Canadian Taxonomy: Exploring Biodiversity, Creating Opportunity

The Expert Panel on Biodiversity Science

Council of Canadian Academies
Conseil des académies canadiennes

Science Advice in the Public Interest

CANADIAN TAXONOMY: EXPLORING BIODIVERSITY, CREATING OPPORTUNITY

The Expert Panel on Biodiversity Science

It is interesting to contemplate an entangled bank, clothed with many plants of many kinds, with birds singing on the bushes, with various insects flitting about, and with worms crawling through the damp earth, and to reflect that these elaborately constructed forms, so different from each other, and dependent on each other in so complex a manner, have all been produced by laws acting around us. [...] There is grandeur in this view of life, with its several powers, having been originally breathed into a few forms or into one; and that, whilst this planet has gone cycling on according to the fixed law of gravity, from so simple a beginning endless forms most beautiful and most wonderful have been, and are being, evolved.

Darwin, Charles R. (1859). *On the origin of species by means of natural selection, or the preservation of favoured races in the struggle for life*. (First ed.). London: John Murray.

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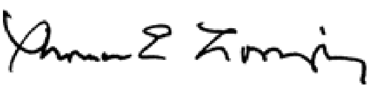

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The reviewers assessed the objectivity and quality of the report. Their submissions — which will remain confidential — were considered fully by the Panel, and many of their suggestions were incorporated into the report. They were not asked to endorse the conclusions nor did they see the final draft of the report before its release. Responsibility for the final content of this report rests entirely with the authoring panel and the Council.

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Elizabeth Dowdeswell, President
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Appendices available at: www.scienceadvice.ca/biodiversity

Executive Summary

The diversity of life on earth is an irreplaceable natural heritage crucial to the function of the biosphere and human well-being. Biodiversity is being lost in Canada and around the world at a rate unprecedented in human history, with massive consequences to ecosystems, culture, the economy, innovation potential, and society. The five major drivers of this biodiversity loss are habitat loss, exploitation, pollution, climate change, and invasive species.

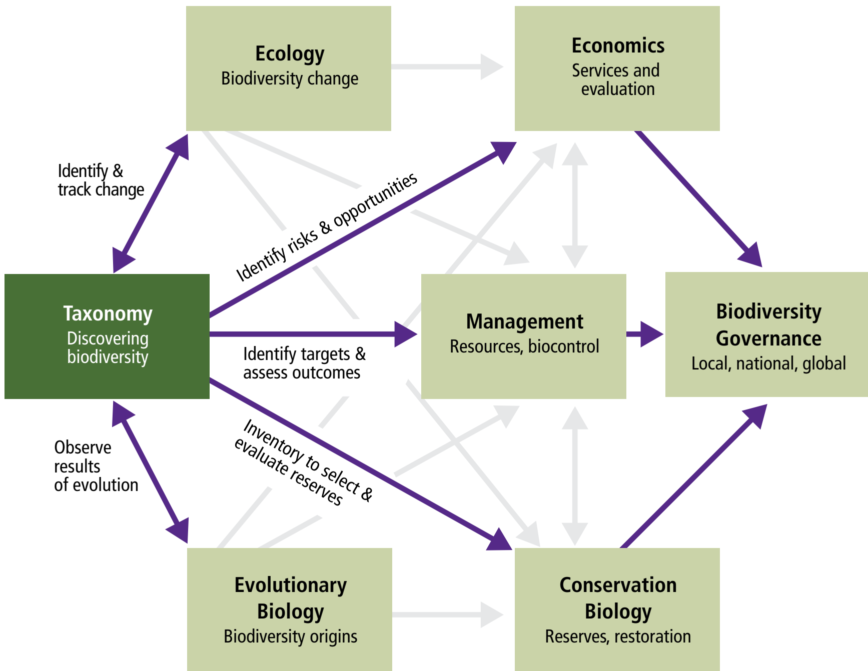
TAXONOMY: THE FOUNDATION OF BIODIVERSITY SCIENCE

Current environmental problems associated with rapid biodiversity change cannot be solved by conventional and narrowly focused approaches. Biodiversity science has emerged as a transdisciplinary field that uses tools and theories from many areas of study. Taxonomy — research that discovers, distinguishes, classifies, and documents living things — is foundational; advances in biodiversity science are built upon the discovery and accurate identification of the species that compose ecosystems (see Figure 1).

Against this backdrop, the Minister of Canadian Heritage, on behalf of the Canadian Museum of Nature, asked the Council of Canadian Academies to appoint a multidisciplinary expert panel to assess the state and trends of taxonomic science in Canada. Discovering and characterizing species requires Canadian scientists, empowered by leading technologies, to contribute to collections and databases as part of a global biodiversity science. The Expert Panel on Biodiversity Science believes that this report is the most comprehensive, up-to-date assessment of Canada's taxonomic expertise and biodiversity collections, and of its efforts to make taxonomic information available via open access online data.

CANADIAN EXPERTISE IN TAXONOMIC RESEARCH

Despite Canada's history of world-class contributions to taxonomic research, the Panel's examination of the "highly qualified personnel" (HQP) pipeline revealed cause for concern. The Panel's online survey, which attracted 432 respondents, showed that while student interest in taxonomy remains and taxonomists continue to be trained, most trainees emanate from a handful of labs, limiting expertise to certain groups of species only. The Panel also documented a loss of taxonomic expertise in highly diverse and poorly understood taxonomic groups, and noted that as taxonomists retire, they are not being replaced.



(Council of Canadian Academies)

Figure 1
The components of biodiversity science and their interconnections

Job openings in taxonomy have virtually ceased, despite a rising trend in biodiversity science jobs in general. For those taxonomists who do find employment, the field has suffered from stagnant levels of inflation-corrected funding per researcher, in direct contrast with the dramatic rise in research costs. A bibliometric analysis of species descriptions revealed that among G20 plus European Union countries, Canada's ranking dropped from 6th in the 1980s to 14th in the 2000s.

As current experts retire, increased collaboration is essential to help fill the expertise gap. Canadian taxonomists in universities, governments, and industry should seek more opportunities to develop innovative partnerships with i) Aboriginal Traditional Knowledge holders who hold valuable, yet largely untapped, information about Canada's historical and current biodiversity wealth; ii) front-line bachelors- and masters-level taxonomists who perform species identifications for environmental assessments, and monitor for invasive species; and iii) naturalists and "citizen science" programs. Nevertheless, such collaborations require taxonomic experts to integrate diverse knowledge sources. If the expertise gap continues to widen, Canada risks the misidentification of introduced species and inaccurate information about their spread and potential for harm; Canada may also become incapable of assessing species decline in some native species. For example, pollinators provide a crucial ecosystem service (via fertilization of crops) to agriculture, yet there is a growing taxonomic expertise gap in pollinator identification.

CANADA'S TAXONOMIC COLLECTIONS

The many specimens contained in Canadian biological collections are an essential resource for taxonomic research — a legacy of past work and a basis for future investigations — and must be preserved for generations. The Panel collected data on collections through an online survey in which 120 biodiversity collections across the country participated.

The number of specimens in Canadian collections totals over 50 million, with collections ranging from a few hundred specimens to the almost 17 million specimens held by the national collections at Agriculture and Agri-food Canada. Many specimens are irreplaceable. Even with the application of an extremely conservative average value of $5 per specimen, the total value of specimens in Canadian collections would still exceed $250 million. Maintaining specimens in multiple collections across the country is important for facilitating research and teaching, exposing youth to collections-based research, and insuring against disasters. Field stations managed by universities or government facilitate the collection of biodiversity specimens, often in remote areas, and some have decades of data on species and ecosystems.

Conditions under which specimens are stored in Canadian collections vary considerably. Although most collections reported that over 75 per cent of their specimens are currently stored in adequate conditions, many are still housed in aging facilities with little physical room for growth. Numerous facilities lack long-term stable funding and are challenged with limited or inadequate curatorial capacity; when staff retire, they are often not replaced, leading to orphaned collections. Collections are governed and managed under an array of different organizational schemes, with no national collections strategy or standards. If this collections gap continues, Canada may lose long-term information essential to understanding changes in Canadian biodiversity and making informed policy and management decisions.

ENHANCING ACCESS TO BIODIVERSITY INFORMATION

Studying and managing Canada's biodiversity resources — including understanding environmental change, identifying and controlling alien species, and identifying and conserving species at risk — require online open access to taxonomic data.

Canada has substantial gaps in the digitization of its collections, biodiversity inventories, and data holdings from remote areas. Canada is opportunistic rather than systematic about collecting new biodiversity data through field observations and, with the exception of some taxonomic groups, notably vertebrates, there are large gaps in field observations. There is a history in the Canadian taxonomic community of retaining data for individual research purposes; these data may be scattered in many databases or reside on paper, collection specimen labels, and other media not amenable to interactive searching or discovery. As the research community ages and retires, more and more data are being lost.

Canada's data-sharing efforts compare poorly internationally, as evidenced by its low participation in the Global Biodiversity Information Facility (GBIF). As of May 2010, Canada was ranked 18th internationally, and only 1.69 million GBIF records came from Canadian institutions, which, even by generous estimates, translates into only three per cent of available specimen data. Of the total 6.35 million records about Canadian species in the GBIF, only 1.33 million are held by Canadian institutions, with 3.80 million held by U.S. institutions and large numbers by other countries. This means that around 80 per cent of Canada's online biodiversity information is being held outside Canada.

Although Canada has impressive specimen collections and a strong digital infrastructure, most specimen information is trapped in cabinets rather than ranging free and accessible on the web. This deficit needs resolution, not just for the sake of taxonomy, but for the well-being of other disciplines in biology that depend upon this information. This data gap means that Canada risks making policy decisions related to the management of biodiversity resources on the basis of inadequate data, with enormous potential impacts for the economy and the well-being of Canadians.

IS CANADA EQUIPPED TO UNDERSTAND ITS BIODIVERSITY RESOURCES?

Canada possesses key taxonomic assets including substantial natural history collections and (currently) the taxonomic expertise to make effective use of them. The knowledge held by Canada's Aboriginal populations and its non-governmental sector represents a significant addition to the taxonomic capacity within the government and university sectors. Young Canadians, raised in a country with magnificent wild lands, are strongly attracted to career opportunities in biodiversity science. Canada has world-class analytical capacity in three fields — informatics, genomics, and remote sensing — that underpin a new approach to the discovery, documentation, and evaluation of biodiversity.

Despite these assets, the Panel's analysis has revealed that not only are certain strengths under threat and potential benefits not fully realized, there are also key gaps associated with taxonomic expertise, collections, and data (see Figure 2). In direct response to their charge, the Panel concluded that *Canada is not yet equipped to fully understand the challenges of our biodiversity resources*.

Current Gaps

- Canada has gaps in species description and geographic distribution data, and lags behind other countries in digitization, systematic inventories, and support for national contributions to international biodiversity data-sharing efforts.
- There is an absence of national collections strategy and standards.
- Many collections are housed in outdated and inadequate facilities with little capacity for growth.
- Highly qualified personnel are being lost because of low job prospects and stagnant research funding levels.
- Taxonomists and naturalists are aging and not being replaced.
- Traditional and community knowledge is at risk.

Consequences

- Insufficient capacity to adequately manage, conserve, and utilize Canadian biodiversity.
- Limited capacity to evaluate the response of Canadian biodiversity to global change, and its value for mitigation and adaptation.
- Limited ability to respond to the risk of invasive species and the spread of pests.
- Limited capacity of taxonomy to provide fundamental support to other elements of biodiversity science.
- Limited ability to identify components of biodiversity in a Canadian context.
- A loss of interest, particularly on the part of young Canadians, in biodiversity and ecosystems.

Outcomes

- Diminished capacity to understand biodiversity, its loss, and erosion of associated ecological services that provide economic, health, and cultural benefits to Canadians. Biotechnology and resource industries, such as forestry, agriculture, and fisheries are particularly vulnerable.

(Council of Canadian Academies)

Figure 2

Gaps in Canadian taxonomy, the consequences of those gaps, and potential long-term outcomes

THE ROLE OF TAXONOMY IN CANADA'S KNOWLEDGE-BASED FUTURE

The science of taxonomy is in flux: recent advances, especially in the fields of genomics and computer science, are revolutionizing both the pace of taxonomy and access to taxonomic information. Exciting new approaches are emerging, some with roots in Canada, including the integration of morphological approaches with genetic techniques such as DNA Barcoding. A growing number of nations are making major investments in taxonomy in response to these opportunities.

The Panel concluded that not only is Canada well positioned to close its gaps in taxonomic expertise, collections, and data, but, it could also build on its strengths to become an international leader in the field if there is bold vision from its scientific community, policy leaders, Traditional Knowledge holders, non-governmental organizations (NGOs), and industry. In the past decade, new scientific linkages have been established and administrative capacity built as a result of regional collaborative initiatives in Quebec, Ontario, and British Columbia; the creation of Canadensys; and the success of Natural Science and Engineering Research Council (NSERC)-led collaborations. These initiatives have set the stage, and Canada's biodiversity science community is now prepared to lead a major endeavour. Although proposing the detailed mechanisms and funding models for this effort is beyond the mandate of the Panel, the Networks of Centres of Excellence (NCE) Program and derivatives of the Canada Research Chair Program have enabled Canada to rise to international prominence in other areas of national interest, such as Arctic science. A similar funding strategy could transform Canada's biodiversity science capacity.

Viewed from a needs perspective, Canada's heavy involvement in the harvest of natural resources means that strong taxonomy has high strategic relevance to Canada's economic well-being, its status as a responsible world citizen, and the protection of its natural resources. Investing in taxonomy would support innovation and enable Canada to launch a major program focused on the discovery of compounds and biochemical pathways for the creation of bio-fuels, the protection of human health, and the development of new manufacturing processes. Strong taxonomy would help Canada meet its national and international commitments to biodiversity conservation and help protect Canada from the devastating effects of invasive species.

Chapter 1 Preface and Charge to the Panel

The biological diversity of life, including the variety of genes, species, and ecosystems, is essential to the Earth's life support system, and to human health, culture, social, and economic well-being. Biodiversity science has taken on the challenge of describing and quantifying the biological diversity on Earth, and has made remarkable progress explaining its origins, the factors affecting its geographic distribution, and its fluctuations through time. Biodiversity science has also identified a declining trend in biological diversity in many parts of the world that is coincident with, and causally linked to, the expansion of human agricultural and industrial activities. The remarkable growth in the global economy has been achieved by the sustained exploitation of diverse biological resources and ecological processes. Current projections indicate that continued economic growth will accelerate the rate of biodiversity loss over coming decades and severely diminish the capacities of natural ecosystems to sustain human society.

Understanding and predicting the consequences of this rapid transformation of the biosphere poses a major challenge for biodiversity science. Fundamental baseline data are limited — we simply do not sufficiently know what species are in Canada, much less how all of them interact in ecosystems. Rapid advances in theory and computing are needed to make reliable predictions about the rate and distribution of change in biodiversity over the coming century. The integration of economics, health, and the social sciences will allow biodiversity science to predict the impacts of biodiversity change on human well-being and suggest corrective policy actions. Significant scientific resources and infrastructure are required to discover, record, catalogue, and track changes in biodiversity at local, regional, and global scales.

1.1 UNDERSTANDING AND ADDRESSING THE CHARGE TO THE PANEL

Against this backdrop, in May 2009, the Government of Canada, through the Minister of Canadian Heritage, asked the Council of Canadian Academies to appoint an expert panel to conduct an assessment of:

The state and trends of biodiversity science in Canada: Are we equipped to understand the challenges of our biodiversity resources?

In addition, the following subquestions were posed:

1. *Do molecular techniques truly supplant traditional taxonomy, or do they create opportunities to focus effort?*
2. *What is required to supplement traditional taxonomy?*
3. *In light of what is globally required in biodiversity research, what does Canada need to do?*
4. *What are the gaps between what Canada needs to do and Canada's existing capabilities?*

This question was initiated by the Canadian Museum of Nature in consultation with the Federal Biodiversity Information Partnership and the Alliance of Natural History Museums of Canada.

Prior to the appointment of the Panel, the Council of Canadian Academies consulted written material provided and engaged in extensive discussions with the sponsor to fully understand the nature of the question. From those discussions it was clear that the Council of Canadian Academies was being asked to conduct an assessment focussing on taxonomy. On that basis, the Council appointed an Expert Panel that included core expertise in taxonomy, expertise in the broader biodiversity sciences such as ecology and evolutionary biology, the social sciences, information technology, and policy. Panel members had a background in academia, museums, government, non-governmental organizations (NGOs), and international organizations; they served on the Panel as individuals committed to providing expert advice, not as stakeholders. As with all Council of Canadian Academy panels, the broad range of expertise provided many perspectives. This Panel was deliberately constituted to not solely have expertise in the topic of taxonomy.

Once convened, the Panel invested considerable time to ensure they had a complete understanding of their charge. This included in-person discussions with the Canadian Museum of Nature and other government departments and agencies with an interest in biodiversity science, and a thorough consideration of background material supplied. It was clear to the Panel that although the question asked for an assessment of biodiversity science, the intent of the sponsor was for a narrower charge that focused on the state and trends of taxonomy in Canada — research that discovers, distinguishes, classifies, and documents living things. In this context, being equipped to understand the challenges of our biodiversity resources includes having the necessary expertise, appropriate biodiversity collections, and easily accessible data. The Panel was not asked to make explicit policy recommendations, but rather to undertake an evidence-based assessment of taxonomy in Canada that can serve as an important resource for future policy decisions.

1.2 APPROACHES

After ensuring a thorough understanding of their charge, the Panel approached the assessment by determining what evidence was available for their consideration, and what additional evidence they needed to collect. In consulting the literature, the Panel located several important reports on specific elements of Canadian taxonomy, reviews of Canadian collections (e.g., Gagnon & Fitzgerald, 2004), briefs like *Systematics: An Impending Crisis* (Federal Biosystematics Group, 1995), and studies of changes in taxonomic science (e.g., Packer *et al.*, 2009) and the need for regional coordination of museums (e.g., Sperling *et al.*, 2003). The Panel could not identify, however, a recent comprehensive study of Canadian taxonomic science, across governments, universities, and other sectors, that could be used as a baseline for this assessment. In particular, the Panel sought data on two important components of taxonomy in Canada: the people with the expertise, including researchers, curators, technicians, holders of Traditional Knowledge, and naturalists; and the biodiversity collections, including the specimens, the data that describes those specimens, and the institutions that house them.

To assess the current state of taxonomy in Canada and to help identify trends, the Panel designed two online surveys. The first survey focused on taxonomic expertise, and invited responses from individuals with such expertise, broadly defined, from all sectors (see Appendix 1 for full methods and results). This survey received 432 complete responses. The second survey, on specimens, collections, and their institutions, invited responses from individuals responsible for Canadian collections (see Appendix 2 for full methods and results). This survey received 120 complete responses. These two surveys provided the Panel with both primary quantitative data and qualitative information. In addition, the Panel visited a selection of five Canadian collections, including federal government, provincial government, and university collections. These on-site visits allowed the Panel to witness first-hand the state of these collections. The Panel also used historical data to analyze trends in taxonomy, with data on funding trends provided by the Natural Sciences and Engineering Research Council (NSERC). Bibliometric analysis was conducted to reveal trends in publications by taxonomic researchers.

The Panel also benefited greatly from written submissions from various individuals and organizations in response to a public call for evidence on the Council's website. This process allowed the biodiversity community the freedom to raise issues they saw as relevant to the assessment at hand. The Panel conducted in-depth face-to-face meetings with representatives from the international biodiversity and the Aboriginal Traditional Knowledge communities. These discussions were in addition to a review of evidence available in the literature, including recent international studies such as the 2009 U.S. report on the infrastructure of federal science collections (National Science and Technology Council, 2009); the 2008 U.K. report from the House of Lords on systematics and taxonomy (House of Lords, 2008); the Australian survey of taxonomic capacity (Australian Department of the Environment, Water, Heritage and the Arts, 2003); the 1998 U.S. *Teaming with Life* report (PCAST, 1998); and others.

There are limitations to all sources of evidence. For example, the quality of data provided by the surveys depends upon the quality and completeness of answers submitted by respondents, as well as the comprehensiveness of the survey distribution; data on funding are affected by changing descriptions of funding codes; information gathered through the public call for evidence depends on individuals' decisions on whether and what to submit; and evidence collected in face-to-face meetings depends on the Panel's process for selecting individuals with whom to meet. Despite these limitations, which are inherent in evidence-gathering for studies of this kind, the Panel believes this assessment presents the most comprehensive, up-to-date report on the state and trends of taxonomy in Canada.

It is important to note that for the purposes of this assessment, the Panel chose to exclude detailed study of live collections. The challenges faced by live animal collections (e.g., zoos and aquaria) differ considerably from those of collections of preserved specimens. The Panel considered the challenges facing microbes, but concluded that the findings of this report might not apply to microbial collections because the research techniques and collection facilities for microbes are dissimilar to those used for multicellular organisms. Live animal collections, as well as type culture collections and seed banks, play an enormously important role in conservation, and microbes are important aspects of Canadian biodiversity. These deserve study beyond what would have been possible in the context of this assessment.

1.3 HOW THE REPORT IS ORGANIZED

The remainder of the report is organized as follows:

- Chapter 2 provides background context for the report. It introduces the concept of biodiversity and establishes its value in Canada and throughout the world. It describes how taxonomy is essential to managing and conserving biodiversity.
- Chapter 3 presents an overview of the discipline including its main roles and activities, and the exciting new opportunities created by recent technological advances and the global shift to collaborative initiatives.
- Chapter 4 provides a comprehensive assessment of the state and trends of taxonomic expertise in Canada based on an online survey by the Panel, analyses of funding data, and bibliometric trends, among others. The Panel seeks to establish if and where the highly qualified personnel (HQP) pipeline to taxonomic expertise narrows, and outlines the risks caused by the widening gap in expertise. The chapter concludes by examining other valuable sources of taxonomic knowledge in Canada: Aboriginal Traditional Knowledge holders, local naturalists involved in "citizen science" programs, and bachelors- and masters-level taxonomists.
- Chapter 5 assesses the state and trends of collections in Canada, including the specimens and the institutions that house them. The Panel provides an overview of the value of Canadian collections, and the challenges faced by various types of collections. Much of the data are based on the responses to the Panel's collections survey.
- Access to data about Canada's biodiversity, whether specimens in collections or field data, is essential to making informed decisions about biodiversity management. Chapter 6 assesses the management of biodiversity information in Canada, our digitization efforts, and our progress in making knowledge about Canadian biodiversity available to researchers, policy-makers, and the public.
- Chapter 7 weighs the strengths of Canadian taxonomy against the far-reaching consequences of its current gaps and weaknesses, in order to address the second half of the question posed to the Panel — whether Canada is equipped to understand its biodiversity resources. The Panel describes the opportunities to enhance collaboration in taxonomy and the benefits this would bring to innovation, meeting international commitments, and protecting natural resources.

Chapter 2 Biodiversity, its Significance and the Role of Taxonomy

The diversity of life on earth is an irreplaceable natural heritage. It is being lost in Canada and around the world at a rate unprecedented in human history, with massive consequences for the biosphere, the economy, and human well-being. Biodiversity science has emerged as a transdisciplinary field, of which taxonomy is the foundation.

