Data platforms must reflect user protocols for appropriate use—preserving anonymity and privacy for data about people, as well as respecting data sovereignty and intellectual property rights.

In this regard, the governance and stewardship of First Nations, Inuit, and Métis knowledge systems must be respected, as required under the United Nations Declaration on the Rights of Indigenous Peoples. Data collection and analysis must be informed by specific protocols and rights regimes, such as the First Nations principles of OCAP® (ownership, control, access, and possession). The National Inuit Strategy on Research also prioritizes Inuit access, ownership, and control over data and information. Data priorities must align with best practices identified by the First Nations Information Governance Centre and the National Inuit Strategy on Research. These principles and practices provide inclusive, respectful mechanisms for the co-development of knowledge with Indigenous Peoples.

6.3. National Coordination

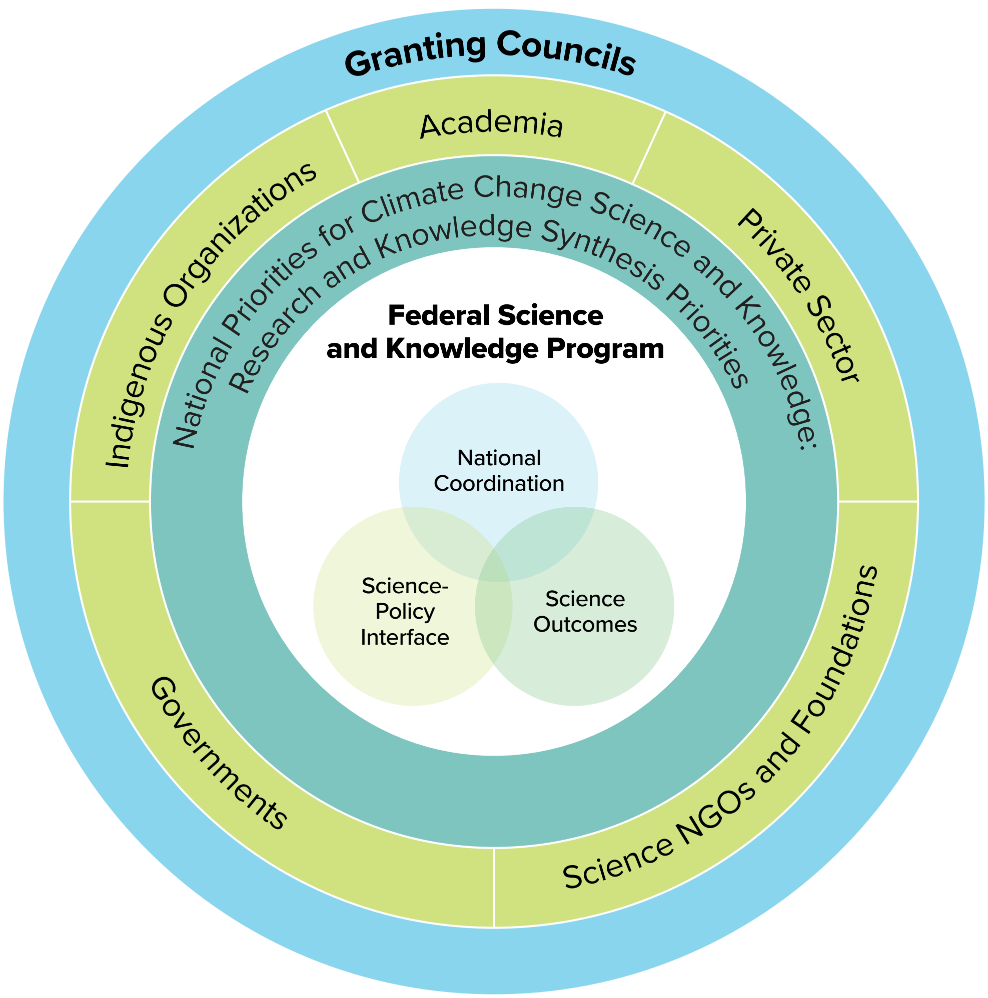


Figure 6.1. Schema showing role of organizations and priorities in climate change science.

Coordination of science, including climate change science, remains largely ad hoc in Canada. Science activities are often carried out in a distributed or fragmented way; as a result, these activities may not be strategic or integrated on a national scale.

National coordination is challenging, because Canada has a broad range of people and organizations participating in climate change science, from government to non-government organizations, universities, Indigenous organizations, communities, and the private sector (Figure 6.1). The current system is difficult to navigate for individuals or organizations looking to collaborate within or across disciplines (multi-, inter-, and transdisciplinary research), or across sectors. The priorities identified in this report will be more successful if they are accompanied by stronger national science coordination as well as stronger relationships between the science community and policy makers.

The engagement to develop this report highlighted some examples of areas important for national coordination:

- **Net-zero pathway science:** Collaborative networks or centres of excellence among government, universities, and think tanks are needed to build knowledge, as well as to engage effectively in, and to draw from, rapidly growing international activity in data and modelling (see Chapter 5.6 Net-Zero Pathway Science).
- **Earth system climate and carbon cycle science:** Although Earth system research in Canada is respected internationally, increased coordination and a more strategic approach across institutions could improve national capacity further. As emphasized in the 2019 Canadian Carbon Cycle Research Workshop, an integrated national network approach to carbon cycle research is essential to improve the understanding of Canadian carbon sources and sinks (see Chapter 5.2 Carbon Cycle Science).
- **Climate change communications and motivating action:** A community of practice on communications strategies and behavioural change is needed. Such a community could organize forums and conferences to allow communicators from diverse knowledge systems, including Indigenous knowledge and traditional science and knowledge, to contribute to climate change narratives (see Chapter 5.9 Social Science and Climate Change).
- **Science-policy dialogue:** Dialogue is needed to inform policy makers of scientific results and research advances, and to help the science community understand the information needs of those designing and implementing climate action. The federal government can create opportunities for science-policy dialogue to:
    - inform prioritization of science activities;
    - facilitate collaborative research partnerships and funding; and
    - serve as a conduit for science outcomes to inform national climate action.

Development of mechanisms and structures to improve national coordination is the next step. Funding opportunities are needed to enable multi-partner, transdisciplinary research frameworks, including private sector and foundation funding, diverse actors, and multiple knowledge systems.

Science networks can enable transdisciplinary collaborative research, as well as knowledge synthesis and mobilization, across the diversity of science communities. Networks, such as ArcticNet, Marine Environmental Observation, Prediction and Response (MEOPAR) Network, and PermafrostNet, have been effective in advancing climate change science in Canada.

Box 6.1 summarizes some of the considerations in developing national coordination capacity.

Box 6.1. Creating National Coordination Capacity

National coordination of climate change science is challenging but increasingly needed. Convening science communities helps build collaborative research partnerships and plan scientific activities strategically.

There are various models for science coordination; one model discussed during the engagement was a secretariat-type organization for Canadian climate change science. Such an organization would facilitate strategic planning and relationship-building, and advise on how to achieve policy outcomes.

Among its objectives, a coordination organization should include the following:

- Science policy dialogue between experts and decision makers at all levels
- National, multidisciplinary climate change science priorities
- Interdisciplinary science networks and collaboration among governments, academia, non-government organizations, the private sector, Indigenous partners, communities, and international partners
- Science assessments, knowledge products, and science advice

It could fulfil the following functions:

- Coordinate the national community to provide standards for measurements, data, and modelling
- Convene networking opportunities, so that researchers can find partners within and across disciplines
- Identify grand science challenges that require interdisciplinary approaches
- Communicate authoritative science and knowledge on climate change; combat disinformation
- Enable collaboration through interdisciplinary, intersectional, and interjurisdictional research

6.4. International Engagement

Climate change is a global issue; Canada's changing climate and opportunities for climate action contribute to larger international science efforts to understand climate change. Canadian science benefits from participation in international science programs. To participate, Canadian data and knowledge must meet rigorous scientific standards for quality and accuracy.

Canadian scientists have taken leadership roles—and Canadian science results have been included—in global and regional science assessments produced by the Intergovernmental Panel on Climate Change and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. As well, Canadian researchers contribute to the assessments and reports of the Arctic Council, which provide a critical pan-Arctic perspective on climate change, biodiversity, health, and sustainable development, among other topics.