The concept of biological diversity refers to the great variety of life in all its manifestations from genes to ecosystems, bacteria to polar bears, and oceans to arctic tundra. It has captured our imagination and has been a focus of scientific study for hundreds of years. The phrase, "biological diversity," (see Box 2.1) has been used by scientists since the early 1980s (e.g., Lovejoy, 1980), and its contraction, "biodiversity," since the U.S. National Forum on BioDiversity in 1986 (Wilson, 1988). With growing concern about the state of the Earth's biodiversity and a greater acknowledgment of the value of biodiversity, the term is now commonly used by the scientific community, policy-makers, media, and the general public alike. The social and political importance of biodiversity was established in 1992 with the creation of the United Nations (U.N.) Convention on Biological Diversity (CBD), to which Canada is a signatory, during the U.N. Conference on Environment and Development in Rio de Janeiro. There is now an established field of study, known as biodiversity science, that has enhanced, and will continue to enhance, our understanding of life on Earth. Taxonomy, the focus of this report, and described further in Chapter 3, is key to understanding biodiversity, as it involves naming, identifying, describing, and locating species, and provides insights to other biodiversity sciences.

Box 2.1
Defining Biodiversity

The Convention on Biological Diversity defines biodiversity as "the variability among living organisms from all sources," which includes diversity within species and between species, as well as variability at other levels of organization, such as between ecosystems and landscapes. This biological variability can be seen to involve three distinct notions: richness, evenness, and heterogeneity.

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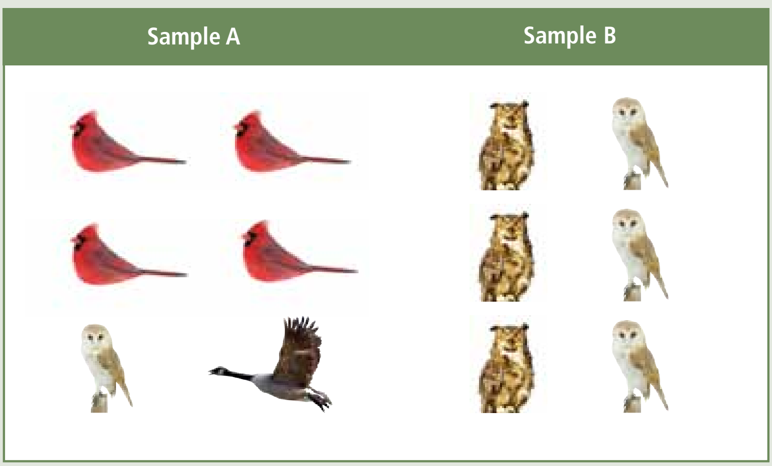
Richness is the multiplicity of elements within a component of biodiversity, for example, the number of genes within a species or the number of species within ecosystems. The example below shows that sample A may be considered more diverse because it contains more species than sample B, and therefore has higher richness.

Evenness is the equitability of the elements within the components of biodiversity. Evenness is an aspect of biodiversity as it is encountered or sampled. In the example below, two randomly chosen individuals from sample B will more likely be of different species than two chosen randomly from sample A. Assuming that both samples are representative of their respective ecosystems, sample B's ecosystem has greater evenness of species abundance than sample A's ecosystem, which evidently has one highly abundant species.

Heterogeneity pertains to differences among the elements in the set. In the example below, sample B has different species of owls but sample A has cardinals, owls, and geese, and therefore sample A has greater heterogeneity.

There are many mathematical formulations, such as Shannon's Index or Simpson's Index, for computing relative values of biodiversity within and between geographical locations (e.g., Magurran, 2004). Nevertheless, biodiversity cannot actually be gauged according to any of these notions or indices unless researchers can identify and reliably assign elements to a component. To do that requires taxonomy.



2.1 VAST WEALTH: THE VALUE OF CANADIAN BIODIVERSITY

Canada's biodiversity wealth stems from its broad landscape. As the nation with the second-largest area in the world, with a vast coverage of different ecosystems, Canada hosts almost 7 per cent of the Earth's terrestrial surface, 10 per cent of the world's total forest cover, 25 per cent of the world's wetlands, and 7 per cent of the world's renewable supply of freshwater (CBD, 2006). Canada's Arctic constitutes about 20 per cent of the world's circumarctic area. Each of these landscapes house many unique assemblages of species and ecological communities. These in turn are the underpinning of significant economic and cultural value (as explored later in this section), and are a source of enjoyment, pride, cultural identity, and emotional, artistic, and spiritual inspiration for Canadians.

Biodiversity is essential to human well-being. The quality of air, water, and food depends on the renewable cycles and stocks characteristic of healthy ecosystems that are driven by biodiversity. Forests are critical to the quality of air and to the predictability and sustainability of water cycles. Equally, organisms in the soil, from bacteria to worms, are critical to the quality of soil, which, in turn, is critical to human food production. Plants, including those we eat, depend on the quality of soil; animals, including those we eat, ultimately depend on plants. In addition, biodiversity changes to ecosystems — populations of plants and animals that interact in complex ways — can often alter the incidence and spread of human diseases. Box 2.2 explains how a better understanding of local biodiversity could help mitigate the risk of humans contracting Lyme disease. Biodiversity also provides a wealth of organisms from which to glean new biomedical knowledge. The eminent biologist, E. O. Wilson (2002) highlighted this opportunity when he warned that, "It is no exaggeration to say that the search for natural medicinals is a race between science and extinction, and will become critically so as more forests fall and coral reefs bleach out and disintegrate."

Economic Value

Our global economy massively undervalues the life support role of biodiversity. As an example, a groundbreaking but controversial study by Costanza *et al.*, (1997) evaluated the world's ecosystem services to be in the trillions of dollars. Although considerable uncertainty is associated with this estimate, many more recent studies have suggested there are good economic reasons to conserve and sustainably use biodiversity (e.g., Balmford, 2002; Rudd, 2009). According to Canada's fourth national report to the Convention on Biological Diversity (CBD, 2006), a significant portion of Canada's gross domestic product (GDP) comes from the use of natural resources that are dependent upon Canadian biodiversity including 2.7 per cent from forests, 8 per cent from agriculture and agri-foods, and 1.5 per cent from the ocean sector. Biodiversity in Canada is essential both for the traditional lifestyles of Aboriginal communities, who rely on biological resources for their subsistence, and for emerging new economic and innovation opportunities (explored further in Chapter 7), such as genomics, biotechnology, and pharmaceuticals.

Box 2.2
Biodiversity and Lyme Disease

Lyme disease, also known as borreliosis, is North America's most important vector-borne disease. It illustrates the need to understand how the different components of biodiversity interact to affect human well-being (Ostfeld, 2010). The disease is relatively easily treated if detected early, but can be profoundly debilitating if allowed to progress untreated. In response to global climate change, the *Borrelia* bacteria that cause the disease are moving northward in several regions of Canada (Ogden *et al.*, 2010).

The main vectors of Lyme disease are ticks in the genus *Ixodes*, and their usual hosts are a variety of mammals and birds. The ticks are especially difficult to identify correctly in the immature stages, which are crucial for disease transmission. Within North America, the assemblage of native hosts of the ticks varies enormously by region, and this can have profound effects on the probability that disease will be transmitted to humans. This is because the presence of a diversity of small mammal hosts has now been shown to provide a kind of "ecosystem service" by diluting the efficiency of transmission of the *Borrelia* (LoGiudice *et al.*, 2003, 2008). For example, when white-footed mice (*Peromyscus leucopus* (Rafinesque)) are the major natural reservoir, the risk of getting Lyme disease in a region increases.

A clear taxonomic understanding of the rich diversity of strains and species that cause and complicate Lyme disease has not yet been achieved, and effective diagnosis of the disease is hampered by the immunological variation caused by this genetic diversity (Sperling & Sperling, 2009).

In addition to direct value, the services provided by diverse functioning natural systems in maintaining clean air and water are enormous, though we have come to take them for granted. The quality and quantity of fresh water have a reasonably straightforward economic value to agriculture, aquaculture, human health, and energy production; these commodities and activities are priced in analyses, but the water on which they depend is either not priced or underpriced and, hence, its value is underestimated. The quality and quantity of water depend on interactions among species in complex ecosystems, of which forests, wetlands, and grasslands are a part. These, in turn, depend on bacteria, fungi, and animal life for decomposition, pollination, and recycling of nutrients. As Dasgupta (2001, 2010) has demonstrated, pricing, and hence economically valuing, biodiversity is uncommon, but recognizing its economic value is essential to ecosystem maintenance. To that end, Dasgupta makes a compelling case that a price attribution will flow only from creating markets and private property rights for natural capital. The World Bank Institute illustrates the issues with an example where the causal connection is clear:

> The classic example of a production externality is that of a factory discharging effluent into a river as a by-product, which subsequently reduces the quality of water used by a downstream producer (such as a fisherman). This negative effect is not taken into account when the factory owners choose how much to produce, and thus how much to pollute, and the factory is likely to pollute too much. By too much, we mean that the total value of the joint output of the factory and the fisherman could be increased if the factory produced less, enabling the fisherman to produce relatively more (Jack, 1999).

The value of biodiversity does not "trump" all other relevant values, but it must be part of the economic analysis. In 2007, the G8+5 leaders initiated a major investigation known as The Economics of Ecosystems and Biodiversity (TEEB). The resulting reports aimed to help integrate ecological and economic knowledge into decision-making on biodiversity and ecosystem services by recommending appropriate valuation methodologies for different contexts, and by examining the economic costs of biodiversity decline and the costs and benefits of actions to reduce these losses (TEEB, 2009) (see Box 2.3).

Box 2.3
Some Findings of *The Economics of Ecosystems and Biodiversity* Report

- The loss of biodiversity and ecosystems is a threat to the functioning of our planet, our economy, and human society.
- Natural resources, and the ecosystems that provide them, underpin our economic activity, our quality of life, and our social cohesion.
- The way we organize our economies does not give sufficient recognition to the dependent nature of this relationship — there are no economies without environments, but there are environments without economies.
- Getting prices right is a cardinal rule for good economics. Since most biodiversity and ecosystem benefits are in fact public goods that have no price, this can be done in two ways: instituting appropriate policies that reward the preservation of the flow of these public goods and penalize their destruction; and encouraging appropriate markets (mainly "compliance markets"), which attach tradable private values to the supply or use of these goods and create incentive structures to pay for them.
- New markets are already forming that support and reward biodiversity and ecosystem services; some of them have the potential to scale up. To be successful, however, markets need appropriate institutional infrastructure, incentives, financing, and governance — in short, investment.

(TEEB, 2009)

Biodiversity has huge economic importance in Canada. A 2005 study, *Counting Canada's Natural Capital* (Anielski & Wilson, 2005), estimated environmental services from our boreal ecosystems, which cover 58.5 per cent of the country's land area, at $93 billion per year, or roughly 9 per cent of GDP. It also estimated that the ecological and socio-economic benefits of current boreal ecosystem services may be significantly greater than the market values derived from current industrial development — forestry, oil and gas, mining, and hydroelectric energy combined. With increasing concerns about global climate change, the current focus on wildlife, endangered species, and protected areas is being expanded toward global "systems concerns" such as climate, water, and the global spread of pests and diseases. In this regard, understanding biodiversity in the context of ecosystem goods and services is essential to Canada's ecological and economic security.

Some examples clearly demonstrate the economic value of biodiversity in Canada. The collapse of the Newfoundland and Labrador cod fishery caused the loss of 35,000 jobs as well as a $200 million reduction per year in the cod catch (MacGarvin, 2001); it has also had longer-term ecological impacts. Similarly, invasive species (see Box 5.2) cause billions of dollars of economic damage each year in Canada (e.g., in the agricultural sector alone, Colautti *et al.*, (2006) estimated losses to be reaching $4.5 billion annually). These same invasives are silently altering the biological landscape of Canada and may have long-term impacts we have not yet detected.

Biodiversity also offers an important source of innovation, for example, in the discovery of pharmaceuticals and biological processes. The economic importance of biodiversity to innovation is underestimated, but actually critical, and is explored in more detail in Chapter 7.

Cultural Value

Biodiversity is important to cultural diversity, as human cultures around the world have been, and continue to be, inspired and even defined by their interactions with the natural world. Numerous spiritual values, and cultural beliefs and practices, such as songs, stories, and legends that encode and carry human relationships with the environment, rely on biodiversity for their continued existence. Major ensembles of biological diversity are managed by cultural groups (Posey, 1999). Aesthetic values are also attached to biodiversity: undisturbed natural landscapes are a delight to watch and offer recreational activities like bird watching, photography, or eco-tourism, which further generate revenue from botanical gardens, national parks, and wildlife conservation areas for example.

Biological diversity and cultural diversity are mutually dependent. The cultures of Aboriginal peoples and local traditional societies come under enormous pressure from biodiversity loss. If the natural environment is changed or lost, the cultural knowledge and traditional practices vital for maintaining indigenous livelihoods in agricultural, pastoral, coastal, and marine settings are also lost. In Canada, an example of how traditional biodiversity-use and knowledge has declined over the years is that of culturally valued food plants such as the marine alga, red laver, (*Porphyra abbottiae* V. Krishnamurthy), and the Pacific crabapple (*Malus fusca* (Raf.) C.K. Schneid). Both these plants were formerly harvested and eaten in large quantities by West Coast First Peoples (Turner & Turner, 2008), and had significant ecological and cultural knowledge and values associated with their harvest, processing, and serving (Kuhnlein & Turner, 1991). Both could be considered, at one time, as "cultural keystone species" over all or part of their ranges (Garibaldi & Turner, 2004). Today, they both fit the criteria for the designation of "culturally at risk."

Languages are considered one of the key indicators for measuring the relationship between the loss of cultural diversity and the loss of biological diversity (UNESCO, 2002). Twenty-two per cent of the 6,900 languages spoken today around the globe have less than 1,000 speakers (Butchart *et al.*, 2010). People who do not speak their mother tongue cannot access their culture's traditional knowledge (see section 3.4), and are thus excluded from vital information about subsistence, health, and the sustainable use of natural resources. Loss of cultural diversity, marked by the disappearance of languages, collectively deprives humanity of unique knowledge about the environment and its many benefits (Maffi & Woodley, 2010). In Canada, only three of about 50 Aboriginal languages are spoken widely enough to be considered truly secure from the threat of extinction in the long run (Statistics Canada, 1998). According to 2001 census data, of the 976,300 people who identified themselves as Aboriginal, only one quarter (235,000 or 24 per cent) reported that they were able to conduct a conversation in an Aboriginal language (Statistics Canada, 2006a). This represents a decrease from 29 per cent in 1996, and appears to confirm most research that suggests that there has been substantial erosion in the use of Aboriginal languages in recent decades.

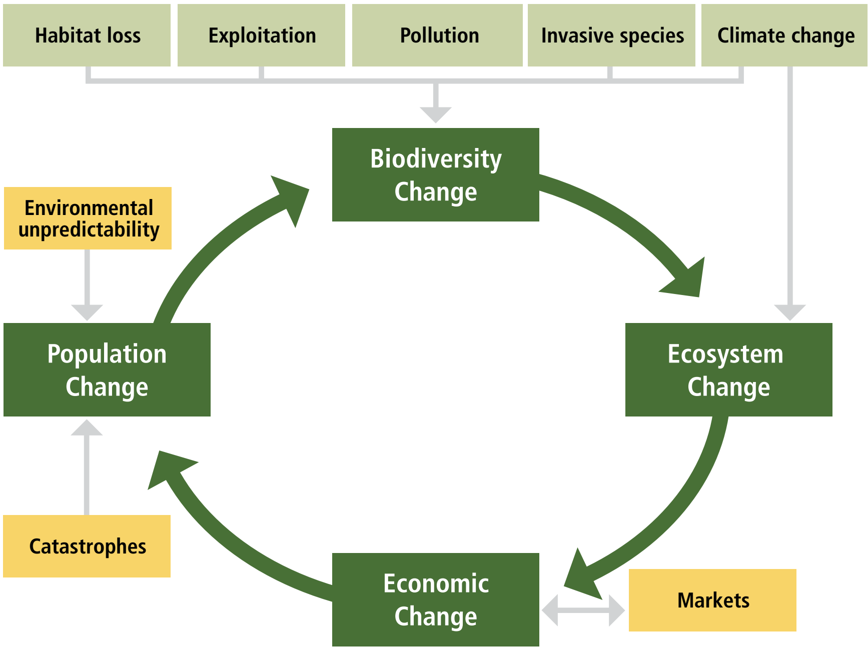
Impacts on bio-cultural diversity in Canada are exacerbated by climate change. Indigenous societies living in the Canadian North are among the first to face the direct impacts of climate change on biodiversity due to their dependence upon, and close relationship with, climate-sensitive arctic biodiversity resources for their livelihoods (e.g., harvesting fish and wildlife, picking berries) (ACIA, 2005; Furgal & Prowse, 2008). Up to 50 per cent of food consumed by Inuit communities in the Arctic is derived from hunted animals. Climate change affects the migratory patterns of animals, which, along with changing snow and ice conditions, can negatively impact hunting practices (Berkes & Jolly, 2002; Krupnik & Ray, 2007). Changes in vegetation due to climate change are likely to have a major effect on vulnerable Northern communities. For example, Inuit communities have used *Rhodiola rosea* L., a traditional medicinal plant, to treat fatigue, depression, and infections, strengthen the immune system, and protect the heart (Sauvé, 2006). Canadian populations of wild *R. rosea* may be significantly impacted by climate change causing rising sea levels and increased competition from invasive species (Cavaliere, 2009).

Many of the problems associated with the loss of biological diversity and the impoverishment of cultural diversity have been dealt with separately in the past. Recognizing their interconnectedness and relevance to sustainable development will lead to a more holistic and comprehensive approach to action at all levels.

2.2 THE GLOBAL EROSION OF BIODIVERSITY

There is now a broad scientific consensus that biological diversity is being eroded globally at a rate unprecedented in human history. This rate is expected to peak in the next 50 years by which point it will be comparable to past terrestrial mass extinction events recorded in the fossil record. The recent *Global Biodiversity Outlook 3* (CBD, 2010), for example, reports that ecosystems across the planet have been impacted by biodiversity loss, and that the average abundance among rare species is declining — over 30 per cent loss globally between 1963 and 2006. The report also identifies five major elements of environmental change that put biodiversity at risk: habitat loss, exploitation, pollution, invasive species, and climate change. The expected strong synergies between these drivers will likely cause an increase in the rate of biodiversity loss that may not peak until the middle of this century (Pimm & Raven, 2000). Rates of species extinction are estimated to be between 100 and 1,000 times the background rate (Lawton & May, 1995). Rates of local population extinction (e.g., the Dwarf Wedgemussel has been absent from New Brunswick since 1968, Fowler's Toads were extirpated from Pelee Island in the 1970s, and the Karner Blue Butterfly was last reported in Ontario in 1991) are projected to be 100 times greater (Hughes *et al.*, 1997). Extensive loss of microbial diversity, although requiring different definitions and methods of assessment (see Box 3.1), might also be anticipated.

This loss of biological diversity is causally linked to human urbanization, agriculture (e.g., conversion of grasslands to croplands or rangelands), fishing, and industrial activities (e.g., oil and gas development, exploration and mining development, and forestry), which have transformed and fragmented terrestrial and aquatic environments (see Figure 2.1). The 2005 Millennium Ecosystem Assessment estimated that approximately 60 per cent of the ecosystem services that support life on Earth are being degraded or used unsustainably (Millennium Ecosystem Assessment, 2005). And, in 2008, the International Union for the Conservation of Nature's *Red List* revealed that 36 per cent of the more than 47,000 species that it has assessed are threatened, an increase from the 22 per cent cited in 1998 (IUCN, 2008). (The conservation status of species is an important indicator of biodiversity trends.)



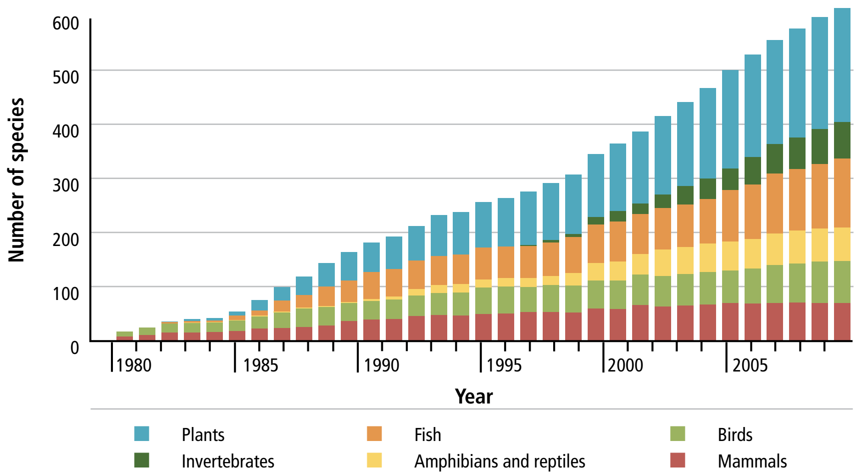
(Council of Canadian Academies)

Figure 2.1

The interaction among the main elements involved in biodiversity change

This figure shows that biodiversity change is linked to ecosystem, economic, and population change and influenced by a range of factors such as habitat loss and invasive species. The effects can feed back, further accelerating and exacerbating change.

Consistent with global studies, biodiversity is also at risk in Canada. As shown in Figure 2.2, the number of species assessed by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) as being extinct or at risk in Canada is growing for all animals and plants being studied. Furthermore, the status of many of these species has been declining. Each at-risk species is reassessed at least every 10 years; of 269 reassessments, 46 species that were previously designated as "at risk" were moved to a higher risk category, while only 27 species improved in status (Mooers *et al.*, *in press*). The list remains far from complete as there are many more species still to be assessed, especially among fish, invertebrates, and plants. Although the trends seen in Figure 2.2 are heavily influenced by the rate at which COSEWIC assesses species, as well as the rate and results of reassessments, among well-known groups the data are clear. For example, as of 2009,



(Data Source: COSEWIC Annual Reports from 1977–2010, compiled by David M. Green, 2010)

Figure 2.2

Numbers of species assessed by COSEWIC as being extinct or a risk in Canada

This figure shows the increase in the number of species across all taxa which are assessed as being extinct in Canada or at risk (extricated, endangered, threatened or of special concern).

18 of the 44 species of amphibians (41 per cent), and 31 of the 44 reptile species (70 per cent) are considered to be at risk in a significant portion of their Canadian range (COSEWIC, 2009).

A number of recent efforts have helped to identify and examine threats to key elements of biodiversity across the Canadian landscape. For example, Venter *et al.*, (2006) systematically identified threats to endangered species in Canada based on published reports and information available from COSEWIC and the Canadian Wildlife Service. They showed that the threats to species in Canada are broadly consistent with issues facing global biodiversity, including the threats posed by increasing habitat loss, invasive alien species, over-exploitation, and pollution. Synergies between these threats are a particular, but poorly understood, emerging threat to biodiversity (Sala *et al.*, 2000). The continued loss of biodiversity will compromise Canada's capacity to respond to and mitigate the effects of climate change. There is no consensus at this time about what rates of biodiversity loss can be sustained by the biosphere and human society, but evidence suggests that the critical planetary boundary defining the safe and tolerable rate of biodiversity loss may have been crossed (Rockström *et al.*, 2009).

High rates of population decline and extinction can erode the underlying genetic diversity needed to adapt to ongoing environmental change and habitat destruction. Critical population sizes have been identified as tipping points beyond which it is very hard for a population to recover from environmental change (Bell & Gonzalez, 2009). Given a sufficiently large number of individuals, populations can often adapt to environmental stress. Antibiotic resistance in pathogenic bacteria is an important example of microbial adaptation, and animals and plants may adapt rapidly to anthropogenic stress, such as pesticides or heavy metal pollution. Nevertheless, populations often fail to adapt to severe environmental change, especially when several forms of environmental change act in concert. Fish populations in lakes that have been rapidly acidified by smelter fall-out usually disappear from the lake, and even microbial populations may be significantly altered (Kwiatkowski & Roff, 1976). The evolution of heavy metal tolerance among plant populations growing on old mine tailings is a classic example of rapid natural selection, however, only a minority of species in the original community evolve high levels of tolerance resulting in biodiversity loss (Bradshaw & McNeilly, 1991).

The threat of widespread and rapid changes in biodiversity across most regions has prompted two decades of research on its impacts on ecosystem functions and services (Naeem *et al.*, 2009). Controlled experiments and ecological theory have established that reduced levels of species and genetic diversity can impact ecosystem processes, such as biomass production, nutrient uptake (Crutsinger *et al.*, 2006; Cardinale *et al.*, 2007), seed dispersal, plant pollination, and the regulation of regional climate. Diaz *et al.*, (2006) have summarized the main scientific findings of the research that has linked biodiversity change to ecosystem processes and the services they underpin. They include biomass production, soil fertility, pollination, resistance to invasive organisms, pest and disease control, climate regulation, carbon sequestration, and protection against natural hazards such as floods and storms.

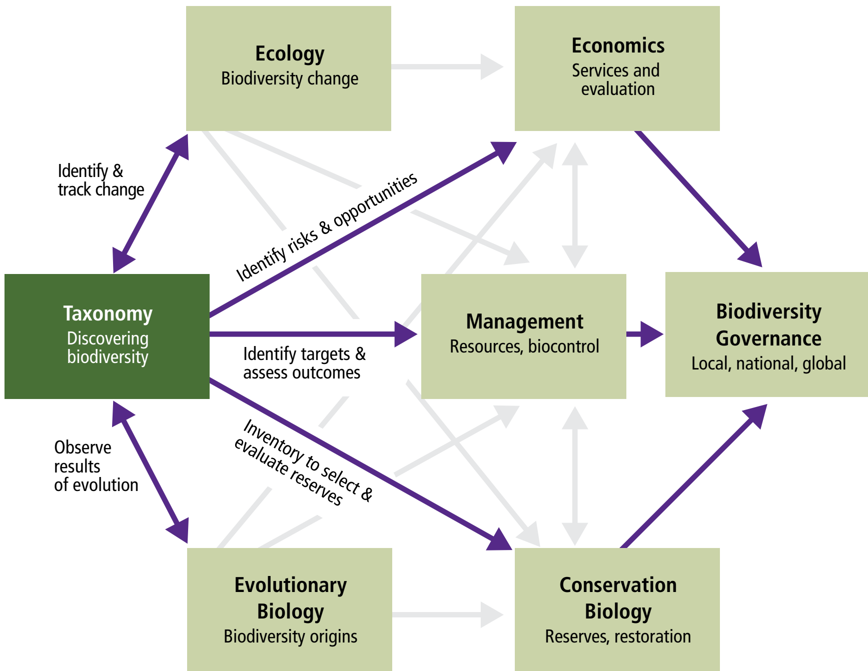
2.3 THE ESSENTIAL ROLE OF TAXONOMY

This chapter has described how biodiversity is fundamental to the function of the biosphere, the stability and productivity of the economy, the sustainability of many cultures, and human well-being. Detecting the loss of species, and indeed the introduction and movement of both native and non-native species, is fundamental to the effort to manage these systems upon which so much of Canadians' livelihood is based. Just as our study of clouds moving across the sky allows us to prepare for the weather to come, tracking the components of biodiversity is fundamental to our understanding of nature as it moves and adapts. Without this understanding, we do not empower ourselves to adapt, to manage impacts on biodiversity, or to prepare for storms that may be on the horizon. Understanding this change and exploring its implications pose a clear and urgent scientific challenge.

Current environmental problems cannot be solved by traditional disciplinary approaches in environmental science. Since biodiversity change is due to the growing influence of humans on their environment, research in both the natural and social sciences is needed. Biodiversity science has therefore emerged as a transdisciplinary field that uses tools and theories from many disciplines including molecular biology, taxonomy, systematics, ecophysiology, evolution, ecology, economics, political science, and the arts. Biodiversity science links these disparate fields into a coherent framework adapted to the methodological, conceptual, and political challenges of biodiversity change in the 21^{st} century. Biodiversity science, however, can only be as strong as each of the disciplines upon which it is built. Taxonomy is foundational; advances in biodiversity science rest on the discovery and accurate identification of the species that compose ecosystems.

Figure 2.3 illustrates the relationships between taxonomy and other disciplines:

- For ecology, taxonomy discovers the species components of ecosystems and assists ecologists with their identification, which is vital for monitoring environmental change.
- Taxonomy's economic roles include helping to track harmful species by providing the means to identify them, and to discover diverse species that may be utilized.
- Taxonomy catalogues and describes the species, which, as the products of evolution, are the sources of basic data for evolutionary biology.
- By surveying species in different geographical areas, taxonomy helps conservation biology select and evaluate reserves.
- Assessment of management strategies by monitoring of target species requires accurate taxonomic identification. By enabling better choices in economics, management, and conservation, taxonomy enables informed governance of our biodiversity resources from local to global scales.



(Council of Canadian Academies)

Figure 2.3
The components of biodiversity science and their interconnections

Chapter Key Messages

The diversity of life on earth is an irreplaceable natural heritage crucial to the function of the biosphere and human well-being, culture, the economy, and innovation potential.

Biodiversity is being lost in Canada and around the world at a rate unprecedented in human history. The five major drivers of biodiversity loss are the same in Canada as the rest of the world: habitat loss, overexploitation, pollution, climate change, and invasive species.

To meet the urgent need to understand biodiversity change and its implications, an integrated biodiversity science has emerged that employs tools and theories from many disciplines.

Chapter 3 Taxonomy: The Foundation of Biodiversity Science

Taxonomy — science that discovers, distinguishes, classifies, and documents organisms — is foundational to biodiversity science. Conventional approaches to discovering, characterizing, and archiving species are being supplemented by recent technological advances, accelerating the exploration of life on Earth.

One of humanity's most ambitious and most vital big science projects began not with the space age, the information age, or the genomic age. Instead, it began millennia ago when indigenous cultures around the world began to find and characterize the incredible diversity of life on Earth. Since the 1750s, a network of thousands of biologists have contributed to a common knowledge base, known as the Linnaean classification, unveiling species that have not only been studied as model organisms and recognized for their key ecological roles, but that have also given us valuable medicines and biomimicking materials.

The project is not complete; by current estimates the majority of the species on Earth are yet to be discovered, and most of those already known are so minimally characterized that few biologists can identify them. An estimated 1.6 million species are currently known to science (May, 2010), and field work continues to uncover new species. Conservative estimates suggest that between 5 million and 10 million species exist in nature (May, 2010), although renewed sampling of the smallest organisms such as invertebrates, fungi, and microbes — the drivers of many fundamental ecosystem processes — may well force an upward revision of these estimates (see Box 3.1 on the diversity of microbes).

Simply scaling up past efforts cannot complete the task efficiently: there is simply too much to do. As the 21st century unfolds, however, a confluence of conventional methods and new technologies spurred by broad international collaborations are creating new opportunities for rapid progress in taxonomy. This is the first generation with the technology to find and document all species on earth, but perhaps the last generation with the opportunity to do so (e.g., Wheeler, 2003).

As described in Chapter 2 (section 2.3), the results of taxonomic research — the science of discovering, describing, and distinguishing species — are fundamental to other disciplines that depend on an accurate picture of what species are on Earth. With each species discovered we have a more complete picture of who participates in our ecosystems and another opportunity to exploit evolutionary innovations.

Species are communities of genetic descent, and so distinguishing species is simply one component of the broader activity of investigating the historical genetic connections of all organisms on the phylogenetic tree of life. There are therefore close ties between the discipline that focuses on the broad-scale tree of life (phylogenetic biology or systematics), and the discipline that investigates lineages at a finer scale to distinguish species. Indeed, some biologists do not recognize the distinction between the efforts to resolve genetic relationships at the broad and fine scales. Nonetheless, there are biologists who do just one or the other, and there tend to be different users of their results, with ecologists relying on species as ecological units, and evolutionary biologists paying as much attention to phylogeny as to species.

The goals of taxonomy are to discover species, to describe distinguishing features so that they may be identified, and to provide baseline data on the species, including morphology, geographical distribution, and natural history. This chapter describes what taxonomy is, why it is important, how it is performed, and how the science is changing.

3.1 THE IMPORTANCE OF DISCOVERING AND DISTINGUISHING SPECIES

How important is taxonomy's task of discovering and documenting species? Any science needs to distinguish the entities in its scope: genomics scientists distinguish the different genes, astronomers the categories of stars and galaxies, and physicists the elementary particles. Considerable expenditure in each of these fields is devoted to this basic mapping of its elements, and for good reason. We cannot understand how polymerase genes work if we cannot distinguish a polymerase gene; we cannot understand how neutrinos behave if we cannot recognize a neutrino. These sciences cannot derive general laws without being able to reliably and repeatedly recognize and gather data about the particular entities.

In biodiversity science, we understand ecosystems by studying the roles of participating species. We cannot determine the role of a species unless we can recognize it and attribute our observations to it. We prospect for biomaterials and chemicals by focusing on species likely to hold useful evolutionary innovations. If we cannot recognize the species, we may be unable to achieve or repeat precise studies. The general principle is simple: when data are gathered in a science, the data concern objects or entities — genes, stars, particles, species — about which we seek predictive theories. If the entities cannot be distinguished, the data will be attributed incorrectly or ambiguously.

We need to distinguish species to record data on them, but how completely or to what precision? A developmental biologist needs to know whether an experimental study concerns the fruit fly *Drosophila melanogaster* Meigan or the Thale cress plant *Arabidopsis thaliana* (L.) Heynh, but these species are model organisms maintained as laboratory strains. A biodiversity researcher may deal with thousands of species. Indeed, there are 1,450 wild species of *Drosophila*, including *D. melanogaster*. Do they all have to be recognized and identified? Is it enough to make low-resolution identifications, for instance identifying a specimen only as a “butterfly” rather than as “*Danaus plexippus* L., the monarch butterfly”?

Misidentification or ambiguous identification of species hinders our ability to understand ecology, but how severely we are hindered is difficult to predict, as ecosystems involve among the most complex processes known to science. If ecosystems were structured entirely by easily identified groups like vertebrates or flowering plants, there might be little problem with low-resolution identification of arthropods (insects, mites, and so forth), fungi, and microbes. But, there is increasing recognition that these poorly known groups of small organisms play important roles in ecosystems (Brussard *et al.*, 1997; Callaway *et al.*, 2004; Wall *et al.*, 2010). Different species within a genus or family frequently differ in basic ecological roles, and so low-resolution identification of samples will often blend organisms with different ecologies, leading to low-resolution ecological results and misleading ecological predictions (e.g., Knowlton *et al.*, 1992; Bortolus, 2008). This problem has been particularly acute in food web ecology where taxonomic “lumping” has masked the diversity and complexity of interactions in ecosystems and led to incomplete understanding of food web topology and dynamics (e.g., Krause *et al.*, 2003). Higher-resolution identification will lead to more precise ecological understanding of the consequences of biodiversity change.

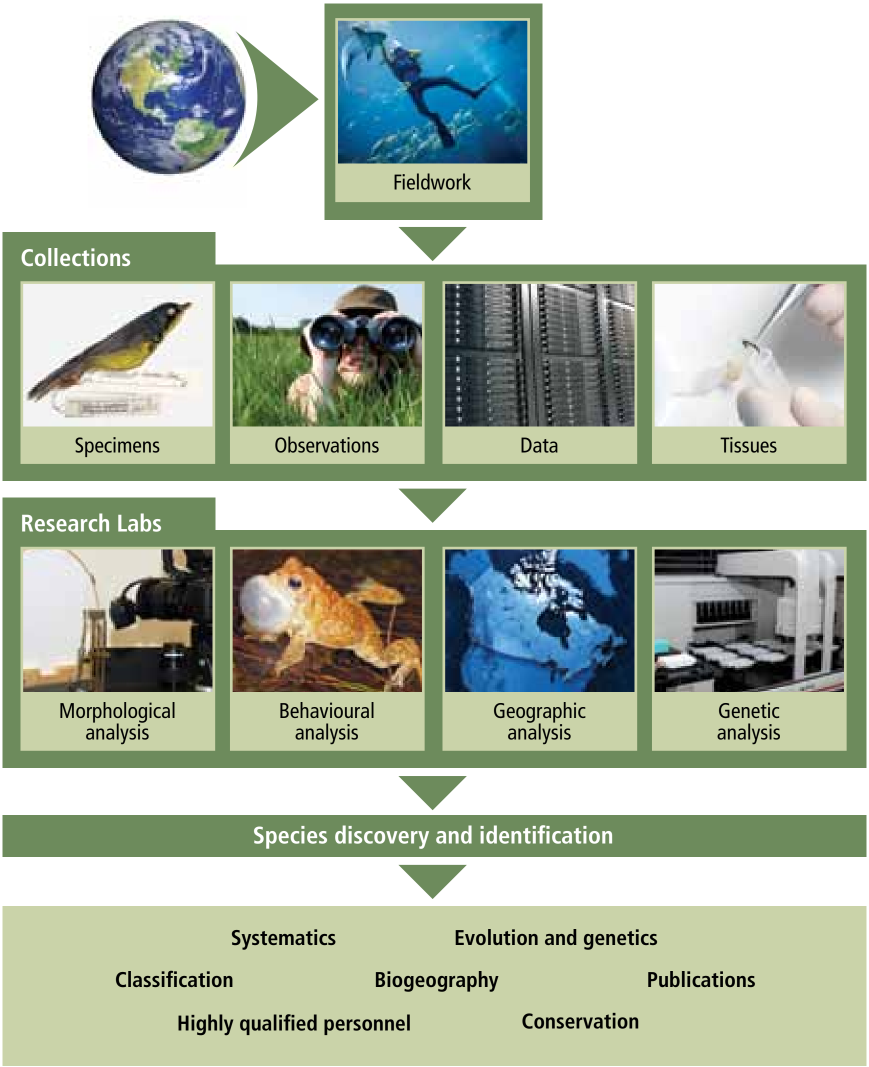
Accurate identification of species is vital not only to biodiversity research, but also for solutions to applied problems. Efforts in conservation biology, agriculture, medicine, and bioprospecting depend on species identifications. A *Spartina* grass intentionally transplanted into San Francisco to bolster a declining local population was later discovered to have been misidentified, and became an alien invasive apparently with unintentional human assistance (Bortolus, 2008). A mealybug attacking mangoes in West Africa was at first unidentified, but a taxonomist recognized it as coming from southern Asia, helping to pinpoint searches for biocontrol agents to Asia, which were ultimately successful (Bokonon-Ganta *et al.*, 2002). In Vietnam, taxonomic work recently distinguished two previously confused mosquito species, one a vector of malaria and the other not, permitting refined monitoring and control efforts (Van Bortel *et al.*, 2001). Knowledge of our species is also essential for bioprospecting to spur innovation, as explored further in Chapter 7. The next opportunity or crisis could arise in nearly any group of organisms. Our current understanding of species in many groups is so poor as to leave us unprepared to rise to these challenges.

Probably less than half of Canadian species are known (see Table 5.1). If we don't identify our species, we won't know in 10 years if unnoticed species are being lost due to global change, and we may not know if species are newly invading. We will know only a fraction of the available targets for bioprospecting. Threats will be poorly diagnosed, and opportunities will be missed.

3.2 HOW SPECIES ARE DISCOVERED AND DISTINGUISHED

Science's mission to discover and document the species on Earth (Figure 3.1) begins in the field: in the oceans, lakes, rivers, mountains, prairies, forests, deserts, and the tundra. Modern ease of travel now facilitates collecting in remote areas, but the collecting of most organisms has not been fundamentally simplified by technology: it still involves hiking, picking, digging, and dipping. Specimens collected are, in most groups, archived in museums for continued and further study.

Taxonomists study specimens, both freshly collected and long-archived, to determine if they may represent species new to science, or to discover new evidence by which to distinguish previously known species. Conventionally, the evidence used to distinguish species has been morphological — examining differences in size, structure, or colouration. Morphological differences can reveal genetic differences, and therefore help to attribute specimens to distinct genetic communities (i.e., different species). Morphological evidence is indirect, but nonetheless the use of these studies over the past 250 years has successfully outlined a first approximation of the delimitation of species, although so far covering only a small fraction of biodiversity. The classification and species delimitations used throughout biology are still primarily founded on taxonomic results from morphological data.



(Diagram images courtesy of: Paul D.N. Hebert (tissues, morphological analysis, and genetic analysis), David M. Green (specimens and behavioural analysis))

Figure 3.1

Workflow of Taxonomy

The taxonomic process generally starts with field work that yields specimens and data on their geographical and ecological context. Specimens are studied both directly and after preservation to describe their distinguishing features (morphological information) and to obtain genetic data. Together the morphological, behavioural, geographical, and genetic data are analyzed to yield an assessment of what the species are, and how to identify them. This knowledge of species and their distinctions is just the first of many outcomes — other key products include whole specimens, tissue collections, databases of specimens, images, genes, and geography, and publications such as identification guides. Affiliated fields that benefit directly from taxonomic work are shown in the lower part of the figure.

Box 3.1
Diversity at the Microbial Level

The organisms that biologists generally call microbes include bacteria, archaea (similar to bacteria in many ways), algae, protozoa (like *Amoeba*), and the smaller fungi (yeasts, for instance, but not mushrooms). It is their microscopic size, habit of growing as single cells (or as clumps or strings of only a few), plus certain ecological similarities that small size brings, that make them all microbes.

Despite these similarities, however, the group is actually very diverse. In biochemical, structural, genetic, and ecological terms, there are more differences and novelties among the microbes than among all plants and animals together. Microbial organisms fill up all of the niches in which life is possible, from within rocks in the frozen dry valleys of Antarctica, to deep sea hydrothermal vents at 120°C, to all of the internal and external surfaces of our own bodies. Microbial (especially bacterial) activities, such as nitrogen fixation, photosynthesis, and methane production, also drive the major biogeochemical cycles that maintain Earth as a habitable planet. Without animals and plants, Earth would be boring: without microbes it would be dead.

There are several ways in which microbial biodiversity studies differ, in methodology and purpose, from biodiversity studies targeting animals and plants. Microbial diversity science seldom involves the preservation of dead specimens in museums; the term "species" may not have the same meaning due to the amazing genetic variation within, as well as between, recognized species; and microbial species are generally thought to be "cosmopolitan" — distributed worldwide wherever appropriate conditions exist. Advances in molecular biology and genomics mean that microbial diversity can now be assessed directly by analysing DNA from environmental samples of soil or water, without cultivating any organisms in the laboratory — an important area of study called metagenomics.

Technology is transforming taxonomy via new data and more rapid methods. Genetic data, first introduced in the 1970s and increasingly easy to obtain, is giving us more direct and higher-resolution views of the boundaries of species, particularly at the microbial level (see Box 3.1). Advances in image analysis, both optical and computational, are enabling rapid documentation of morphology. Database technology permits high efficiency tracking of specimens and species, and new methods use the internet for rapid and broader dissemination of results.

Despite these advances, most species described by science cannot be easily or adequately identified by the published information. Old literature is scattered and based on poorly described or difficult-to-assess data. However, recent advances promise to overcome this. Information technologies including the internet are bringing together comparative data and revolutionizing identification through databases, identification guides, and online communities. DNA sequence comparison methods (see Box 3.2) promise to facilitate identification considerably. Technology may soon permit rapid genetic identification of species quickly and at low cost, but the data needed to identify most known species are not yet compiled. The development of such methods is a key goal for taxonomy: rapid, accurate identification in the field would greatly facilitate the gathering of basic data for many ecological studies.

New versus Conventional Taxonomic Methods

With taxonomy facing new demands and opportunities, it is not surprising that taxonomists have been working to understand the best way to advance the mission of discovering biodiversity (e.g., Godfray, 2002; EDIT, 2008). Technological advances, demands for rapid and high-accuracy assessments of ecosystems, and the daunting task of documenting such a large proportion of biodiversity all bring their own challenges. This concern is reflected in one of the sub-questions given to the Panel: *Do molecular techniques truly supplant traditional taxonomy, or do they create opportunities to focus effort?*

With 1.6 million species known (May, 2010), and millions others yet to be found and distinguished, building a comprehensive DNA-based identification system will be a decades-long effort, in which morphological taxonomy will play a major role. To build the database of sequences for so many species, sampling needs to be targeted efficiently to maximize species catalogued. Lest we waste all our resources sampling starlings and dandelions, the choice of specimens to be examined is best guided by specialists who know the habitats likely to hold unsampled species, and who can rapidly assess morphology to choose specimens likely to represent distinct species.

DNA data may or may not substantially replace morphological data for species identification, depending on the organisms. For example, fungi are highly diverse yet have few distinguishable morphological features, and thus genetic determination is a boon to fungal specialists. Birds, though, are well characterized morphologically and most researchers will undoubtedly continue to identify birds in the field using visible features. The outcome may also depend on advances in competing fields such as image analysis. However, the eventual outcome is largely irrelevant to our choices in the near future. We need to invest in building genetic databases for identification; they will be valuable. But, even if the ultimate goal were DNA-based identification, morphological taxonomy is needed to accomplish it.

Box 3.2
Molecular Identification of Species

In many instances, it is possible, even necessary, to identify a species even if the whole organism is missing. For example, how can products from legally versus illegally harvested species of fish be told apart? The answer lies in their genes, as Bartlett and Davidson (1991) showed by identifying samples of tuna meat based on the DNA sequences of mitochondrial genes. This is the essence of the technique of DNA Barcoding, which employs sequence diversity in standardized gene regions to create a digital system for species recognition (Hebert *et al.*, 2003). DNA Barcoding works so well for so many species that it has allowed the creation of identification systems with broad application and holds the promise that a select number of gene regions will permit the identification of virtually all eukaryotic species. The practise of DNA Barcoding recognizes the need to record the details of collection, identification, and long-term storage of each specimen, thus binding specimen and sequence information together. The *Barcode of Life Data* (BOLD) informatics platform, now includes nearly 1 million barcode records derived from more than 100,000 species.

DNA Barcoding presumes that most species display enough genetic differences from related species to permit their diagnosis with very limited sequence information. Nevertheless, forensic identification of species must be exact and defensible enough to stand up to legal scrutiny in a court of law. Forensic entomology was an early test for the validity of employing molecular sequences to identify insects in a legal context. The fly maggots present on a corpse are reliable indicators of the state of decay, and thus the time of death, and such evidence is well accepted in court. But maggots can be difficult to identify to species unless they are reared to adulthood and this may mean that a significant amount of time may elapse before they can be used as evidence. Using DNA sequences to identify maggots can greatly speed identification (Sperling *et al.*, 1994), but DNA has not yet become the primary accepted method for identifying insects in court cases. As long as uncertainty remains that standard DNA Barcodes necessarily conform to species determined by other means (Wells *et al.*, 2007), corroborating evidence from other means of identification will likely remain essential, alongside molecular characters, for identifying forensically important species.