Canadian participation in global monitoring programs enables our scientists to access the breadth of monitoring technologies, platforms, and databases. This is particularly important in Earth system climate science, where global surface, ocean, and space-based observations are essential to understand Earth systems. Canada is a member of the international Group on Earth Observations (GEO) network, which supports United Nations programs for the environment, climate, ocean, sustainable development, and disaster risk reduction. Canada participates in several Earth system global observing networks, including the Global Atmosphere Watch Programme, the Integrated Global Greenhouse Gas Information System (IG3IS), and the Global Ocean Observing System. The European Union's Copernicus Earth Observation Programme agreed in 2022 to share data reciprocally with the Canadian Space Agency; further cooperation with Copernicus would benefit multiple science priorities.

Because Canada's emissions information is used as input to Earth system climate modelling, Canada provides data consistent with the contributions of other countries. Consistency and comparability in global information allow Canada to evaluate progress toward net-zero and assess future climate risks. Canada's data contribution strengthens Canada's position at the UNFCCC and other environmental policy tables. Canadians have been involved in international emissions initiatives, including the IPCC Task Force on National Greenhouse Gas Inventories, the International Methane Emissions Observatory, and the Global Fire Emissions Database.

Canada's current engagement in international research organizations and consortia provides opportunities for Canadians to contribute to leading-edge international science. These include many disciplinary and transdisciplinary research programs and strategic planning exercises, such as the World Climate Research Programme; the United Nations' Global Alliance for Buildings and Construction (GlobalABC); the International Council for Research and Innovation in Building and Construction's New Task Group on Nature-based solutions for climate-resilient buildings and communities; the Integrated Assessment Modeling Consortium; the Food and Agriculture Organization's Global Soil Partnership; and the Global Research Alliance on Agricultural Greenhouse Gases.

6.5. Conclusion

Canadians are already seeing climate-related changes and extreme events across the country. These changes and events have significantly affected people, businesses, communities, and the environment, and they will continue to do so. To address these impacts, decision making needs to incorporate climate change science and knowledge considerations, more urgently than ever before.

This report is part of a broader effort to enable urgent climate action and strengthen the resilience of natural and human systems to the impacts of climate change. It emphasizes monitoring, data, modelling, research, and analysis as the evidence base for action. The report recommends priority science activities across several themes that will increase the creation, dissemination, and use of climate-related information across Canada. The report's ultimate objective is to advance the tools, services, policies, and programs essential for GHG emissions mitigation and climate change adaptation.

The urgency of climate mitigation and adaptation action requires effective deployment of national science resources. Everyone in the climate change science and knowledge community will have a part to play in ensuring that climate action is based on the best available science. This report aims to guide climate change science and enable greater coordination of the science for delivery of results over the next five to ten years. The next step is for those across the Canadian climate change science community to use this report to guide science investments, coordinate and plan research activities, and mobilize the necessary knowledge to support and inform a more resilient, net-zero future for Canada.

Annex – Climate Change Science Priorities

The following are the science activities identified as important areas for **research** and **knowledge mobilization**.

Acronyms

- Research priority – R
- Knowledge Mobilization priority – KM
- Indigenous Science and Knowledge – ISK

Indigenous Climate Change Science and Knowledge (ISK)	
ISK1.	Develop Indigenous leadership in climate change science and Indigenous science networks; support science and knowledge clusters and networks that actively build relationships with Indigenous Peoples in creating pathways that respect local grassroots climate science concerns and priorities.
ISK2.	Braid and weave Indigenous and Western science planning and implementation with Indigenous governments, organizations, and citizens to craft approaches to climate change science and knowledge that are relevant to regions, based on distinctions, and uphold Indigenous rights and self-determination.
ISK3.	Create materials for Indigenous climate change science and knowledge that are responsive to Indigenous Peoples' goals of cultural revitalization, and develop policies, programs, and initiatives respecting Indigenous languages.
ISK4.	Strengthen scoping and funding mechanisms to establish Indigenous science research capacity.
ISK5.	Train and build capacity in Indigenous local and regional place-based science and knowledge practice.
Healthy and Resilient Canadians (HRC)	
R1. (HRC)	Understand the impacts of climate change on health and health systems, to advance effective, equitable, and feasible measures for health adaptation.
R2. (HRC)	Conduct research to support the transition to a sustainable, low-carbon health system.
R3. (HRC)	Improve understanding of policies, programs, measures, and new technologies available to health authorities and their partners to develop low-carbon and sustainable health systems.
KM1. (HRC)	Conduct regular national, regional, and local-scale assessments of climate change and health.
KM2. (HRC)	Develop innovative strategies and approaches for knowledge exchange among health professionals, practitioners, and administrators.
KM3. (HRC)	Effect behavioural change among decision makers, stakeholders, and the public by improving strategies for effective communication of the health risks of climate change, adaptation options, and the health benefits of proactive action.

Resilient Net-Zero Communities and Built Environment (RNCBE)	
R1. (RNCBE)	Generate climate data, predictions, and projections to inform risk assessment, adaptation, and actions to reduce greenhouse gas (GHG) emissions for the built environment.
R2. (RNCBE)	Create maps of multiple hazards to identify and prioritize high-risk areas, manage interdependencies, and address potential cascading risks to infrastructure systems.
R3. (RNCBE)	Expand the use of performance-based design to find innovative construction and operating solutions.
R4. (RNCBE)	Develop and apply an equity-based lens to better inform climate change adaptation and GHG emission mitigation actions.
R5. (RNCBE)	Inform the transition to low-carbon buildings, transport, and infrastructure.
R6. (RNCBE)	Improve understanding of nature-based solutions for use in the built environment.
KM1. (RNCBE)	Develop guidance for effective governance, coordination, and implementation of various adaptation and mitigation measures at various levels of government and at various phases of infrastructure life cycles.
KM2. (RNCBE)	Translate research results into guidance, protocols, and tools for practitioners to help them develop low-carbon, resilient built environments.
KM3. (RNCBE)	Incorporate behavioural science and understanding of the socio-economic contexts to foster climate action in the building, transport, and infrastructure sectors.
KM4. (RNCBE)	Advance methods, tools, and technology to benchmark and increase community resilience, including investments in climate action.
Resilient Aquatic and Terrestrial Ecosystems (RATE)	
R1. (RATE)	Better understand climate change impacts on ecosystems and biodiversity resilience and change.
R2. (RATE)	Advance multidisciplinary science and knowledge to inform climate adaptation solutions that promote resilient ecosystems in a changing climate.
KM1. (RATE)	Synthesize and mobilize knowledge of ecosystem resilience to support and improve adaptive management and evidence-based decision making in a changing climate.

Sustainable Natural Resources (SNR)	
R1. (SNR)	Understand how natural resource sectors in Canada are affected by climate change.
R2. (SNR)	Develop and track indicators of social-ecological resilience in natural resource sectors and communities and understand how these sectors contribute to climate action.
R3. (SNR)	Use collaborative research and transdisciplinary approaches to explore mitigation and adaptation actions, trade-offs, and benefits across natural resource sectors.
KM1. (SNR)	Develop relevant tools to enable evidence-based climate actions for all levels of policy and decision making.
KM2. (SNR)	Incorporate behavioural and social science in decision making and communication strategies specific to each sector.
Informing Progress Towards Net-Zero Greenhouse Gas Emissions (IPNZ)	
R1. (IPNZ)	Enhance GHG data reporting by making advances in measuring and modelling GHG emissions and reconciling complementary techniques for estimating emissions.
R2. (IPNZ)	Monitor, analyze, and assess changes in ecosystem carbon stocks.
R3. (IPNZ)	Better understand the contribution of land use and land-use change to achieving net-zero by developing land-use monitoring systems with high spatial resolution.
R4. (IPNZ)	Examine trade-offs involving GHG emissions and removals in economic, policy, health, and social spheres of Canadian society.
KM1. (IPNZ)	Reconcile publicly available data, information, and knowledge needed to inform calculation of emissions.
KM2. (IPNZ)	Conduct intercomparisons and make improvements to ecosystem models to understand anthropogenic drivers of carbon change in the land sector.
Predicting and Projecting Climate Extremes and Extreme Events (PPCEE)	
R1. (PPCEE)	Improve predictions and projections of extremes, on time scales of seasons to decades, and on kilometric spatial scales.
R2. (PPCEE)	Improve monitoring, data collection, and accessibility.
R3. (PPCEE)	Co-develop approaches to monitoring, conducting research, and predicting climate change with affected communities, including municipalities and First Nations, Inuit, and Métis communities.
KM1. (PPCEE)	Synthesize and mobilize existing knowledge on the physical science of climate change, including extremes.