Morphological data also provide an important quality-control mechanism as efficient DNA-based identification is being developed. The best data for distinguishing species are, in principle, many genes in the genome sampled for many specimens from many species, but this is too costly. Thus, researchers use shortcut methods using only a few gene loci, such as DNA Barcoding. For these approximate genetic methods, morphological information plays an important role to catch errors or to corroborate whether two species are distinct, because morphology reflects a broad portion of the genome (see Box 3.2). Without the participation of morphological data and taxonomists, a DNA-based identification system would be disconnected from the existing classification of organisms based on morphology. Integrating with the existing classification is important because almost all results from the last centuries of biology are attributed to species identified and classified using morphology. Thus, to preserve continued access to this legacy data, DNA reference standards must link the genetically characterized species to the conventional classification using morphological identification, requiring a substantial effort from morphological taxonomy. Morphological and DNA-based taxonomy are necessary collaborators.

Another role of morphological taxonomy has been to provide a baseline characterization of organisms. For most species known to science, the only data we have are those contributed by taxonomists. This includes data on natural history as well as morphology. Even these minimal baseline data, such as whether the organisms are large or small, hairy or spiny, toothed or not, can prove critical for ecological interpretation or bioprospecting. The value of this baseline data on morphology and other non-genetic ("phenotypic") data is recognized in the Barcode of Life initiative,[1] which encourages the recording of digital images of specimens as they are vouchered.

In fact, initial concerns among taxonomists that fashionable genetic data might lead to the extinction of taxonomy's morphological foundations have proven, so far, unfounded (Packer *et al.*, 2009). As the Barcoding effort (Hebert *et al.*, 2003) expands, so too do the project's requirements for the collaboration of taxonomists who know the morphology and natural history of specific groups of organisms, both for integration of results into the existing classification and for sampling of specimens. Morphological taxonomists have therefore found themselves valued partners in the effort to make a genetic reference database for species identification, and are increasingly in demand.

1 http://www.boldsystems.org

3.3 ARCHIVING SPECIES IN COLLECTIONS

With millions of species around the world, the information gathered about biodiversity is extensive. This information must be shared, not only with current researchers, but also with researchers of the future through long-term archives. The greatest storehouse of information about species we have are the biological specimens collected and stored by individuals and institutions for centuries. Some specimens contained in collections, such as the Natural History Museum in London,[2] date back to the 16th and 17th centuries and, even today, are in remarkably good condition. The Linnaean Society,[3] also in London, houses much of the 18th century collection upon which Carl Linnaeus based his initial species descriptions. The point is that somebody understood the value of these fragile specimens and created the necessary conditions for their maintenance for future generations. Although biologists of many disciplines contribute specimens to collections, specimens of most species are contributed by taxonomists in their quest to understand species diversity.

Each specimen carries a wealth of information into the future. Specimens in collections are often irreplaceable sources of DNA and data about morphology, location, and natural history. Some, such as microbes or seeds, are living, but most are preserved. Preservation methods are varied, but now include special fluids and freezers for genomic studies. However preserved, the task of collections is to maintain specimens, if possible, for hundreds of years. This is especially important given that some of the species in current collections either are or may soon be extinct, rendering these specimens the only trace we will have of their species. Centuries-long maintenance is not easily achieved, given fluctuating economies and scientific priorities.

For the sake of communicating about the species we discover, we need names to apply to the species and, for the sake of stability, these names need to be grounded to reference specimens. Therefore, for every named species there is a particular specimen, or series of specimens, known as the type or type series, which permanently anchors the name to that biological species. These type specimens, along with the data on where and when they were collected, have central importance to our entire system of biological knowledge. They must be securely housed somewhere. That is one of the primary roles of biological collections.

2 http://www.nhm.ac.uk/

3 http://www.linnean-online.org/

Box 3.3
Uncovering Hidden Biodiversity

The discovery of new species of Canadian animals and plants is an ongoing process not limited to the very smallest of our wildlife. Museum collections contain a wealth of non-traditional specimens, such as frozen tissues and DNA samples, that can uncover unexpected diversity.

(Courtesy of David M. Green)

Until the mid-1990s, spotted frogs were considered to be a single, widespread species inhabiting most of mainland British Columbia and the northwestern United States. However, genetic studies showed that populations of these frogs living on the Pacific coast from the Fraser River Valley south to California were so distinct from the rest that they could only be considered a distinct species (Green *et al.*, 1997). Now known as the Oregon spotted frog, it is considered to be endangered throughout its range. The much more widespread Columbia spotted frog is not at risk. Only once the genetic information had shown these species to be distinct did scientists begin to realize that there were morphological distinctions as well (Matsuda *et al.*, 2006).

The killer whales living in the waters of the Pacific Ocean off British Columbia have long been recognized as forming distinct populations, called ecotypes, that differ in morphology, behaviour, and diet. The resident killer whales regularly seen in the Strait of Georgia and other inshore waters feed on fish, particularly salmon. The offshore, transient killer whales, though, feed on seals and other marine mammals. The resident and transient whales have different vocal languages, do not intermix socially, and do not interbreed. Recent genetic analysis of their mitochondrial DNA indicates that the ecotypes diverged from each other some 150,000 to 700,000 years ago, indicating that they are distinct species, as yet un-named (Morin *et al.*, 2010). All the killer whale populations of Canada's Pacific waters are considered to be either endangered or threatened.

Biological collections are used broadly by many disciplines. As the basic materials of the taxonomic and systematics fields, the collections and their data document the results of biological research in the form of voucher specimens that can later be re-analyzed, perhaps using new techniques for DNA extraction and sequencing, to provide data on historical trends and new insights (see Box 3.3 for examples of the value of museum collections). Ecologists can examine gut contents, trace element incorporation, or compare growth forms to understand ecological contexts. Natural history field guides (see Box 6.2) also depend heavily on biological collections. In addition, as records of where species were, and when, they can contribute to new studies in other scientific areas such as climate change and human health.

The Expanding Role of Information Technology

Standardized data storage, whether in electronic databases or in paper monographs and catalogues, has been the core of taxonomy since Linnaeus established standards for species descriptions and classification. Data are stored about specimens (collecting data, morphology, DNA sequences) and species. Today, databases are not just technologies; they are commitments to archive and to share. Long-term storage of data on specimens and species needs to be assured. In addition, access to the data to varied audiences, from biologists to the public, needs to be designed to enhance science as well as public understanding. Increasingly international standardization of data stored for both specimens and species is being designed by international networks and working groups such as the Global Biodiversity Information Facility (GBIF)[4] and Biodiversity Information Standards (TDWG).[5] Along with online databases, standardized data now permits the broad sharing and exchange of information on species and the collected specimens that represent them. Filling these databases requires both digitization of existing collections and of new incoming collections. This will enable comprehensive synthetic studies, for instance, to ask whether the ranges of species are expanding or shrinking. Image databases, as well as online taxonomic keys, are disseminating the means to identify species to biologists and to the public. The internet now provides the means to coordinate research and to communicate its results broadly as never before.

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4 http://www.gbif.org/

5 http://www.tdwg.org/

3.4 THE SHIFT TO COLLABORATIONS

The mission to discover all species of life on Earth will require much more than technology — it will require extensive national and international collaboration.

Collaborations among Universities, Government Research, and Museums

Museums specializing in archiving have a long-term mission; universities, which emphasize training, and government agencies conducting research tend to have shorter-term missions. If these groups are isolated from one another, students may never encounter taxonomy and collections-based research, which means that taxonomic research cannot be effectively integrated with other biological disciplines (ecology, physiology, etc.). Integration of taxonomic research with other disciplines is vital to ensure its results are delivered effectively by people, databases, and devices to the biologists who depend on it. Increasing interchange, virtually and otherwise, will yield important synergies.

Multidisciplinary Collaborations

Insofar as it discovers the elements of biodiversity, taxonomy is foundational to all studies of biodiversity (see Chapter 2). It therefore has long been an indispensible collaborator for ecological studies, which seek to understand how Life's elements interact. This collaboration has expanded as global climate change studies require tracking of the geographical and seasonal ranges of species, for which legacy data in taxonomic studies and collections provide an important historical baseline. Conservation biology is increasingly dependent on taxonomy because the recognition of biodiversity hotspots for possible reserves requires the accurate distinguishing of species and quantification of diversity. As bioprospecting expands its search for species with useful features for everything from pharmaceuticals to nanotechnology, the basic map of biodiversity provided by taxonomy is a necessary guide. Contributions from other disciplines into taxonomy have grown enormously over the last decades, especially via informatics (databases) and molecular biology (genetic analysis).

Taxonomic Science and Traditional Knowledge

The term Traditional Knowledge (see Box 3.4) encompasses the knowledge, innovations, and practices of indigenous and local communities embodying traditional lifestyles that are important to the preservation and sustainable use of biological diversity. Many species are isolated to local areas, and combinations of species into ecosystems are often locally unique. Thus, local knowledge gathered and passed down from generation to generation, often through legends, songs, cultural and spiritual values, traditional laws, languages, and rituals is particularly valuable in understanding biodiversity (Brown & Brown, 2009). Traditional Knowledge is often not confined within ethnic or geographical boundaries.

Many indigenous and local communities create and manage biodiversity through their actions and social organizations. Research has begun to elucidate this role, and it is increasingly being taken into account by national parks as they enter into co-management agreements with Aboriginal communities (Canadian Parks Council, 2010). Collaboration between biologists and Traditional Knowledge holders should integrate this knowledge into scientific literature before the knowledge is lost.

Box 3.4
Traditional Knowledge

Traditional Knowledge was first recognized officially at the UN Conference for Environment and Development in Rio de Janeiro in 1992. Article 8j of the Convention on Biological Diversity calls on signatory states to respect, preserve, and maintain the traditional knowledge of indigenous and local communities that contributes to the conservation and sustainable use of biodiversity. Access to Traditional Knowledge must be based on the prior informed consent of the knowledge holders and their equitable participation in the benefit-sharing arising from the use of such knowledge.

Taxonomic Researchers and the Public

If members of the public are not aware of biodiversity, they will not know how to value it or understand how their choices affect it. Those who survey biodiversity can transfer their own knowledge and excitement broadly to the public, especially to children. Showing children the wonders of biodiversity outside their urban worlds and introducing them to biodiversity scientists as potential role models is an important investment for the future of biodiversity.

Conversely, taxonomic researchers can benefit tremendously from an exchange of knowledge with members of the public such as bird watchers and wildlife photographers, including a rapidly expanding community of amateurs using digital cameras to capture images of smaller organisms such as insects. These individuals, often referred to as naturalists, along with hunters and fishers, have a broad range of skills and specific local biodiversity knowledge related to their interest in watching, learning, and understanding the natural environment, and often recognize and document biodiversity changes.

The collaboration between taxonomic researchers and the public has long taken place in museums and through books. Museums use their research expertise and collections to bring biodiversity to the public, and field guides (see Box 6.2) facilitate the public's discovery of biodiversity *in situ*. A new venue for collaboration is, of course, the internet. Not only can museums and biodiversity scientists communicate with the public online, naturalists can share with each other their photographs, stories, and enthusiasm through blogs and other forms of social media. For instance, many websites, from the general (flickr.com) to the specialized (bugguide.net), encourage the public to post photographs of organisms and solicit identifications from professional and amateur experts. This form of crowd-sourcing, which taps into what Janzen (1993) termed the "taxasphere" — the global community of taxonomists — provides sufficiently rapid feedback for it to become an important educational resource for building biodiversity-literate communities of people with diverse interests and abilities.

Chapter Key Messages

Taxonomy is the foundation of biodiversity science because it discovers and identifies the fundamental elements of biodiversity. There is a huge need for taxonomic research.

Taxonomic science needs to integrate classic morphological approaches with new genetic and computational techniques. This represents a synergy among approaches, not a segue from "old" to "new."

There are exciting and important new approaches and opportunities for collaborations among scientists, Traditional Knowledge holders, naturalists, and the public.

Chapter 4 Canadian Expertise in Taxonomic Research

Canada has historical strength in biodiversity science and taxonomic research. People with expertise and interest in taxonomy remain in Canada, but the lack of support and job prospects are preventing Canada from realizing our full contributions to biodiversity science.

Canada has a long-established reputation for its expertise in biodiversity-related fields, including ecology, evolution, taxonomy, and systematics. A 2006 report released by the Council of Canadian Academies found that biodiversity science ("Ecology and Evolution") was one of only 4 out of 125 sub-fields of science and technology in which Canada ranked in the top 30 countries worldwide for both publication quality and intensity (Council of Canadian Academies, 2006). The Council of Canadian Academies also reported a remarkable 25 per cent jump in publication volume within Ecology and Evolution between the periods of 1997 to 2000, and 2001 to 2004 within Canada, compared to a worldwide increase of 16 per cent. Indeed, Canada's research productivity per grant dollar in biodiversity science is one of the highest in the world (Peters *et al.*, 1996). This excellence is reflected in the Canada Research Chair program, with 75 out of 1,760 allocated research chairs being awarded in ecology and evolution (28 Tier 1 chairs; 47 Tier 2 chairs).

The success of biodiversity science in Canada can be attributed to multiple factors. Success breeds success; having excellent colleagues in a research area improves the ability to recruit top-quality researchers from around the world. In addition, the range of ecosystems in Canada provides a natural resource that not only attracts biodiversity scientists but also generates a need for a variety of experts to understand, interpret, and manage these diverse resources. For example, field stations provide access and improved research capabilities in a diversity of environments, from marine stations to the polar ice (Appendix 3). Another potential factor contributing to the disproportionate success of ecology and evolution in Canada is a difference in funding policies relative to other nations. As noted in the recent *Report of the International Review Committee on the Discovery Grants Program* (NSERC, 2009), Natural Sciences and Engineering Research Council (NSERC) scientific research funding, which is distinguished by its support of successful scientific research programs rather than of specific projects, provides a more stable base of long-term funding than in many other countries. Consistent funding is particularly important in biodiversity sciences because of the need to observe long-term trends, establish field sites, carry out substantive taxonomic revisions and monographs, and undertake basic scientific discovery with non-model organisms. On the other hand, this chapter will demonstrate that the amount of research dollars per grant is stagnant in Canada. This stagnation constrains Canadian research scientists, biasing research activities away from costly endeavours such as molecular analyses, remote field work, and radiotelemetry.

Overall, in terms of productivity per grant dollar, publication record, and international reputation, Canadian research in biodiversity science, broadly defined, is vibrant and influential. The important question for the purposes of this assessment, however, is whether the field of taxonomic research in Canada can be equally characterized as flourishing and healthy.

4.1 CANADA'S CONTRIBUTIONS TO TAXONOMIC RESEARCH

Canada has a history of world-class contributions to the mission of discovering species on Earth. In much of the second half of the 20th century, Canada was at the forefront of morphological taxonomic research, with many of the most prominent entomological systematists in North America having worked or been trained in Canada. The much-lauded three-volume *Manual of Nearctic Diptera*[6] (McAlpine *et al.*, 1981–89), which remains the standard reference for identifying and characterizing this economically important group of insects, was largely carried out by research scientists and illustrators of the Canadian National Collection in Ottawa. Since its publication, the corps of experts that produced it and similarly influential works, such as Goulet and Huber's (1993) *Hymenoptera of the World*, has been reduced through attrition, and these National Research Council-supported publication projects have been discontinued. Specific targeted programs have, however, supported major renewal in certain areas, such as the Intergrated Microbial Biodiversity Program (see Box 4.1), which is internationally recognized for its leading role in training, species discovery, and taxonomic revision.

Against this backdrop of research strength, the Panel is aware of widespread and growing concerns that Canada is losing biodiversity expertise in particular areas, most notably in taxonomy. This is in keeping with a mounting sense of disquiet about the decline in the number and training of taxonomists worldwide.

6 Nearctic is the term used to describe the ecological zone covering North America, Greenland, and part of Mexico. Diptera are commonly known as flies.

A 2008 U.K. report, for example, outlined various signs that taxonomic expertise is on the brink of extinction in certain areas (House of Lords, 2008). And, according to a recent report from British Columbia, the loss of already limited taxonomic expertise has impacted the capacity to address some of the gaps in biodiversity knowledge in that province:

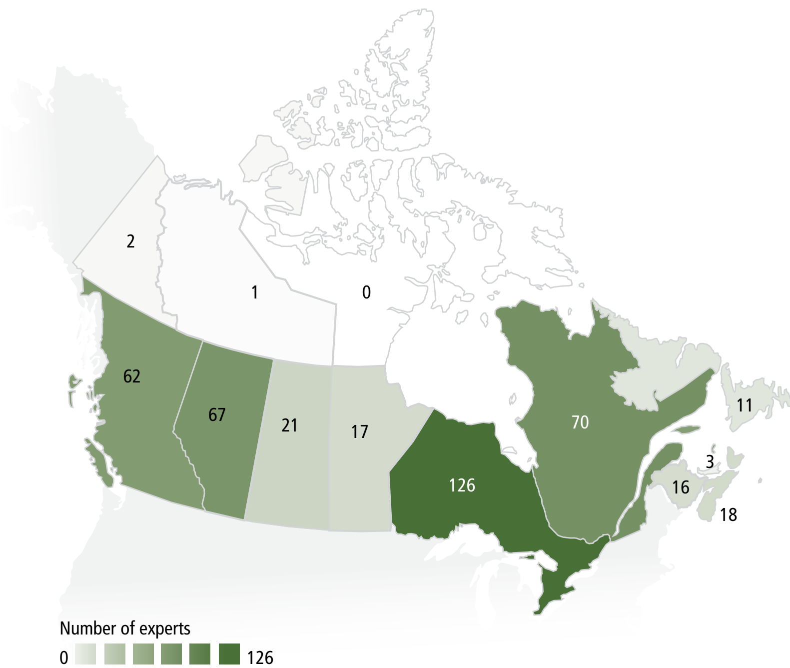
> Thousands, if not tens of thousands, of species in B.C. have not been scientifically described or are not documented as being present in the province. Species groups for which such information is particularly lacking include most of the invertebrates and non-vascular plants. This taxonomic knowledge gap is currently being exacerbated by an "extinction of experience: as the scientists with the knowledge, skills and inclination to do the work required to fill the gaps are retiring and often are not being replaced" (Austin *et al.*, 2008).

Box 4.1
Microbial Biodiversity: A Success Story in the Development and Support of Expertise

The work of the Canadian Institute for Advanced Research (CIFAR) illustrates how networking can transform scientific fields and practices. Its former (1986–2007) Program in Evolutionary Biology together with the new (since 2008) Integrated Microbial Biodiversity Program have linked, and continue to link, Canadians and their colleagues around the world in environmental microbial discovery. Previously unknown major groups of viruses, bacteria, algae, and protozoa have been described and characterized, many times even to the extent of complete genome sequencing. In part because of CIFAR's targeted investments in support of faculty, post-doctoral fellows, and graduate students, Canada is widely regarded as leading the world in protist diversity: we have created a remarkably cohesive cadre of experts where previously there were only a few isolated (albeit excellent) individual researchers.

Assessing the status of taxonomic expertise in Canada is especially important because taxonomists are often the only people with first-hand knowledge of many species in their natural environments; they know where a species can be found, the community in which it lives, and the effects it might have on ecosystem services. Morphological taxonomists and others with taxon-specific expertise typically develop deep knowledge of the natural history of their organisms, thus providing ecological and behavioural information that can both test the species distinctions and provide stimulus for further studies. Loss of taxonomic expertise not only impacts our capacity to categorize species but also our ability to relate species-specific data to community- and ecosystem-level data, and to document trends over time.

To assess the current state of taxonomy in Canada and to help identify its major trends, the Panel designed a web-based survey (see Appendix 1) that invited responses from individuals with taxonomic expertise, broadly defined, from all sectors. All provinces and territories were represented in the 432 responses received, except for Nunavut (Figure 4.1). The majority of respondents had PhDs with taxonomy as the primary focus (142) or with some elements of taxonomy (127); the remainder had PhDs with no taxonomic component (31), did not report the subject of their PhDs (11), or had not attained PhDs (121).



(Council of Canadian Academies)

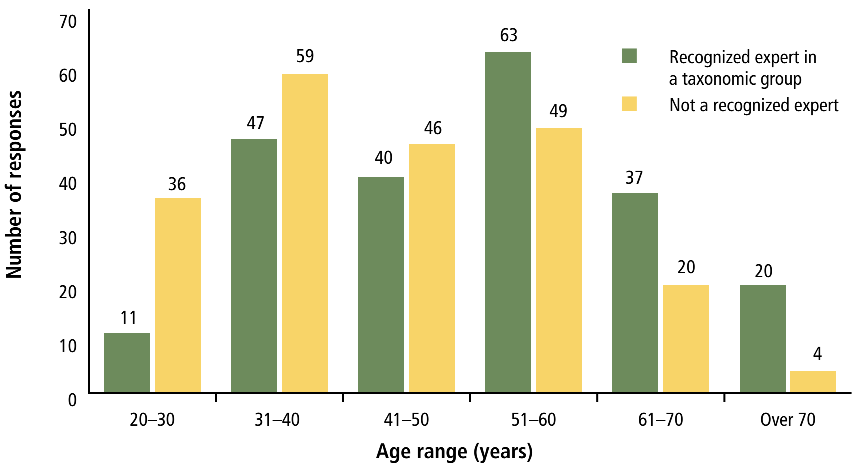
Figure 4.1

Location of survey respondents across Canada

The largest number of respondents to the survey of taxonomic expertise were from Ontario, Quebec, and Alberta. Few were from northern territories.

4.2 AGE PROFILE OF CANADIAN EXPERTS

With the increase in global concern for the loss of taxonomic knowledge, the Panel examined the age distribution of survey respondents for evidence that taxonomic expertise would soon be lost through retirement. Individuals who self-reported that they were "recognized internationally as an expert" in a group of taxa were, on average, 7.3 years older than the remaining respondents (see Figure 4.2), a difference that was highly significant ($p < 0.0001$, based on 10,000 random permutations, hereafter referred to as "permutation test"). Similarly, those respondents who had published at least one taxonomic paper were substantially older than those who had not, even when analyses were restricted to PhD-level respondents (Figure 4.3; mean difference in age category = 7.9 years, $p = 0.0006$, permutation test). This concentration of taxonomic expertise in the oldest age class is even more striking when considering those respondents who have published substantial numbers of papers and/or who have published more extensive publications, such as monographs and taxonomic reviews (see Appendix 1). Survey results, as shown in Figures 4.2 and 4.3, demonstrate that taxonomic experts, many of whom will soon retire, are substantially older than the rest of the respondents. It takes years, however, to build a publication record and to gain recognition for taxonomic expertise, and the question remains as to whether, as time passes, the younger respondents will develop the same high level of expertise that distinguishes the group that will soon be retiring.

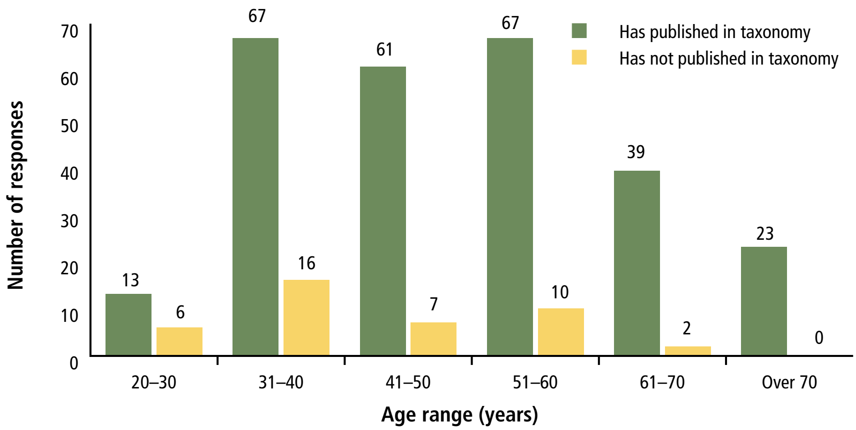


(Council of Canadian Academies)

Figure 4.2

Recognized expertise in taxonomy by age class

This figure shows respondents that self-reported as "recognized internationally as an expert" in the survey of taxonomic expertise and those that did not. Half of all respondents self-reported being an international expert.



(Council of Canadian Academies)

Figure 4.3

Respondents that have published in taxonomy by age class

The majority of survey respondents report peer-reviewed publications in taxonomy. Only PhD-level respondents are included.

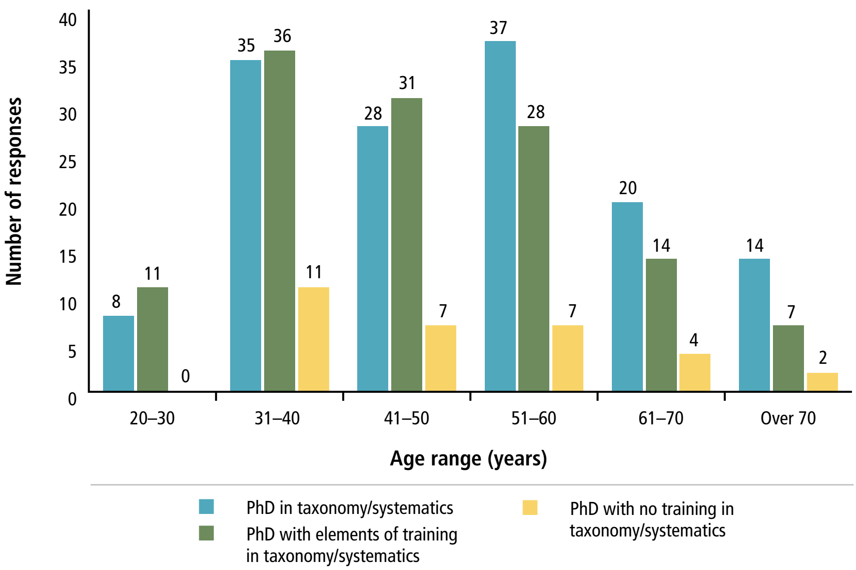
4.3 THE HQP PIPELINE TO TAXONOMIC EXPERTISE

To determine whether taxonomic expertise is being lost, the Panel analyzed the highly qualified personnel (HQP) pipeline that connects younger students to retiring experts in taxonomy in Canada. While recognizing that individuals with a range of educational backgrounds make important contributions in taxonomy, for the purposes of this report, HQP refers to those with PhDs related to taxonomy. In particular, the Panel sought to determine the level of student interest in taxonomic training, the existing training capacity, and whether students are then able to obtain research funding, secure jobs, and devote their careers to taxonomic pursuits.

The Demand for Taxonomic Training

As a first step, the Panel examined the age distribution of those individuals with PhDs focused on taxonomy to determine whether younger individuals continue to receive substantial levels of taxonomic training in graduate school. While the mean age category of respondents with PhDs primarily in taxonomy/systematics was 3.0 years older than those with little to no training in taxonomy/systematics during their PhDs (Figure 4.4), this result was not significant (two-tailed $p=0.07$, permutation test). Indeed, nearly half of the respondents under age 40 (42 per cent) had PhDs focused on taxonomy/systematics.

To determine whether there has been a shift in focus over time away from taxonomy and toward systematics, the results were filtered by whether individuals had received taxonomic training. The results were nonetheless similar; the mean age of individuals with PhDs primarily in taxonomy/systematics, and who had also received taxonomic training, was 1.1 years older than the remaining respondents, a suggestive but non-significant difference ($p = 0.51$, permutation test).



(Council of Canadian Academies)

Figure 4.4

PhD training in taxonomy by age class

The majority of survey respondents report a PhD either in taxonomy/systematics or with elements of training in taxonomy/systematics. The figure shows that Canada has continued to train taxonomists. Eleven respondents did not report the field of their PhD.

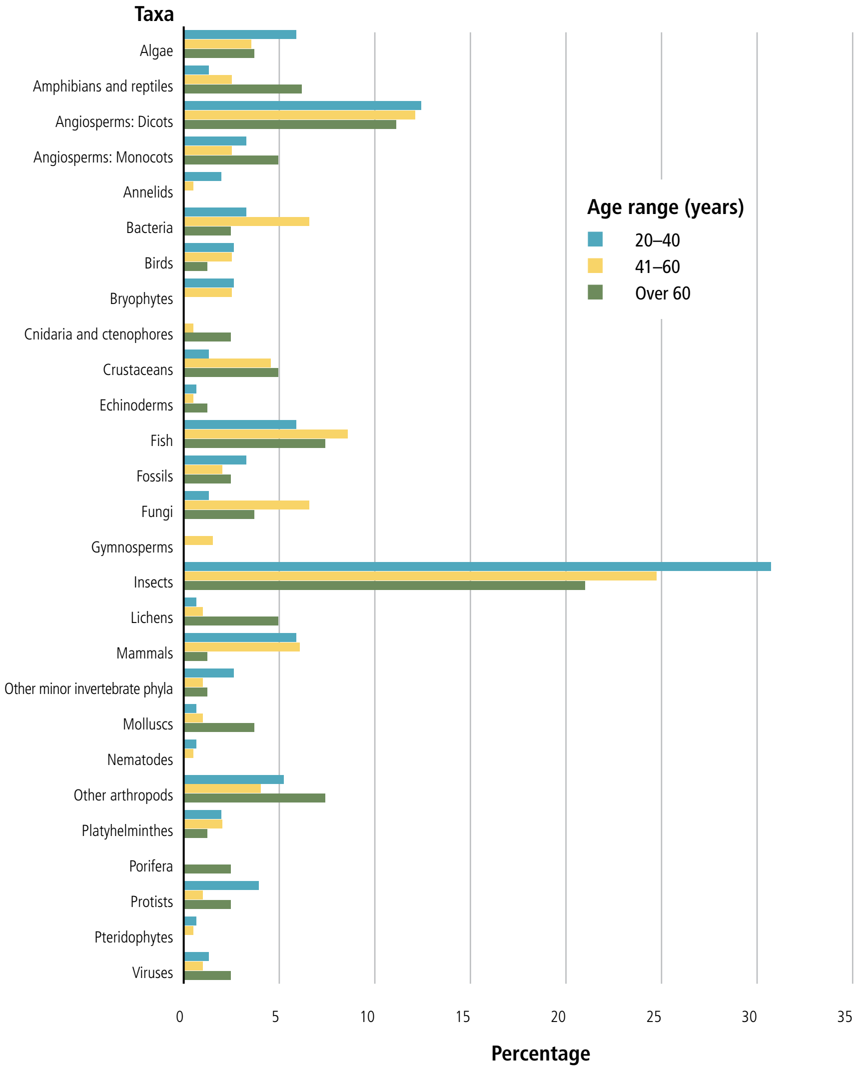
The fact that respondents with taxonomic training and with PhDs focused on taxonomy/systematics are not substantially older than the other respondents indicates that interest in taxonomy remains amongst younger cohorts. This suggests that the beginning of the pipeline leading to taxonomic expertise has not narrowed substantially. Packer *et al.*, (2009) also noted, based on personal experience, that the number of students interested in taxonomic research has not declined.

Taxonomic Training Capacity

The strong interest of Canadian graduate students in learning taxonomic methods is matched by a corresponding desire on the part of Canadian taxonomists to transmit their taxonomic skills and knowledge to students; taxonomists have trained thousands of students at all educational levels (see Appendix 1). One survey participant pointed to the urgent need for training: "I am preparing to dedicate the remainder of my life to training young people as naturalists and taxonomists. I feel we as a society are now so far removed from any real understanding of or connection to wild places as to require urgent remedial action."

A total of 124 survey respondents reported teaching undergraduate courses covering the principles of taxonomy and systematics (out of 350 responses), and 40 reported doing so at the graduate level (out of 295 responses). Many of their trainees have continued on to a career in taxonomy. The problem is, however, that this training capacity does not have a broad foundation because most trainees have emanated from a handful of labs. Only 11 respondents, almost all of whom are nearing retirement, reported a lifetime total of more than five Masters or more than five PhD students who went on to careers in taxonomy.

Since many students are trained in the same few labs, it is likely that taxonomic expertise will become increasingly concentrated in those taxonomic groups where training remains possible. Examining the "broad taxa of expertise" as a function of the age of respondents (Figure 4.5), younger researchers, as compared with older researchers, work disproportionately on insects and angiosperms, suggesting growth in these areas. By contrast, reduced expertise in the youngest age class is spread across a number of taxonomic groups. If this trend continues, Canadian capacity to distinguish novel and taxonomically difficult species will become increasingly limited to certain groups of species. Taxonomic expertise is already disproportionately low in all groups other than plants and vertebrates, relative to the number of Canadian species in each group (see Appendix 1, Figure A1.5); and several survey respondents highlighted losses in taxonomic expertise in algae, byrophytes, fungi, certain groups of insects, isopods, and amphipods.



(Council of Canadian Academies)

Figure 4.5

Taxa studied by age class

The figure shows the percentage of respondents within an age group who identified a particular taxa as their "broad taxa of expertise" (e.g., 25 per cent of respondents between 41 and 60 years old report studying insects).

To ensure that Canadian experts remain able to recognize native and invasive species throughout the tree of life, training must be supported, with an explicit view to maintaining a broad base of taxonomic expertise. To be most effective, this training must take place under the guidance of scientists who have specialized expertise in a particular group of organisms. A student learning taxonomy of fungi is best trained in a laboratory focusing on fungi, and not on conifers or spiders. An arachnologist cannot adequately train a student in the complex features unique to fungi and their diversity, nor in the methods for collecting and examining them. While students can be trained at their home institutions in molecular techniques and in the broad context of taxonomy, a complete education requires taxon-specific training. Where this expertise is not housed at a university or in Canada, the Panel believes that logistical and financial support for training across institutions and countries is needed to safeguard against a narrowing of taxonomic expertise.

Although Canada currently retains substantial capacity for training in taxonomy, many of the current generation of taxonomists will soon be retiring. In order to renew this training capacity, the next generation of experts need to have access to sufficient job opportunities and targeted research funding if they are to pursue careers in taxonomy. As emphasized by one survey respondent: "We cannot underestimate the importance of taxonomic research in Canada, whether in the field of forestry, aquaculture, or the protection of Canadian biodiversity. We must find new sources of funding and support such research if we want to protect and exploit our biodiversity in a sustainable way."

Job Availability

To examine whether declining job availability in Canada might be restricting research capacity in taxonomy, the Panel surveyed job advertisements appearing at five-year intervals from 1965 to 2004 in the journal *Science* (see Appendix 4, Figure A4.1). This exercise revealed that, although there is a rising trend in the total number of jobs available in biodiversity sciences, job openings in taxonomy have virtually ceased. Only one job was advertised in Canada in taxonomy in the most recent years surveyed (1989, 1994, 1999, 2004), compared to seven in the previous years (1969, 1974, 1979, 1984). The decline in taxonomic positions over time is extremely significant, especially in comparison to the rising trend in other areas of biodiversity science.

The lack of jobs in taxonomy reflects a shift in the culture of universities and the research areas highlighted as desirable in a candidate. It also reflects reductions in staffing associated with biodiversity collections, with retrenchments at several institutions. To document the extent of this retrenchment, the Panel requested longitudinal data about staffing trends from 63 Canadian collections that have traditionally hired taxonomists. Out of the 46 responses, 22 reported declines in taxonomic staffing and 12 reported increases (the remaining 12 reported approximately stable staffing levels). The decline in the number of professional positions was particularly striking at two collections that have historically been large employers in Canada (see Table 4.1).

Table 4.1

Number of professional staff at two of the larger employers of taxonomists

Institution	1950s	1960s	1970s	1980s	1990s	2000s	2010
AAFC National Collection of Vascular Plants (professionals)	10–15	14	12	12–14	6–8	6	6
Canadian Museum of Nature (PhD level scientific staff)	n/a	n/a	n/a	27	20	18	16

(Council of Canadian Academies)

These numbers were retrieved from the follow-up questions sent to the survey respondents.

These declines were reflected in comments from several other respondents: "A number of departments have experienced a steady lack of position replacement, including single positions representing whole orders (e.g., spiders, Trichoptera)." Another respondent noted: "In the past 30 years we've lost two full-time entomologists and a full-time mycologist … Several people with taxonomic expertise still reside here but we do less and less taxonomy." Echoing these comments, Packer *et al.*, (2009) reported a 13 per cent decline in professional taxonomists (professors and government taxonomists) working on insects and related taxa over the eight-year period from 1989 to 1997 (dropping from 79 to 69).

Many of the survey respondents indicated that the lack of jobs in taxonomy was a strong disincentive to continuing in taxonomic research. As one respondent put it, "I have always had a keen interest in taxonomy but did not pursue it specifically as a career because there were so few opportunities available." Another person lamented: "Taxonomy is a field of strong interest among young Canadian researchers and students — unfortunately, there are no decent permanent jobs available in our native country and we are forced to move to foreign countries or change professions."

The pipeline to taxonomic expertise is severely narrowed at the point where PhD scientists search for jobs in taxonomy. The lack of job opportunities stands in stark contrast to the growing needs for taxonomy: to identify species at risk (especially following the 2002 enactment of the *Canadian Species at Risk Act*), to evaluate introduced and potentially invasive species, and to discover and document Canada's biodiversity.

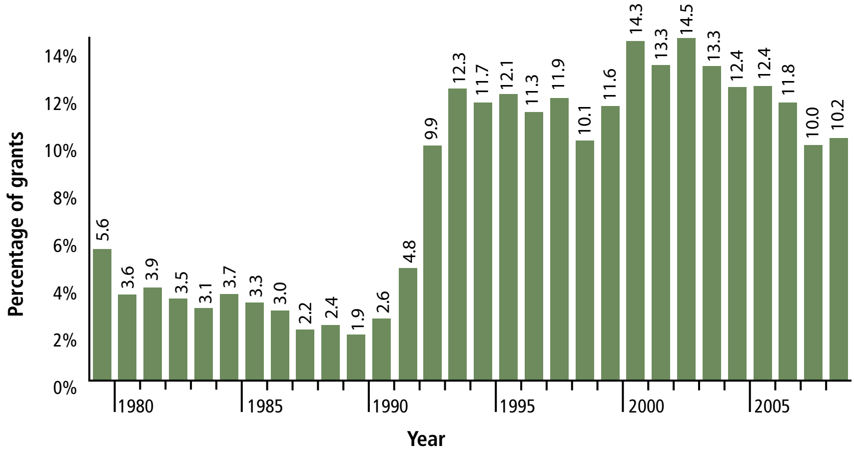
Research Funding

Even among those taxonomists who do succeed in obtaining a job, restricted access to research funds is another hurdle that can prevent researchers from pursuing taxonomic research. The Panel assessed changing trends in research funding by examining data from NSERC's Discovery Grant Program, focusing on those grants that listed "Taxonomy, systematics and phylogenetics" (Research Subject Code 4709) as their primary or secondary subject code. Analyses were limited to the Grant Selection Committee in Ecology and Evolution (GSC18), where the majority of these grants were held.

Figure 4.6 shows that the number of grants to researchers in "Taxonomy, systematics and phylogenetics" grew over the last 30 years relative to other areas in Ecology and Evolution. The majority of this growth occurred during the 1990s and partially reflects the addition of phylogenetics to the subject code in 1990 (4709 was previously called "Taxonomy and systematics"). Indeed, it appears not to reflect an increase in support for taxonomy *per se*: an analysis focused on practicing taxonomists (identified by reputation and/or published research) documented a 23 per cent decline in the number of grants received from NSERC's GSC18 between 1991 and 2007 (Packer *et al.*, 2009).

Funding levels also grew slightly during this time period for grants in "Taxonomy, systematics and phylogenetics" relative to the remainder of GSC18 (Figure 4.7). The growth observed after 1998 in both grant numbers (Appendix 4, Figure A4.2C) and average award size (Figure 4.7) in this subject likely reflects the additional allocation in 1998 of $320,000 by NSERC to increase taxonomic capacity (Federal Biosystematics Group, 1995; Packer *et al.*, 2009). The increased award size appears to have been short-lived, however, and current average levels of funding are now back to pre-1998 levels (Figure 4.8).

The overall trend toward increasing grant size in Figure 4.7 is misleading, however, because of the decreasing value of the Canadian dollar due to inflation. Grant sizes in constant 2010 dollars declined across GSC18, especially over the last decade (Figure 4.8).

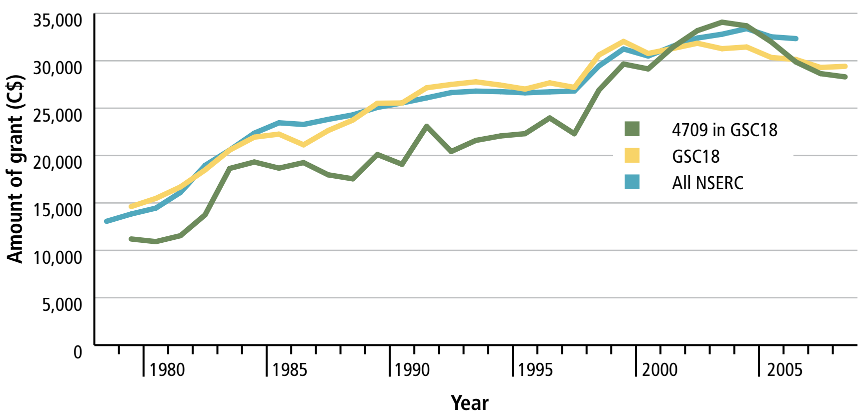


(Data Source: NSERC)

Figure 4.6

Proportion of GSC18 grants awarded in taxonomy, systematics, and phylogenetics

This figure shows the percentage of grants awarded by NSERC's Ecology and Evolution sub-committee (GSC18) to applications using the subject code "Taxonomy, systematics and phylogenetics" (code 4709, NSERC personal communication). See Appendix 4 for additional details.

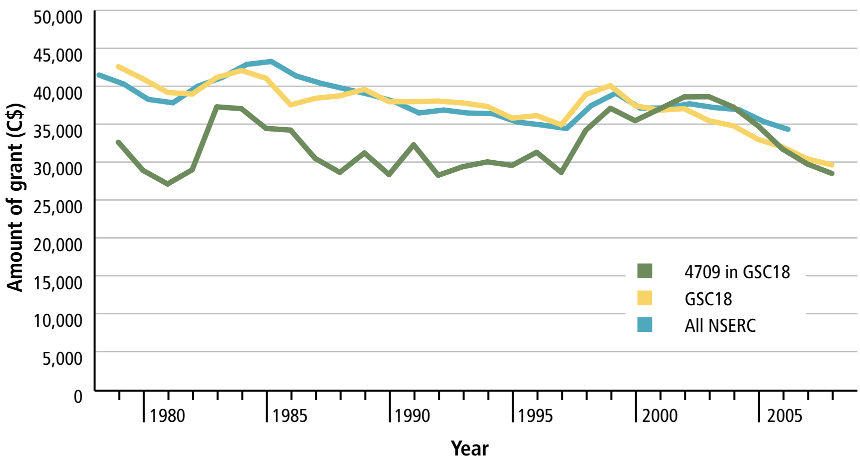


(Data Source: NSERC)

Figure 4.7

Trends in average NSERC grant size, 1978/79–2008/09

This figure shows the average value of grants awarded across the entire NSERC Discovery Grants program (blue, from NSERC, 2007), the Ecology and Evolution sub-committee (GSC18, yellow, from NSERC, personal communication), and the 4709 subset of GSC18 using subject code "Taxonomy, systematics and phylogenetics" (green, from NSERC, personal communication). See Appendix 4 for more details.



(Data Source: NSERC)

Figure 4.8

Trends in average grant size reported in constant 2010 dollars

Details as for Figure 4.7 except that amounts are reported in constant 2010 dollars (see Appendix 4 for more details).

To the extent that the 4709 subject code is representative, these data indicate that taxonomic, systematics, and phylogenetic analyses have grown in total funding level, relative to other areas in ecology and evolution. In absolute terms, however, all of these areas have suffered from stagnant levels of inflation-corrected funding per researcher (Figure 4.8). Furthermore, a more specific analysis focused on practicing taxonomists documented a 45 per cent decrease between 1991 and 2007 in total inflation-corrected funding (Packer *et al.*, 2009), indicating that taxonomists have suffered disproportionately from low NSERC funding levels relative to non-taxonomists using subject code 4709.

Although it is difficult to document trends in the costs of research, two aspects of taxonomic and systematics research suggest that overall costs are rising faster than inflation. First, travel is an important part of taxonomic and systematics research, both for field collection of specimens and research visits to museums and other collections holding relevant specimens. According to the 2010 Consumer Price Index, over the period 1991 to 2009, transportation and energy costs rose 55 per cent and 67.8 per cent, respectively, outpacing the 38.5 per cent increase in overall cost-of-living in Canada (Statistics Canada, 2010). Second, taxonomic studies increasingly supplement traditional morphological data with molecular genetic analyses, adding to the expense of species descriptions. Indeed, over the last decade, more than 35 per cent of publications describing new species mention molecular data analysis in the title, abstract, or keywords, rising from less than 5 per cent in the 1980s and less than 25 per cent in the 1990s.[7] This evidence suggests that a full analysis of costs of research might well demonstrate a substantial erosion in the purchasing power of grants awarded for taxonomic and systematics research.

The telling comment of one survey respondent reflected the sentiments expressed by many others: "What funding [exists] is frequently barely enough to support one graduate student with very limited funding left over for supplies, field work or DNA analyses."

4.4 PUBLICATION TRENDS

With few jobs or funding opportunities, many trainees in taxonomic research are seeking other career tracks. As a consequence, the Panel hypothesized that Canadian contributions to taxonomic research, once strong, might be declining over time.

To examine this hypothesis, the Panel used the *Web of Knowledge*[8] to track the proportion of taxonomic articles since 1973 that have listed Canada as an author's address (Thomson Reuters, 2010). Specifically, a topic search was undertaken for "n.sp. or sp.nov.", two terms that are consistently used in taxonomic papers when describing new species. While the *Web of Knowledge* is not an exhaustive database containing all taxonomic sources, the list is extensive, with articles describing new species being drawn from over 3,411 different sources (the four most common being the *International Journal of Systematics and Evolutionary Microbiology*, *Zootaxa*, the *Journal of Parasitology*, and the *International Journal of Systematic Bacteriology*).