Carbon Cycle Science (CC)	
R1. (CC)	Conduct collaborative research in Earth system modelling and in understanding the carbon cycle.
R2. (CC)	Monitor carbon stocks to understand their responses to changing climate conditions and disturbances.
R3. (CC)	Improve, compare, and apply ecosystem models to estimate carbon fluxes on a national scale.
KM1. (CC)	Undertake regular science assessments of the carbon cycle and the potential for increased carbon uptake in Canada.
Water-Climate Nexus Science (WCN)	
R1. (WCN)	Understand future water sustainability, including supply, demand, quality, and effects on human and ecosystem health.
R2. (WCN)	Model water-related risks to the health of humans and ecosystems as well as the burden of disease (illness and death) due to further warming.
Arctic Climate Change Science (ACC)	
R1. (ACC)	Understand climate change influences on traditional and cultural activities.
R2. (ACC)	Conduct research to support secure and sustainable food systems, along with surveillance of the exposure of northerners to emerging food- and water-borne infectious diseases, contaminants, and parasites.
R3. (ACC)	Conduct hazard mapping, vulnerability assessments, and adaptation planning for built infrastructure in northern communities.
R4. (ACC)	Design monitoring programs that integrate surface observations and satellite data (existing and planned missions), to track key climate indicators and determine risks from changes in disturbances (such as wildfires and melting sea ice).
R5. (ACC)	Advance and evaluate Earth system modelling to better represent the atmospheric, cryosphere, hydrological, oceanographic, ecological, and carbon cycle processes in northern regions.
KM1. (ACC)	Co-develop a distributed approach to delivering climate services for northern communities to inform evidence-based decision making.
One Health and Climate Change Nexus Science (OHCC)	
R1. (OHCC)	Strengthen understanding of risks and drivers of change across the human, animal, plant, and environment interfaces.
R2. (OHCC)	Advance transdisciplinary approaches as well as First Nations, Inuit, and Métis ways of knowing in knowledge-sharing, data braiding, and analytics.
KM1. (OHCC)	Develop decision support and visualization tools that are transdisciplinary and interactive, supporting decision making and ecosystem management.

Net-Zero Pathway Science (NZP)	
R1. (NZP)	Build foundational knowledge, including societal and economic considerations, to inform net-zero scenarios for transformational change in Canada.
R2. (NZP)	Understand socio-political, attitudinal, and behavioural processes in net-zero pathways and improve how these are integrated in modelling and analysis.
R3. (NZP)	Develop a national strategy for modelling net-zero pathways to inform transformational change in Canada.
Climate Change Research and Sustainable Development (CCRSD)	
R1. (CCRSD)	Examine the relationships between climate change and sustainable development.
Climate Change and Security (CCS)	
R1. (CCS)	Evaluate climate change policy pathways and their security implications.
R2. (CCS)	Study the risks and threat-multipliers of climate change for the operations of security institutions and for emergency preparedness.
R3. (CCS)	Develop a suite of climate change responses, in all contexts, at the local, regional, national, and international levels.
R4. (CCS)	Develop a "system of systems" response to climate change, reflecting the interconnections and cascading responses across social and economic sectors and communities.
Social Science and Climate Change (SSCC)	
R1. (SSCC)	Understand Canadian audience segments and develop communication products that target these audiences.
R2. (SSCC)	Develop narratives about climate change impacts and action to empower Canadians, inspire hope, and accelerate societal transformation.
R3. (SSCC)	Understand public trust and information flow to support the flow of credible information, while limiting the spread of incorrect or misleading climate information.
KM1. (SSCC)	Conduct regular, substantive science and knowledge assessments (on a five- to 10-year cycle), complemented by shorter, more frequent updates and targeted products.
Data Infrastructure (Data)	
R1. (Data)	Create, maintain, and strengthen accessible and interoperable platforms for data on climate, greenhouse gases, ecosystems and biodiversity, and related socio-economic and health indicators.