The message is clear: Canada has rapidly lost ground as a world leader in taxonomy. Among the G20 nations plus European Union countries listed in Table 4.2, Canada's ranking dropped from 6th place in the 1980s, to 14th place in the 2000s. Only the ranking of India dropped further (from 5th to 15th place). Out of the total number of publications, Canada's contribution has dropped 30 per cent over the last three decades, from 4.5 per cent of the world's total in the 1980s to 3.1 per cent in the 2000s.

7 *Web of Science* search (July 25, 2010) comparing Topic=((n.sp or nov.sp) and (molecular or DNA or sequence)) to Topic=(n.sp or nov.sp).

8 http://wokinfo.com/

Table 4.2

Ranking by country of new species descriptions

Country	1980–1989	1990–1999	2000–2009
USA	1 (2916)	1 (3171)	1 (5413)
China	10 (189)	10 (582)	2 (3627)
Germany	21 (81)	3 (1405)	3 (2968)
Japan	8 (431)	4 (1178)	4 (2541)
France	3 (685)	2 (1469)	5 (2153)
UK	2 (731)	5 (1151)	6 (1893)
Australia	7 (530)	6 (1016)	7 (1650)
Brazil	17 (110)	13 (394)	8 (1566)
Spain	12 (163)	9 (597)	9 (1344)
South Korea	25 (8)	22 (125)	10 (1274)
Russia	4 (669)	11 (508)	11 (1145)
Italy	9 (200)	7 (648)	12 (1022)
Belgium	13 (149)	12 (445)	13 (980)
Canada	**6 (621)**	**8 (632)**	**14 (926)**
India	5 (666)	14 (374)	15 (791)
Argentina	19 (100)	16 (292)	16 (685)
Netherlands	11 (169)	15 (342)	17 (652)
Mexico	18 (103)	21 (175)	18 (581)
Sweden	15 (119)	18 (267)	19 (465)
South Africa	14 (142)	17 (275)	20 (444)
Austria	20 (94)	20 (207)	21 (428)
Switzerland	16 (114)	19 (252)	22 (366)
Turkey	24 (10)	24 (38)	23 (235)
Norway	22 (78)	23 (124)	24 (210)
Indonesia	26 (5)	26 (9)	25 (90)
Saudi Arabia	23 (20)	25 (14)	26 (46)
Worldwide numbers	**13,694**	**15,766**	**29,151**

(Data Source: Thomson Reuters, 2010)

The number of publications in the *Web of Knowledge* containing the topic “n.sp.” or “sp.nov.”, ranked by country listed as an author’s address. The number in parenthesis gives the total number of papers for the time period. The number of worldwide publications is also given, note that papers in the worldwide count may be listed more than once in the table if there are multiple authors from different countries (details in Appendix 4).

The decline in Canadian taxonomic output is not reflected in related fields of biodiversity science. *Web of Knowledge* searches in evolutionary ecology and in systematics and phylogenetics both displayed slight to appreciable growth relative to the worldwide total number of papers in these topics (Appendix 4). It is reasonable to conclude that the reduction in number of jobs in taxonomy has already had a negative impact on Canadian capacity in this area. In the words of one survey respondent: "It is sad to see that Canada, the unquestioned world-leader in the training and development of taxonomists and systematists [in the] 1960s through 1980s, and perhaps even into the 1990s, has really lost that leadership role."

Along with declining publication rates, there has been a reduction in capacity for publishing taxonomic treatises (monographs and revisions) within Canada. In March 2010, NRC Research Press ceased publication as a press and transferred its journal publications to a new not-for-profit group. Unfortunately, their highly regarded monograph series was not transferred. These have traditionally been an important vehicle for taxonomic discoveries, including a series on the *Insects and Arachnids of Canada and Alaska*, and important books on Canadian biodiversity, such as the *Flora of the Yukon Territory* and *Climate Change & Northern Fish Populations*.

The declining technical contributions of Canadian taxonomists to the worldwide effort to discover and classify new species both reflects and reinforces the reduction in taxonomic capacity and HQP training in Canada. The following quotation from a survey respondent reflects a developing sense of despondency within the field: "As a postdoc, I need high impact publications and grants to get noticed on job applications. A single species description requires more work than running an experiment, and there is no benefit to my career. Sometimes I wonder whether my species descriptions actually look *bad* on my CV."

Risks Associated with the Expertise Gap

As outlined in the previous sections, Canada is facing a widening expertise gap in taxonomy, with the impending retirement of many experts, the lack of job openings to help renew this expertise, and the decline in Canada's contribution to taxonomic discovery and publications. This gap will hamper Canada's abilities to manage its biodiversity sustainably and lead to lost opportunities associated with species discovery. Species are going extinct faster than taxonomists are able to describe them (Hambler & Speight, 1996), a situation that will only worsen if the loss of taxonomic expertise continues. Indeed, the lack of Canadian expertise in a number of taxonomic groups, including terrestrial and freshwater molluscs, lichens, and mosses, has made it difficult for COSEWIC to fill positions on several of its subcommittees. This has led COSEWIC to seek specialists from outside of Canada, who may be less familiar with the specific ecological and legal issues facing species at risk in Canada.

The risks associated with a taxonomic expertise gap are manifold. Canada risks the misidentification of introduced species and inaccurate information about their spread and risk of harm (e.g., Choudhury *et al.*, 2006). Without the expertise to identify species, there is the risk of misattributing the provision of ecosystem services to the wrong species or failing to distinguish species-specific differences in disease transmission, bioremediation potential, and invasiveness (Bortolus, 2008). Canada could then become incapable of assessing species declines in native taxa (Haas, 1998) and in important ecosystem service providers. For example, pollinators provide a crucial ecosystem service (via fertilization) to agriculture, yet there is a growing taxonomic expertise gap in pollinator identification. A 2008 Canadian Wildlife Federation report described the challenge this way: "A number of recommendations aimed at halting pollinator decline require knowledge of the species found in an environment … However, when it comes to furthering our understanding at the species level, it is often difficult to find an expert for the identification or validation of specimens. The decline in specialists in insect pollinator taxonomy is cause for as much concern as the decline in the insects themselves" (Chagnon, 2008). Taxonomy is also key to understanding and predicting changes in the Arctic, as discussed in Box 4.2.

To reverse the widening taxonomic expertise gap in Canada, the evidence presented in this chapter indicates that the HQP pipeline must be widened at the point where trainees seek jobs and there must be more support and recognition for the activities of taxonomists. Without such support, the ability to inventory Canada's biodiversity and to document changes to species abundance and ecosystem composition will be placed at grave risk.

4.5 OTHER TAXONOMIC KNOWLEDGE HOLDERS IN CANADA

The first part of this chapter has focused on highly qualified taxonomists, those with a PhD or equivalent qualification. The rest of this chapter explores the essential role of other taxonomic knowledge, and the collaborations among different knowledge holders that are essential to fully understand Canadian biodiversity.

Box 4.2
Taxonomy in the Arctic

The effects of climate change are already evident in the Arctic (IPCC, 2007). The *Global Biodiversity Outlook 3* (CBD, 2010) describes how the loss of Arctic sea ice threatens an entire biome as many algae, invertebrate, fish and mammal species that are adapted to life on or under the ice are put at risk. Other habitats are also under threat, and paleolimnological studies have shown that some ponds that have been present for millennia, melting for brief periods every summer, are now drying up (Smol & Douglas, 2007). In addition, climate change is opening up the Arctic to increased economic activity (e.g., mining, oil and gas drilling, and tourism).

This rapid change increases the urgency of discovering and understanding Arctic biodiversity. Canada has a responsibility to the world to discover, learn from, and share information about Arctic biodiversity, from microbes to musk ox, before it is lost. We need data to measure environmental change over time. Several important initiatives aim to do just this, including the International Polar Year (IPY),[9] which focused scientific attention on the Arctic from 2007 to 2009, the Arctic Census of Marine Life,[10] and the Arctic Council's Circumpolar Biodiversity Monitoring Program,[11] based in Whitehorse, Yukon. However, these types of efforts need support and expansion as accurate identification of all species is required to perform comprehensive environmental assessments for proposed development, and to monitor environmental impacts.

Taxonomy and Traditional Knowledge

The emerging and evolving relationship between Traditional Knowledge and science is of particular relevance to taxonomy in Canada, where long-established Aboriginal communities can contribute significantly to the broad understanding of species and ecosystems. In his evidence to the Panel, Henry Lickers (Haudenosaunee citizen of the Seneca Nation and Director of the Department of Environment for the Mohawk Council of Akwesasne) explained: "Because of their medicinal and nutrimental uses, species and their unique ecosystems were

9 http://www.ipy.org/
10 http://www.coml.org/projects/arctic-ocean-diversity-arcod
11 http://cbmp.arcticportal.org/

known by Native peoples. As my grandfather said, 'All species were known and our people sang their praises.'" Many Aboriginal communities are now seriously concerned about the continued loss of their specialized knowledge of biodiversity (see also section 2.3). For example, changes in the social and natural environment in the Canadian Arctic have affected Inuit ecological knowledge: children no longer know the names for plants or animals, have lost the ability to fish or hunt caribou, and no longer have contact with their environment (UNESCO, 2009). The camas bulb described in Box 4.3 is another example of this decline in knowledge. The reasons for the erosion of indigenous ecological knowledge are complex and multifaceted, and involve a combination of social, cultural, and environmental factors.

Box 4.3
The Decline of Ecological Knowledge: Camas Bulbs

The story of the liliaceous edible camas bulb (*Camassia* spp. Lindl) is just one example of the decline in traditional ecological knowledge (Turner & Turner, 2007, 2008). Camas was once the most important food source of the Salish Coast First Peoples (British Columbia), and possessed spiritual and cultural value; camas bulbs were eaten at family meals, feasts, and potlatches, and were the subject of ceremonies, dances, and stories. Camas harvest, preparation, and consumption were vital for knowledge and cultural transmission between generations, and the management of the camas ecosystem was a sophisticated and complex process. Over time, however, the knowledge and use of camas has declined steadily, and has largely been forgotten.

With the ongoing decline of Traditional Knowledge in many communities, it is even more imperative that this knowledge be linked more effectively with biodiversity science, particularly through intercultural education. Opportunities exist to increase training of students in both indigenous and Western traditions, who are then able to work in both cultural contexts. Some universities have established Indigenous programs (e.g., Trent University, University of Alberta), and research centres to address indigenous concerns about the integrity of their culture and environment (e.g., Centre for Indigenous Peoples' Nutrition and Environment (CINE) led by McGill University). Disciplines such as ethnobiology, ethnobotany, ethnoecology, or ethnozoology are also becoming increasingly important.

Collaborations between scientists and indigenous experts that are involved in taxonomic work could lead to stronger collecting, curating, databasing, and reporting. Partnerships among indigenous observers, biologists, taxonomists, and ecologists could also create new frameworks for understanding Canada's biodiversity history, future environmental changes, and biodiversity management strategies. Examples of successful partnerships include:

- ArcticNet, a Canadian Network of Centres of Excellence (NCE) that brings together scientists and managers in the natural, human health, and social sciences with their partners from Inuit organizations, northern communities, federal and provincial agencies, and the private sector to study the impacts of climate change in the coastal Canadian Arctic;
- The Northern Biodiversity Program (McGill University), which uses insects and spiders as models for monitoring environmental change across the boreal, sub-arctic, and high-arctic eco-climatic zones; and
- The Aboriginal Fisheries Research Unit at the University of British Columbia, which integrates Traditional Knowledge, aquatic ecology, fish biology, and taxonomy to benefit indigenous peoples' resource management.

In addition to such university-based examples, there are several successful community-based partnerships that facilitate the sharing of regional biodiversity knowledge, including the Arctic Borderlands Ecological Knowledge Co-op, the Nunavut General Monitoring Program, and the Northwest Territories Cumulative Impact Monitoring Program (NWT CIMP). Enabling researchers and indigenous experts to work together on an equal footing — through exchanges, in research centres, or in the field exploring the interlinkages between their ways of thinking — can lead to new approaches and discoveries in biodiversity science. Indigenous leaders invited to give evidence to the Panel highlighted the importance of a dynamic exchange of knowledge under a fair and equitable framework.

The Role of Community Naturalists

Naturalists, including bird and bug watchers, gardeners and plant enthusiasts, and mushroom foragers, make an essential contribution to Canadian biodiversity expertise. They often have an excellent understanding of the species that live in their region and play an important voluntary role in documenting and recognizing changes in biodiversity. Some naturalists organize themselves into natural history societies or similar groups, but membership of these organizations is aging and recruitment seems to be a problem. For example, the Lepidopterists' Society, a North American group of naturalists and professionals, has seen a steady decline of 5 per cent to 10 per cent per decade since 1985 and, even more alarmingly, the average age of its members is increasing by six months every year (F. Sperling, personal communication).

The increased urbanization of Canadian communities has dramatically reduced the connection between youth and nature; over the last century, the number of Canadians living in urban rather than rural environments has doubled, and now exceeds 80 per cent (Statistics Canada, 2006b). This is an international phenomenon well described in Richard Louv's book *Last Child in the Woods: Saving our Children from Nature Deficit Disorder* (Louv, 2008), which shows the benefits of a relationship with nature to children's health and well-being. Providing opportunities for children to explore and be inspired by nature benefits both their emotional and intellectual development and encourages a desire to protect and restore the environment (Miller, 2005). In recognition of the need to witness nature first-hand, the Get to Know network (Get to Know Society, 2010) has partnered with over 100 institutions to promote nature appreciation and literacy in Canada.

Although fewer Canadians are living in close contact with wildlife than ever before, the public increasingly values biodiversity and places a high priority on the need to preserve nature. When asked to choose where they would prefer to spend more tax dollars, Canadians prioritized "Protect our environment, ecosystems, and biodiversity" alongside "Reduce poverty and inequalities in wealth within Canada" at the very top of 20 quality-of-life investment goals (Rudd, 2010). Canadians also placed a high monetary value on preserving species at risk, with a willingness to pay tens of millions of dollars for species such as the porbeagle shark to hundreds of millions for Atlantic salmon (Rudd, 2009).

This desire to reconnect with and preserve nature is evidenced by the large number of contributions to databases such as the *Encyclopedia of Life*[12] and the growing number of amateur-expert collaborations through BioBlitzes and Christmas Bird Counts[13] (see Chapter 6). Indeed, there is a growing network of "citizen science" programs, such as those sponsored by Environment Canada including FrogWatch,[14] WormWatch,[15] and PlantWatch,[16] which are used to collect national information on ecosystem health.

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12 http://www.eol.org/
13 http://www.bsc-eoc.org/national.html
14 http://www.naturewatch.ca/english/frogwatch/pq/
15 http://www.naturewatch.ca/english/wormwatch/
16 http://www.naturewatch.ca/english/plantwatch/

For Canada to adequately document trends in Canadian biodiversity over the coming decades, a framework is required that incorporates community-based contributions to record and monitor species, alongside industrial, non-governmental organizations (NGOs), governmental, and university efforts. Citizen science is an important component that facilitates sampling from more numerous localities and more frequent time points. To be effective, however, citizen science must be coupled with scientific expertise (see Box 4.4), especially taxonomic expertise, to reduce the risks of misidentification and insufficient data collection. It must also be given sufficient funding to put these contributions to optimal use. As an example of such a partnership, images submitted to the *Encyclopedia of Life* are tagged as "has not been reviewed," until confirmed by an expert.

Community naturalist programs, if adequately funded and well-run, can provide valuable biodiversity information, help Canadians develop biodiversity expertise, and encourage interest in and respect for the natural environment. They can allow Canada to leverage existing taxonomic expertise to assess a broader swath of Canadian species and to expand the geographic reach of our data. Such efforts also build biodiversity-literate communities — real and virtual — that can engage and inspire new generations of naturalists and taxonomists.

By investing in biodiversity networks that catalyze the exchange of information among citizen scientists and taxonomists, as well as stakeholders in industry and government, Canada has the potential to develop an extensive monitoring system for the spread of invasive species and the decline of native species.

Box 4.4
The Value of an Alert Citizenry

The importance of community naturalists is exemplified by the Asian long-horned beetle (Family Cerambycidae), a devastating killer of a wide variety of trees, especially maple trees. The beetle was first discovered in North America by New York residents who alerted authorities about the unusual tree damage in their neighbourhood (Milius, 1999). At this point a taxonomist with expert knowledge of cerambycid beetles identified the species, its provenance, and initiated an effective eradication campaign. By comparison, in Halifax, a lack of local taxonomic expertise delayed awareness of a similar invasion of another species, the brown spruce longhorn beetle, by at least a decade, even though voucher specimens from a general survey had already been deposited in a regional collection (Smith & Hurley, 2000).

Training Taxonomists for the Front Line

Although this report has focused on the status of practicing taxonomists — those who describe new species, revise our understanding of species relationships, and teach us how to distinguish among species — people trained to use and apply taxonomic knowledge play a critical role within Canada today. Often trained at the bachelors- or masters-level, practitioners who have learned how to key out and identify species form the front line in describing and monitoring biodiversity in Canada today. Such people work in government, NGOs, and universities, or may serve as volunteers to carry out a variety of tasks that are essential to our ability to assess the health of Canadian biodiversity, including:

- Environmental assessments and impact statements
- Species-at-risk reports
- Biodiversity surveys
- Agricultural analysis of weeds and invasive pests
- Border control of endangered or non-native species
- Nature guides

Taxonomically trained Canadians also play a key role in species discovery, as they are often the conduit between community naturalists and the taxonomic experts who are capable of describing the species in question. As citizen science becomes an integral part of biodiversity surveys, this cadre of experts will serve an important bridging role by validating identifications and other data.

To serve this critical bridging role, however, these experts must be trained. With a diminishing number of taxonomists in university positions, Canada may lose its capacity to teach courses targeted at identifying different groups of species. Sponsored courses and workshops that are open to students from throughout Canada would be an excellent way for Canada to maximize the taxonomic capacity that we do retain. Funding for these courses could be targeted to those groups where Canada has a relative lack of expertise (Figure 4.5 and Appendix 1, Figure A1.5) and to groups of particular economic importance. Ideally, these courses would be available to undergraduate students and open to members of the public and private sector whose work would benefit from such training.

Collaboration Among Different Taxonomic Knowledge Holders

By investing in training and in biodiversity networks that catalyze the exchange of information among Traditional Knowledge holders, citizen scientists, and taxonomists, Canada has the potential to develop an extensive monitoring system for the spread of invasive species, like the Asian long-horned beetle, and the decline of native species. It will be better positioned to understand, monitor, and ameliorate ecosystem changes caused by human activities, locally and globally. It will amass a more complete inventory of our natural resources. These natural resources support and inspire our society and provide sources of pharmaceuticals, antibiotics, and enzymes vital to industry. Together, Canadians can realize a most ambitious and vital big science project: to discover and document all the biodiversity living within its borders.

Chapter Key Messages

Canada was once a leader in taxonomy, but its position has greatly diminished over the last 30 years.

Student interest remains and taxonomists continue to be trained, but there is cause for concern that existing expertise will not be renewed. Job prospects are very low; trainees shift focus away from taxonomy to get hired and to publish in high-impact journals.

Research funding levels are stagnant. The lack of jobs and funding in taxonomy has led to a dramatic reduction in the contribution that Canada makes to worldwide efforts to discover and describe Earth's biodiversity.

Collaborations among Traditional Knowledge holders, citizen scientists, industry, governments, and universities are key to tracking and documenting changes in biodiversity, including through long-term monitoring programs.

Chapter 5 Canada's Taxonomic Collections

Biological collections are the foundation for taxonomic research, a legacy of past work, and a basis for future investigations. Canadian collections, a national treasure with more than 50 million specimens and growing, require a national strategy and investment to preserve and develop for future generations.

A biological collection is a knowledge bank with each specimen representing vast amounts of information encoded in its genes and expressed in its morphology. A biological collection is also an innovation bank because the many and diverse species it contains represent evolutionary innovations that humankind can exploit for sources of food, pharmaceuticals, and other goods and services.

Museum displays and teaching tools related to biological collections are a popular source of inspiration for the public, particularly children. Museum collections staff routinely visit schools and naturalists' organizations to promote interest in, and love of, nature. Public attendance at museums is huge: for example, some 300,000 visitors a year visit the Manitoba Museum; the Canadian Museum of Nature attracted 250,000 visitors a year even during its recent reconstruction; and the Royal Ontario Museum's attendance jumped to nearly 1 million visitors in the year following its own extensive renovations.

The more than 50 million specimens contained in Canadian biological collections, the oldest of which date back to the early 19th century, are of central importance to biodiversity studies. There are more than 80,000 type specimens in Canadian collections from which species and subspecies have been described. A good portion of these will be species found in Canada, but our collections also hold many specimens, including many type specimens, from species resident in other parts of the world.

This chapter examines the current state of Canadian collections of biological specimens (section 5.1), the facilities in place for their care and curation (section 5.2), and the institutions that house and study the specimens, including their organization, governance, and policies (section 5.3). The final component of biological collections — the data — is the subject of Chapter 6.

Box 5.1
Johansen's Sulphur: An Ice Age Arctic Butterfly at Risk to Climate Change?

(Courtesy of Agriculture and Agri-Food Canada, Canadian National Collection of Insects and Arthropods)

When the last ice age, with its mile-high ice sheets, swept down through Canada 100,000 years ago and then began its retreat 20,000 years ago, it wiped out almost all butterfly populations. A few relict species, however, clung to isolated ice-free refugia high in mountains or in coastal regions — the oldest extant butterfly populations in Canada and of enormous scientific and conservation interest. One of the most intriguing butterfly relicts is Johansen's Sulphur (*Colias johanseni* Troubridge & Philip). A single specimen of this butterfly was discovered in 1916 by Fritz Johansen, a member of an ill-fated Arctic expedition. The specimen (see photo) was collected at Bernard Harbour on the Canadian Arctic coast and eventually ended up in the Canadian National Collection (CNC) in Ottawa, placed in a drawer of a look-alike species known from the Rocky Mountains.

In the 1990s, after noting this butterfly's unusual location reference on the label and then referring to Johansen's diary, two taxonomists, Jim Troubridge and Kenelm Philip, revisited Bernard Harbour and found more individuals of the species on the hillside location indicated by Johansen. After careful review of the literature and specimens of similar species, they identified it as a new species: a Canadian endemic that appears to have survived the ice age in an Arctic Ocean coastline refuge.

Having survived the ice age and then awaited re-discovery for 80 years (made possible by the single specimen held in the CNC), Johansen's Sulphur may soon face another risk: the arctic ice cap is now forecast to continue melting at an accelerated rate due to climate change. With markedly increased temperatures, rising sea levels, and other effects still undetermined, what then will happen to Johansen's Sulphur and other similar relict organisms in the face of such enormous changes to their ecosystems?[17]

(Hall, 2009)

[17] Adapted from a story by Don Lafontaine, Canadian National Collection of Insects, Agriculture and Agri-food Canada, Ottawa.

Much of the Panel's analysis in this chapter is based on the responses to its collections survey, which was distributed to biological collections holders across Canada. One hundred and twenty institutions and collections, which hold the vast majority of biological specimens in Canada, responded to the survey (see Appendix 2). The actual number of collections and specimens held in Canada will be somewhat larger than reported in the survey as, of course, some "orphan" collections with no owner or curator were not reported.

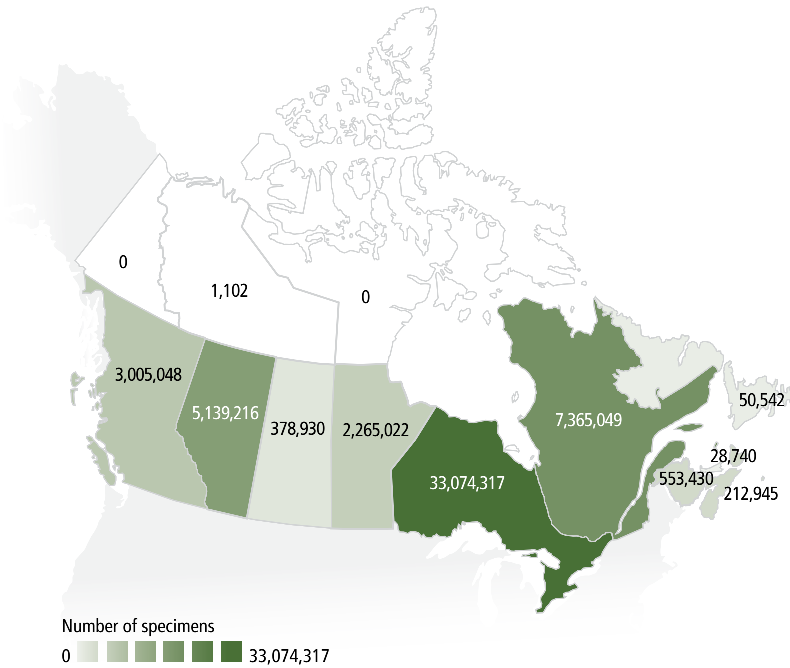
The main purposes for maintaining Canadian biological collections are as varied as the institutions in which they are housed. The purposes mentioned by survey respondents include: species identification, taxonomic research, economics research, medical research, natural heritage preservation, documentation of biodiversity, analysis of genetic resources, and education. (Box 5.1 provides an example of the historical value of collections.) One respondent warned: "Natural history collections are the archives of the Earth — Canada needs to recognize that these archives are of increasing value as our wild areas shrink and climate changes. Documenting change without knowing the past is not possible." Collections data combined with other data, such as field data on size and status of populations, can greatly contribute to documenting climate change.

5.1 SPECIMENS

Biological collections are held in all provinces but only one territory – the Northwest Territories – reported a collection (see Figure 5.1 for specimen holdings by province and territory). As reported by survey respondents, 62 per cent of Canadian collections are mainly local or regional, 18 per cent are mainly national, and 33 per cent are international.[18]

The specimens in Canadian collections come from a variety of sources. The institutions themselves often employ scientists and technicians who collect on behalf of the organization for the specific objectives of that organization. These institutions are often involved in exchanges of material to fill gaps or loans of material that are temporarily housed in the collection. As well, many collections accept donations from private individuals who have amassed their own collections. Such donations, which can number in the tens of thousands of specimens, can be historically very important. Finally, individual specimens, or sometimes whole collections, are purchased by institutions.

[18] The total of these percentages does not equal 100 because some collections self-reported as being international as well as either mostly local or mostly national.



(Council of Canadian Academies)

Figure 5.1
Specimen holdings by province and territory

Number of Specimens by Species

According to a 1995 estimate carried out for the Canadian Museum of Nature, there are 106,000 species in Canada (Mosquin *et al.*, 1995; see Table 5.1). Although this number (which does not include microbial species) is small compared with the 5 to 10 million species estimated globally (May, 2010), these species are critical to our ecosystem health and services. And yet, as shown in Table 5.1, only about 65 per cent of our larger species have been named and described to date. And if smaller organisms, such as microbes, were included (see Box 3.1 on the diversity of microbes), the actual percentage known would indeed be very small. According to the survey, most Canadian described species are represented in Canadian collections (see Appendix 2, Table A2.6). The numbers of estimated specimens by group, based on the collections survey carried out for this report, have been added to the last column of Table 5.1 (presented according to the descending order of *percentage of species described*).

Table 5.1

Estimated number of species and specimens in Canada and the number of specimens reported in the Panel's survey

Group	Reported number of species	Total number of species	Percentage of species described	Number of specimens reported in survey of Canadian collections (millions)
Vertebrates (excl. fish)	662	662	100	1.1
Plants	4,120	4,256	97	7.0
Algae	5,300	7,280	72	0.2
Fungi & lichens	11,130	16,455	69	0.8
Fish	1,021	1,521	67	3.7
Invertebrates (excl. insects)	17,362	28,327	61	6.6
Insects	29,985	54,653	55	29.9
Microbes	n/a	n/a	n/a	0.02
Fossils	n/a	n/a	n/a	2.7
Total	**69,580**	**106,602**	**65**	**52.1**

(Data Source: Gagnon & Fitzgerald, 2004; Mosquin *et al.*, 1995 & Council of Canadian Academies)

The first four columns are modified from Gagnon & Fitzgerald (2004), including taxonomic groupings. The final column is the total number of specimens reported for each taxa in the survey of Canadian collections.

The number of specimens in collections of any particular species depends on who collected them and for what purpose, as well as on the rarity of the species collected. Some very rare species are only represented in a single collection by one or, possibly, a few specimens. In other research studies, however, large samples of some species were collected for a variety of reasons, including taxonomic reviews (DNA and morphological), distribution records over time, ecological data that may be variable, and vouchers for studies referring to multiple specimens. (See Box 5.2 for an example of multiple specimens held in a collection from which later studies benefitted.) Some collections also contain specimens of species that are now extinct, and exist only in collections, for example, the stuffed specimens of the passenger pigeon in the Beaty Biodiversity Museum, Vancouver.

Box 5.2
Enos Lake Sticklebacks: Collection Shows Evolutionary Havoc Wreaked by Invasive Species

(Courtesy of Janette Boughman & Tiffany Malek)

In the cabinets of the new Beaty Biodiversity Museum at the University of British Columbia, there are specimens of extinct local stickleback fish (*Gasterosteus* sp.) that originated in Enos Lake on Vancouver Island. Two distinct types of sticklebacks lived in Enos Lake, one (benthic) living along the shore and the other (limnetic) in the open water (McPhail, 1984). For decades, these two closely related species lived side by side, remaining distinct in morphology, genetics, habitat, and nesting sites. Then, in the early 1990s, a species of crayfish (*Pacifastacus leniusculus* Dana) was introduced by humans to Vancouver Island. The crayfish wreaked havoc on the environment, eating small fish and literally overturning the habitat. Sticklebacks remain in Enos Lake but they now exist as a single hybrid swarm, intermediate in form between the formerly distinct benthics and limnetics (Kraak *et al.*, 2001). The species pair is gone.

The stickleback species pair was noticed and understood as a result of field work and natural history collecting. Because the specimens, and their associated data, were preserved for posterity in the museum, their significance can continue to be studied and appreciated. By comparing the fish before and after the arrival of crayfish, and analyzing the DNA archive, or genetic "fossil record," of the specimens, scientists have been able to document the genomic consequences of the species' collapse (Taylor *et al.*, 2006). The story of the Enos Lake sticklebacks demonstrates the treasure trove of irreplaceable information held in collections, and its significance for future generations.

Number of Specimens by Collection

The 120 collections that responded to the survey differ considerably in size, ranging from the 16.7 million specimens held by the national collections at Agriculture and Agri-food Canada to a few hundred specimens held by small, specialized collections (see Table 5.2 for the largest collections in terms of number of specimens). Eighty-one per cent of the collections appreciably increased the size of their biological holdings in the last 10 years, while about three per cent decreased their holdings. Financial/budgetary constraints were identified as the biggest factor in decreases in collection size (32 per cent). As long as there are gaps in our knowledge of Canadian species and their distributions, further specimens will need to be collected and preserved.

Although there may be some advantages in concentrating specimens in large institutions for cost-efficiency-of-scale or to avoid duplication of effort, there are valid reasons for maintaining multiple collections across the country, including facilitating research and teaching at multiple institutions, exposing youth to collections-based research, and insuring against disasters. Regional holdings, for instance, are valuable for environmental consulting firms that need reference collections in order to identify species. Such firms would otherwise either have to develop their own reference collections, travel long distances, or simply not validate their material. Regional holdings also tend to have much better representation of local flora or fauna than large collections aiming to be global in scope. Furthermore, taxonomic expertise could become more limited if scientists working in taxonomy were to be concentrated in only a few, large institutions. The same logic supports the maintenance of collections in Canada even though large institutions in other countries also hold substantial numbers of Canadian specimens.

Table 5.2

Largest Canadian collections by estimated number of specimens as self-reported in the survey

Collection institutions	Type of collection	Location	Number of specimens (millions)
Canadian National Collection of Insects, Arachnids and Nematodes	Federal government	Ottawa, ON	16.7
Canadian Museum of Nature	Federal government	Ottawa, ON	7.4
University of Alberta	University	Edmonton, AB	3.5
McGill University	University	Montréal, QC	3.4
Royal Ontario Museum	Provincial government	Toronto, ON	3.2
University of Guelph	University	Guelph, ON	2.5
Université de Montréal	University	Montréal, QC	2.5
University of Manitoba	University	Winnipeg, MB	2.1
University of British Columbia	University	Vancouver, BC	2.1

(Council of Canadian Academies)

These are self-reported numbers and may not be comprehensive. Only biological specimens are included, not cultural or geological specimens.

Estimating Specimen Values and Costs

Institutions and managers have generally not attempted to put any monetary value on their collections. In the Panel's survey, there were very few answers to a question on collection value. Most specimens, particularly historical specimens with full data, are considered irreplaceable or priceless, though it is important that biological collections apply some monetary value to their specimens for insurance purposes. The Canadian National Collection of Insects applies an average value of $5 per donated specimen for the purposes of issuing tax receipts, provided the specimen is of good quality, has been identified, and has its basic data attached. This value increases, however, for voucher specimens, and specimens of particularly large or rare species. Some large fossil specimens may be valued at thousands of dollars each. If one were to apply the Canadian National Collection's $5 average value per specimen to all specimens in Canadian collections, the total value would exceed $250 million. The true cost of replacement for all this material would be much higher, especially for rarer and more remotely collected specimens. For those taxa that are no longer available for sampling, there can be no replacement.

Costs associated with collections are often considered by managers as they must be included in annual budgets for most institutions with collections. The costs of acquiring specimens, as indicated by survey respondents, however, vary from one dollar to thousands of dollars per specimen, with most in the lower part of this range. Acquisition costs are partly dependent on the size or importance of a collection (the larger the collection, the lower the cost per specimen tends to be). Maintenance costs of specimens per year vary even more than acquisition costs, ranging from $0.001 to $500 per specimen depending on type, size, and condition, and the actual costs that were included in the calculation.

In reality, the actual cost of a collection involves many factors. The cost of specimen acquisition itself includes salaries, travel, shipping, and sometimes purchase; but much higher costs are associated with maintaining a collection over time, including building facilities, heating and cooling, electricity, preservation methods, other supplies, and, of course, staff salaries.

5.2 COLLECTION FACILITIES

This section looks at the state of collection facilities in Canada, including storage and building conditions, accessibility for research, level of curatorial care, use of tools and technologies, availability of best practice standards, and projections for the future.

Storage Conditions and Conservation

The conditions under which specimens are stored in Canadian collections differ considerably depending on the resources available to individuals and institutions. Specimen size and storage methods are also extremely varied — a frog, a butterfly, a plant seed, and a dinosaur skeleton all require different expertise and facilities for their preservation and display, with each prone to a number of factors causing deterioration.

The condition of the specimens themselves varies widely depending on a number of factors: date of collection, method of collection, condition upon collection, curation method, storage facility, pest control, and environmental conditions (light, temperature, and humidity). The term most often used for these factors is conservation, which can be defined as, "The employment of best practice to prevent or arrest the long-term physical deterioration of natural specimens and associated artifacts and documents to preserve their scientific and cultural worth" (Carter & Walker, 1999). The ten agents of deterioration that could damage or destroy collections specimens include physical forces, fire, flood, contaminants, pests, light and ultraviolet light, incorrect temperature, incorrect relative humidity, custodial neglect, and criminal activity (Canadian Museum of Nature, 2010).

In the Panel's survey, 48 (40 per cent) respondents felt that the condition of their collection had improved in the past 10 years, 20 (17 per cent) reported a deterioration, and 44 (37 per cent) stated there was no significant change in collection condition. (Eight collections did not respond.) The majority reported that over 75 per cent of their collection was currently stored in adequate conditions (Appendix 2, Figure A2.6). This represents about 78 per cent of specimens currently being held in adequate conditions — a tremendous asset for Canada.

State of the Buildings

The age of the buildings where collections are held ranges from 150-year-old neo-gothic museum facilities to modern institutes built in the last decade. The state and condition of these buildings is equally varied depending on the costs of much-needed renovations and the resources available to the individual holders. While some national collections in other countries, such as the Smithsonian Institution in the Washington D.C. area and the Natural History Museum in London, U.K., are establishing new storage facilities with state-of-the-art climate and pest control systems, Canada's national biological collections are housed in a wide variety of mostly older facilities, with only the Canadian Museum of Nature collections of mostly larger specimens (mammals, birds, etc.) in recently built, adequate facilities.

Canada's National Insect and Plant Collections, for example, are housed in two heritage buildings at Ottawa's Central Experimental Farm. These buildings were not designed to hold large biological collections; the huge insect collection has no climatic controls for its long-term preservation (climate controlled storage is also beneficial for molecular taxonomic research material). The buildings are now full and these conditions restrict future growth. Compact storage is being installed to temporarily ease this situation (see Box 5.5).

Accessibility for Research

Another important issue for collection facilities is the accessibility of the specimens for research purposes. Even if specimens are adequately conserved, they may be housed in off-site facilities or inadequately curated and catalogued, which makes them difficult to locate. Large donations are often submitted in no taxonomic order and are stored intact with no clear, accessible record of specimens contained. Only 73 survey respondents (61 per cent) indicated that all of their specimens were accessible for research or other purposes.

Collections with parts inaccessible or stored under inadequate conditions (see Appendix 2, Figure A2.7) reported that, in order to rectify the situation, their top needs were as follows: increased curatorial or technical staff (34 responses); increased additional on-site storage (18 responses); and new and improved storage equipment, like shelving, cabinetry, and racks (13 responses).

Curatorial Care

All collections require some curatorial capacity for their long-term maintenance, with curatorial personnel playing widely differing roles in different types of institutions. Larger organizations often have dedicated personnel for collections preservation. In some institutions, this role falls to the scientists or the technicians. Some biological collections, or parts of larger collections, have had no curatorial capacity for many years. These are often referred to as orphan collections. Over 30 respondents commented that all or parts of their collections had no or very limited curatorial care. In some institutions, curating is done by volunteers, often retired scientists or technicians who continue on with some curatorial activities after retirement. While extremely helpful, such individuals should not replace permanent curatorial capacity.

Best Practice Standards

The term "best practices" is a difficult one. It implies that acceptable standards are applied to Canada's biological collections, that such standards are readily available and agreed upon, and also that there are resources available to maintain them. Many of the world's top natural history museums, such as the Canadian Museum of Nature,[19] the Natural History Museum in London, U.K.,[20] and the American Museum of Natural History[21] in New York, U.S., have established their own publically stated standards to which they attempt to adhere. These standards for collections care deal with conservation, risk management, collections-related services, data management, ethics, governance, and accessions and de-accessions.

For the most part, individual Canadian biological collections operate under a wide variety of standards. Usually standards are contained in policy statements, but only 49 survey respondents (41 per cent) reported having publically accessible policy statements. See Box 5.3 for Natural Sciences and Engineering Research Council (NSERC) guidelines for university research collections.

Every collection policy should contain a risk assessment plan for unforseen events such as fire and water damage. Collections should always have an adequate record of conservation activity, including how the specimens were collected, the procedures for acquisition, preservation methods, and usage (loans, visiting researchers, etc.). As staff members turn over in any institution, such records are invaluable for passing along the history of the collections and best practices related to them.

Box 5.3
NSERC Guidelines for Museums

In 1999, NSERC issued guidelines for researchers working with university-based collections funded by federal granting councils (NSERC, 1999). These guidelines, which cover ownership and transfer of specimens, curation, documentation (labeling and databasing), and accessibility of data and specimens, focus on the need to establish the responsibilities of researchers and their institutions for properly maintaining a collection. They also emphasize the importance of giving Canadian institutions a right of first refusal when identifying a long-term repository for specimens. The growing collections of genetic material associated with specimens, as well as changing opportunities for databasing specimens, should be reflected in future updates to the guidelines.

19 http://www.nature.ca
20 http://www.nhm.ac.uk
21 http://www.amnh.org

Future Projections

A total of 104 collections managers responded to the survey question that asked for a brief description of their five-year projections with regard to space, finances, and research capacity: 57 per cent plan to maintain the status quo providing funding is not decreased, 21 per cent definitely plan to expand facilities, 10 per cent plan to expand if funding is available, 7 per cent plan to decrease facilities, and 5 per cent plan to cease collections facilities. The overall impression is that without increased funding, or in some cases substantial new funding, many facilities will run out of space in the next five years for any future growth of collections. One survey respondent explained: "Many collections do not have sufficient space for growth and development and all collections should have a 20-year plan. The federal government in recent years has had discussions about better coordinating their collections activities, but no funded strategy has yet been approved."

New Approaches and Technologies

Many new approaches have become available in recent years to improve how biological collections are managed, including new storage facilities (e.g., compact storage, climate controls); collections of DNA; database methods for specimen label information; imaging technologies for specimens (particularly type specimens); tools for maintaining collections of microbial and fungal cultures; and computerized data and information sharing.

Where resources have made these new approaches and new technologies available to collections managers in Canada, access to collections and information has greatly improved. Examples of gains include increased room for growth, better preservation of specimens, online access to images and data, increased use of living materials, and acceleration of species descriptions. Access to and management of biodiversity data is discussed in Chapter 6.

5.3 TAXONOMIC INSTITUTIONS

Natural history collections in Canada are held in a variety of institutions (see Table 5.3). In the Panel's survey, universities and colleges accounted for 43 per cent of all collections; provincial and federal governments, combined, made up 39 per cent; and private institutions, and personal or private collections, accounted for the remaining 18 per cent. Most of these collections are in museums, and the largest of these institutions are either operated by governments or exist as arms-length corporations. Field stations are also an important type of taxonomic facility where much specimen collection and some specimen preservation occurs. As well, some government laboratories and consulting firms may have some preserved specimens, though such collections may end up being discarded after data workup for lack of further interest and curatorial capacity.

Table 5.3

Distribution of survey respondents and specimens by institution type

	Respondents		Specimens	
Type of institution	Number	% of total	Number (millions)	% of total
Federal government	26	22	26.5	51
Universities	52	43	18.5	36
Other government	20	17	4.6	9
Other collections	22	18	2.5	4
Total	**120**	**100%**	**52.1**	**100%**

(Council of Canadian Academies)

This table shows the number of collections responding to the survey by type of institution, as well as the total number of specimens represented in this category. Most specimens are in federal government collections (see Appendix 2 for more details).

In general, museums have two interrelated, but not necessarily compatible, components: a visible museum of public exhibits, displays, and educational activities on one hand; and an inner museum of collections and research on the other. Museums may be wholly devoted to one or the other: some museums consist entirely of public exhibits while others have no public exhibits at all.

Canada's museums vary tremendously in size, personnel, and purpose. Almost all museums of note are at universities or associated with governments at some level. Museums and their collections are governed and managed under an array of different organizational schemes, with no consistency as to how they are operated. Although most of the larger institutions are safeguarded, smaller collections often have no long-term organizational security. This is a substantial problem that threatens to jeopardize care of, and access to, a significant fraction of Canada's biodiversity collections.

University Museums

Some university museums are modest collections, used only for research or teaching, that fit into one or a few cabinets or a single room; others consist almost entirely of public displays of mounted specimens that may date to the 19th century; and a few are large academic institutions with extensive research and teaching collections, public exhibits, and outreach programs. Although there are some large university museums, including the Beaty Biodiversity Museum and the Redpath Museum, 20 out of 28 university museums (71 per cent) that responded to the survey's follow-up questionnaire reported having no more than two people involved in looking after the collection.

Most university museums are specialized research and teaching collections of particular sorts of organisms. Many of the smaller collections stem from the research and teaching activities of an individual professor. For example, Professor J.P. Bogart built a herpetological collection at the University of Guelph, Professor Y. Alarie amassed a collection of aquatic insects at Laurentian University, Professor W. Schofield assembled a collection of bryophytes at the University of British Columbia, and Professor P. Brunel accumulated a collection of marine invertebrates at the Université de Montréal. These sorts of small teaching collections often become orphaned when a department changes emphasis or the researcher retires. These legacy collections remain valuable for training purposes, but often go unsupported both curatorially and financially.

Formally designated departmental museums either originate from individual collections such as these or are derived from outside donations of specimens. For example, the Herbarium at the University of British Columbia now possesses Schofield's bryophytes as well as the seaweeds collected by Professor R. F. Scagel. The Fowler Herbarium of the Department of Biology at Queen's University, the Claude E. Garton Herbarium of the Department of Biology at Lakehead University, and the George F. Ledingham Herbarium of the Department of Biology at the University of Regina are among university herbaria based originally on individual collections. At McGill University, the Redpath Museum's holdings were originally based on Sir William Dawson's paleontological, zoological, and geological collections (see Box 5.4). Also at McGill, the Henry H. Lyman Entomological Museum run by the Department of Natural Resource Sciences began as an insect collection bequeathed to the university by Lyman in 1914.

Box 5.4
The Redpath Museum, McGill University

(Courtesy of David M. Green)

The changing fortunes of the Redpath Museum over more than a century illustrate the renewed importance of museums with biodiversity collections in Canada. The museum, financed by Peter Redpath and designed specifically for Sir William Dawson in 1882, was the first purpose-built museum building in Canada. Yet by 1910, with its original supporters having passed away, the museum's perceived value and relevance to the university was small; it remained largely a backwater for the next 40 years. The museum turned primarily toward public exhibits during the 1950s, but in 1970, the university concluded that it could no longer support a public natural history museum in the heart of its campus and closed the museum. All the while, though, researchers and curators still carried on their work.

The modern era for the Redpath Museum began in 1986 when it once again had permission to begin a modest public program in concert with its academic contributions to the university. The museum was transferred administratively to the Faculty of Science in 1995 and the building was restored to its earlier splendour. Today, the Redpath Museum is far more productive, and has far more personnel, than ever in its history. Its collections now contain over 400,000 paleontological and zoological specimens. Dawson would be impressed to see how his 19th century museum has evolved into a vibrant 21st century hub for biodiversity research and education.

(Redpath Museum, 2007)

Most university museums are departmental, though there are significant exceptions. The Thomas McCulloch Museum at Dalhousie University is typical in that it has a curator who reports to the head of the Department of Biology, though some university professors who look after their own collections point out that they do so on their own.

In some instances, universities have made efforts to bring various, disparate departmental collections together administratively, or even physically. Although the University of Alberta's various museums and art galleries, including its natural history collections, remain physically separate and located mainly in academic departments, an administrative Department of Museums and Collections Services now oversees them all in support of museum policies, databasing, and outreach. The Beaty Biodiversity Museum at the University of British Columbia carries this amalgamation much further by bringing together previously scattered departmental research and teaching collections into a single, new building and administrative structure. Although the museum is administered overall by a director who reports to the university's Dean of Science, the integration is as yet not complete. Each collection retains its own director and the management of each collection is slightly different. At McGill University, there is a long history of dealing with its various museums in different ways. All McGill museums, at one point, were administered by a museums committee and then by the University Secretariat, but that model, now effectively used at the University of Alberta, never took hold. Most McGill museums, including the Lyman Museum and the McGill University Herbarium, are now departmental. The exception is the Redpath Museum (see Box 5.4), which functions as an academic department in its own right, with tenure-track academic staff, a small but growing slate of graduate and undergraduate courses, and a director who reports to the Dean of Science.

Government Collections

Although government-operated museums and collections (federal, provincial, and territorial) are fewer in number than university museums and collections, they include some of the largest collections in the country. The nation's single largest collection is the Canadian National Collection of Insects, Arachnids and Nematodes (see Box 5.5), which contains 16.7 million specimens. Other major government collections include the Canadian Museum of Nature (federal) and the Royal Ontario Museum (provincial). There are also many smaller collections in the public sector, such as the Dr. Marjory Helen MacGillivray Aphid Collection, the National Mycological Herbarium, and the Prince of Wales Northern Heritage Centre, all with no more than two people involved in looking after the collection. These smaller collections amount to 16 out of 25 (64 per cent) of the federally, provincially, and territorially operated museums that responded to the survey's follow-up questionnaire.

The larger of the government-operated museums are generally organized on a corporate model. For example, the Canadian Museum of Nature is a federal crown corporation governed by a board of trustees that reports to the federal parliament via the Minister of Canadian Heritage. An executive, consisting of a president, vice-president and management team, is responsible for the museum's performance. The Royal British Columbia Museum is a corporation operated by a CEO and an executive which reports to a board of directors. The Manitoba Museum has a CEO who reports to a board of governors.

Other federal and provincial museums are more tightly linked to their respective governments. The New Brunswick Museum is a provincial institution funded by the Province of New Brunswick and governed by a president and board of directors.

Box 5.5
Insect and Plant National Collections in Ottawa

Agriculture and Agri-food Canada (AAFC) holds the single largest collection of biological specimens in Canada: the Canadian National Collection of Insects, Arachnids and Nematodes. The collection's estimated 16.7 million specimens, combined with the million specimens in the vascular plant and mycology national herbariums, and the live fungal and bacteria collection also stored at AAFC, account for about one third of all the biological specimens held in Canada. The insect collection is the third or fourth largest in the world.

Overcrowding, with storage in the corridor. (Courtesy of Peter Hall)

Agricultural research has been the primary objective of the AAFC's collections, with a large focus on insects as crop and livestock pests, but, over the years, many other sectors, including forestry, conservation and parks, have contributed to and benefitted from the collections and their research efforts. Dozens of visiting scientists and thousands of requests for data and information come each year from around the world. The main work of the collection's research scientists is the identification, description, and classification of organisms — the backbone of the science of biosystematics. A total of 77 taxonomic research and technical staff work in the AAFC National Collections in Ottawa. Many of these staff are approaching retirement age: 38 staff (50 per cent) have 20 or more years of service and half of these, 19 staff (25 per cent of total), have 30 or more years service (AAFC, personal communication).

The Royal Ontario Museum is an agency of the Government of Ontario, with a board of trustees appointed through the Lieutenant Governor in Council as its governing authority and a senior administration headed by a director and CEO. The Royal Saskatchewan Museum is a branch of the provincial Ministry of Tourism, Parks, Culture and Sport. The smaller government-operated museums and collections are often at the low end of a very long administrative hierarchy, with most ultimately reporting to a minister. One survey respondent explained: "I report to a research scientist, who reports to local management. I don't have an org chart beyond that but there are about 17 levels between me and the Minister of Natural Resources, to whom I ultimately report."

Other Collections and Museums

Twenty-two other collections or databases, including private and non-profit museums, and a hospital, were reported in the survey. Most are small and receive little outside support. (See Box 5.6 on Canada's microbe collections).

Box 5.6
Canada's Microbe Collections

It is extremely difficult to inventory Canada's microbe collections as most culture collections of environmentally derived microbes are found in individual investigators' laboratories and maintained in support of their own research, rather than as public resources. Microbes that cause diseases in humans, and the plants and animals they exploit, are more commonly kept in public collections. The most extensive collections (in terms of numbers of isolates) of any kind are probably in hospital clinical labs and comprise infectious agents (viruses, bacteria, fungi, and protozoa) isolated from human patients. A 2007 CRTI-Sporometrics study noted a decline in Canadian "Secure Biological Resources Centres" from 140 in 1986, to 86 in 1994, to at most 40 in 2006. Most notably, no Canadian centre employed more than three full-time employees, in stark contrast to the 450 employees of the American Type Culture Collection, a traditional source of cultures for Canadian microbiologists. Moreover, many of Canada's remaining small centres face closure as the academics who have curated them as a service to the larger microbial community retire, and universities, or other institutions in which they are held, face funding cuts and demands for cost-recovery or rapid results.

Field Stations

Collections are kept up-to-date, in part, by adding new specimens when new species are identified, existing specimens become damaged, or more specimens are needed to support research into more accurate taxonomy. Canadian universities have at least 20 research field stations (see Appendix 3) that provide basic infrastructure (accommodation and laboratory facilities) for biologists and taxonomists to complete field work, and that help train new taxonomists and biologists. These field research stations, which the Panel heard are now at risk as a result of NSERC funding cuts, have the potential to extend collections by acting as a focal point for related taxonomic research, and to provide additional data and specimens as needed to support biodiversity science. There are also government-run field stations that have served as long-term field sites and monitoring stations. Leveraging existing infrastructure and investments in remote areas, whether physical or logistical, has worked in the past, and can play an important role in the development of a sustainable approach to collecting data about Canada's biological diversity.

Funding of Institutions

Institutional funding essentially encompasses salaries and operating funds (supplies, etc.). Building maintenance and operations (the cost of maintaining the rooms in which collections are housed) are usually excluded. In general, the majority of funding for a collection comes from the institution to which it belongs (e.g., university, government) with relatively few funds coming from other sources. For example, only 11 out of 120 collections reported receiving money from foundations, with this source accounting for less than 25 per cent of total funding. Of the 13 collections that reported public donations, public funds accounted for less than 10 per cent of total funding for 10 out of the 13. One survey respondent declared: "Our museum is a hidden gem in the department. The university has tried to eliminate it several times and does not support it financially except when forced to." Another respondent explained that, "There is no baseline support for the [collection]. It appears nowhere as a line item in any budget. Funding is based on our ability to attract external funding, though the Department Heads over the years have provided small amounts of money for essential supplies."

Only the largest collections have dedicated personnel whose salaries are paid by the institution. While it appears that curation of collections often falls to personnel whose primary task is not collection care, the survey does not allow us to analyze this situation further. Answers to the question about approximate annual funding varied widely, with some responses including salaries, and some not. Some of the largest institutions have sizeable budgets (up to $25 million, including salaries), but most collections have small operating funds, ranging from $0 to $5,000 (most larger amounts appear to include some salary, though this was not always specified by respondents).

Although NSERC's guidelines (see Box 5.3) emphasize the deposition of specimens in established Canadian collections, university or otherwise, there is no accompanying NSERC funding program to support the collections that are supposed to become the repositories of these specimens. The full financial burden of the policy therefore lies with the institutions that own the collections. In the

United States, the National Science Foundation's Improvements to Biological Research Collections (BRC) program provides "funds for improvements to network, secure, and organize established natural history collections for sustained, accurate, and efficient accessibility of the collection to the biological research community" (NSF, 2010a). The Panel believes that the lack of funding support for the NSERC policy is a gap in the overall funding of biodiversity collections in Canada.

The recent funding provided by the Canada Fund for Innovation (CFI) for biodiversity-related infrastructures has significantly improved the support systems of collections such as the Beaty Biodiversity Museum at the University of British Columbia, the Biodiversity Institute of Ontario at the University of Guelph and the Centre sur la biodiversité at the Université de Montréal (Box 6.4). The CFI grant to the Centre sur la biodiversité was also central to the establishment of Canadensys, the university biodiversity network. CFI grants, however, do not support collection operation or personnel, although smaller grants to individual researchers have financed equipment, such as compact storage and research tools.

Canadian biodiversity collections that are nationally recognized as museums (except federal government institutions) may apply for short-term, project-oriented funding from Canadian Heritage's Museum Assistance Program (MAP); its "Access to heritage" and "Organizational development" programs provide funding for projects to strengthen the overall management of key museological functions. In 2008–09, however, no biodiversity collection received a MAP grant (Canadian Heritage, 2010).

Chapter Key Messages

We have more than 50 million biological specimens in Canada held in many public and private collections. These biodiversity collections must be housed and conserved for future generations.

New approaches and technologies have become available in recent years to improve how we manage our biological collections, yet many biodiversity collections are housed in aging facilities with relatively little physical room for growth.

Collections are governed in different ways and there is no national collections strategy, standards, norms, or sources of assistance. Many collections lack long-term stable funding and are challenged with limited and often inadequate curatorial capacity. When staff retire they are often not replaced, leading to orphaned collections.

Research field stations provide invaluable infrastructure for biologists and taxonomists and help to train new taxonomists and biologists.

Chapter 6 Enhancing Access to Biodiversity Information

Canada is lagging in the digitization of its collections and field data, has limited data holdings for most taxonomic groups, and has large geographic information gaps in remote areas and Canada's North. This information is essential for understanding and adapting to the challenges facing Canada's biodiversity resources.

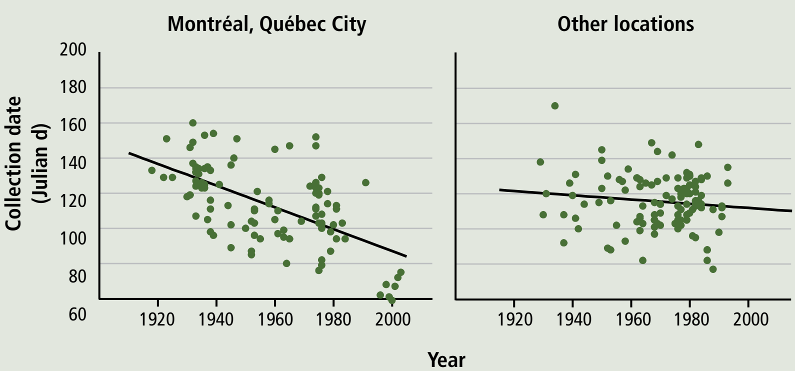
Fully understanding Canadian biodiversity will depend upon the quantity and quality of the information residing in Canada's biodiversity collections and generated by Canadian taxonomic scientists and other knowledge holders. Therefore, it is vital that data about the elements of biodiversity — including species, genes, and ecosystems — is created and organized to be easily accessible to the public, decision-makers, and scientists alike. These data require long-term stewardship and are essential for, among other things, understanding the impacts of alien invasive species and identifying and conserving species at risk.

As mentioned in Chapter 3, technological advances in electronic storage media, database technology, the internet, and tools that facilitate digitization of data have revolutionized the way biodiversity data can be created, maintained, distributed, and used. For example, current technology can accurately document the location information of any observation or specimen so that it can be plotted on maps and compared against other geographic information such as topography, roads, waterways, and the presence of co-occurring species. Complemented by ecological information, this georeferencing allows researchers to evaluate the impacts of alien invasive species, conserve species at risk, and assess the vulnerability of a species to urban development, pesticide use, or climate change (see Box 6.1). Rapidly accessible taxonomic information is also needed to protect Canada against invasive alien species. How will we know if an invasion has occurred? Do we know the impact of an invasive species on species endemic to Canada, on our economy, well-being, or culture? To what extent has the invasion spread? What are the control options? Answers to these basic questions require taxonomic data.

This chapter assesses the development and management of taxonomic data, including: the digitization of specimens, field data, and "citizen science" contributions; data publication; and issues relating to Canada's capacity to manage, access and share data, including the role of data standards.

Box 6.1
Documenting Ecological Change Using Data from Biodiversity Collection Specimens

Data from biological collections may be used to reconstruct recent changes in the distribution and phenology of species. For instance, plant ecologist Claude Lavoie *et al.* (2007) traced the spread of common ragweed (*Ambrosia artemisiifolia* L.) throughout southern Quebec over the last two centuries (1822 to 2005) using data from the specimens of seven herbaria. They were able to show that the species, initially known only in the Montréal area, had spread throughout southern Quebec by the 1950s, a dispersal notably helped by the development of the road system during that time period. Lavoie, with Daniel Lachance (2006), also used flowering dates obtained from herbarium specimens and from adjacent meteorological stations to show that the flowering of Coltsfoot (*Tussilago farfara* L.) in urban areas like Montréal and Québec City occurred significantly earlier at the end of the 20th century than at the beginning, though such a signal could not be retrieved from other areas of southern Quebec, suggesting a shift in flowering time unique to urban environments (see graphs below). Ragweed is a significant allergen; understanding its spread and behaviour in urban environments can contribute to efforts to improve the health and well-being of allergy sufferers.



(Reproduced with permission from the American Journal of Botany) (Lavoie & Lachance, 2006)

6.1 DEVELOPING BIODIVERSITY INFORMATION

Technological advances have heightened expectations about Canada's ability to query biodiversity data and information. However, Canada currently has limited and poorly supported efforts in place to digitize information held in Canada's collections. For example, the Global Biodiversity Information Facility (GBIF),[22] an international effort to ensure free and open access to data about the world's biodiversity, has only 1.69 million digitized records from Canadian institutions,[23] just three per cent of the number of specimens reported in the Panel's survey (Table 5.1). As a consequence, access to biodiversity data in a comprehensive and timely manner is extremely restricted within Canada, representing a knowledge gap, and compromising our ability to address important challenges facing our biodiversity.

Digitizing Biological Collections

As discussed in Chapter 5, Canada's biological collections contain more than 50 million specimens. Each of these specimens has information associated with it that is, for the most part, not currently accessible electronically and therefore not readily available to inform decisions across Canada. In the Panel's survey of Canadian collections, the majority of respondents reported that either none or less than 10 per cent of their collections' data are available on the internet, with the proportion varying by taxa. For example, for insects, 28 of 44 collections, including the Canadian National Collection of 16.7 million insects, arachnids, and nematodes, reported online access to 10 per cent or less of their specimens. For molluscs, this level dropped to 11 of 21 collections, while for fish, 9 of 20 collections reported online access of 10 per cent or less. See Appendix 2, Table A2.9 for further details.

The relative dearth of computerized collection data can be attributed to a lack of consistent investment in this area. Canadian museums have few staff engaged in the digitization of their collections. In the survey of Canadian collections, only 13 collections reported permanent full-time bioinformaticians, and only one collection had more than one. Accurate identification of collection specimens is fundamental to creating quality data, and the scarcity of qualified taxonomists creates basic limitations to digitization. Where funding has been made available for digitization tools and technologies, it is often not supported by money to fund data entry. In many cases, volunteers and students, in addition to researchers and curators, perform digitization as time permits (see Appendix 2). Frequently, even where data has been digitized, the data remains unavailable, as technological tools are local rather than developed as part of a larger infrastructure for sharing data. Often, the only way a potential user can access important data about specimens is to travel physically to the place where the specimen is housed or to contact the relevant collection manager or taxonomist, if such a person is in place for that

22 http://www.gbif.org/
23 Data correct as of 25 May 2010

taxonomic group. In some cases, those with an interest in these data conduct their own digitization effort, which serves a specific research interest, and which in turn, may not be connected or shared with a broader digitization effort. This may lead to a duplication of effort, as the process of digitizing itself needs to be managed.

Data Associated with Field Observations

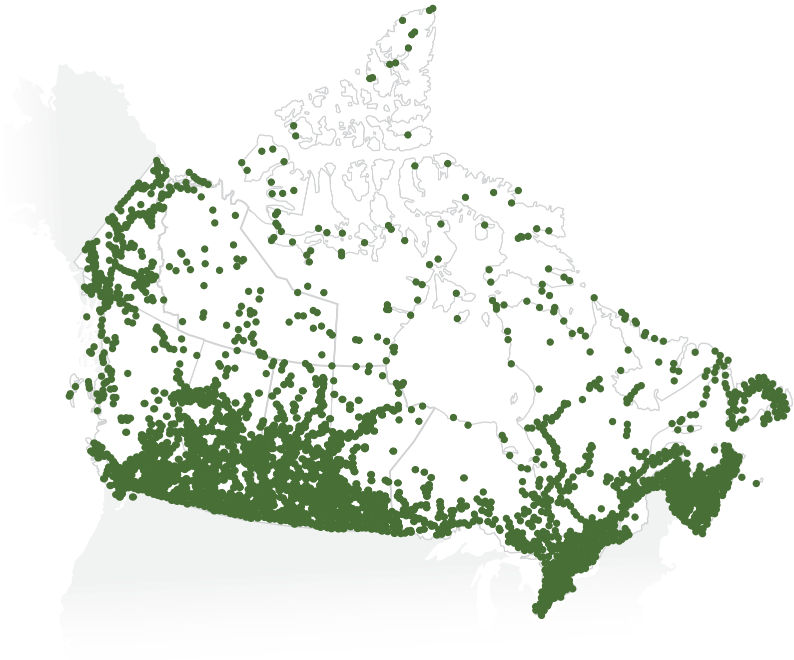
Of equal importance to collections are the data associated with field surveys and inventories. Field observation involves taxonomists or well-qualified parataxonomists (e.g., graduate and trained undergraduate students, and other competent naturalists) who go out onto the Canadian landscape to conduct surveys or inventories for one or more species. They collect data about individual organisms and their locations, often without taking a specimen. Depending on the level of expertise of the observers, field observations result in large volumes of valuable data that are distinct from, but complementary to, the specimens held in collections. The GBIF reports that more than 60 per cent of its total data holdings are associated with field observations, exceeding data available from specimen records. Field observations can be used in a variety of ways, including to direct additional research, model species range and distribution, identify specific habitat needs, explore climate change impacts, and guide biodiversity conservation actions. There is an important interplay between specimens in collections and field observations, particularly to ensure accurate species identification. The actual specimens held in collections are vitally important baseline references for species identification.

Gaps in Canada's Observational Data Holdings

Canada is opportunistic rather than systematic in its collection of biodiversity data through field observations. Aside from vertebrates, there are large gaps in field observations for most taxonomic groups in Canada. The NatureServe Canada network, which holds taxonomic data on more than 48,500 species in Canada, actively tracks, or aims to collect, observational data regularly on more than 10,500 species chosen according to their conservation status. However, the spatial coverage of NatureServe Canada's data is not complete, nor is it as comprehensive as similar data for the United States. For example, there are no spatial data for Nunavut or the Northwest Territories, and little for the Yukon, the northern portion of most provinces, and large portions of eastern Canada.

Butterfly data, one of the most comprehensive datasets held in the Canadian Biodiversity Information Facility (CBIF — a federal government effort to coordinate biodiversity data[24]), helps to demonstrate further the opportunistic approach to gathering observations (see Figure 6.1). As a relatively charismatic,

[24] http://www.cbif.gc.ca/home_e.php



(Adapted and reproduced with permission from Larry Speers)

Figure 6.1

Butterfly data held in the Canadian Biodiversity Information Facility (CBIF)

Each dot on the map represents a specimen record. Data as of March 2010.

well-observed taxonomic group, most butterfly data are collected in the populated parts of Canada. For more remote areas, specimen records can easily be seen to largely coincide with roads and waterways. Large areas away from these more easily travelled routes remain unsurveyed for butterflies and most other species as well.

The limited coverage, both spatial and geographic, of Canada's observational data underscores the need to conduct further inventories of species in Canada. Where data exists it is extremely valuable to other branches of science, for example the butterfly data shown in Figure 6.1 has been used to study climate change (e.g., Kharouba *et al.*, 2009). To date, Canada has not set in place a coordinated, effective inventory program to fill its key biodiversity information gaps, even for priority species listed under the federal *Species at Risk Act*. In 2001, the federal Office of the Auditor General recommended that Environment Canada, Fisheries and Oceans Canada, and Parks Canada develop a comprehensive inventory of species at risk under their jurisdictions. The Office of the Auditor General subsequently reported unsatisfactory progress on this recommendation in a March 2008 report (Auditor General of Canada, 2008).

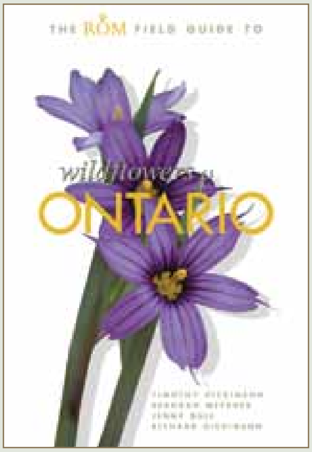
"Citizen Science:" The Public's Role in Generating Biodiversity Data

The recent launch of the *Encyclopedia of Life*, an ambitious project aiming to have a web page for every species on Earth, clearly demonstrated the public's interest in accessing biodiversity information when 11.5 million people visited the website on the first day — so many that it crashed the servers (SEED, 2010). The public also makes significant contributions to biodiversity data holdings, an important complementary effort to the efforts of professional biodiversity researchers in Canada. As an example, the GBIF reports that 56 per cent of all Canadian records are observations for bird species (the abundance of these data imply under-representation of many other taxonomic groups), many of which are contributed by amateur naturalists. The primary source of these data is the Avian Knowledge Network (AKN), a western hemispheric initiative which reports data from its offices in the United States. The AKN gathers data in Canada through its eBird project, developed by Bird Studies Canada, the Cornell Lab of Ornithology, and the National Audubon Society. The project documents the presence or absence of species, as well as bird abundance through checklist data. A simple and intuitive web-interface engages tens of thousands of participants, many in Canada, to submit their observations or view results via interactive queries into the eBird database. eBird encourages users to participate by providing internet tools that maintain their personal bird records and visualizing data with interactive maps, graphs, and bar charts. These data can be used to model bird distributions and explore factors affecting their conservation.

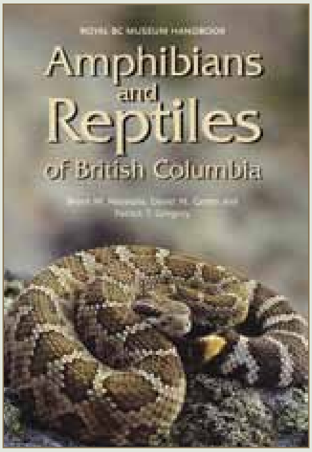
There have been efforts in Canada to draw on citizen science to cover other taxonomic groups. Working together, Environment Canada, Nature Canada, and the University of Guelph have developed Canada's NatureWatch program, which aims to collect data through citizen scientists about frogs, plants, and worms in Canada. The program also contributes data to the GBIF, though it has not been nearly as successful as the eBird program. The ongoing evolution of technology and growth in the sophistication of the internet means more and enhanced opportunities to expand citizen science programs. As Global Positioning Satellite (GPS) technologies and hand-held computers move into the mainstream, citizen scientists can help to greatly enhance the spatial accuracy of observations and can assist with more accurate species identification. In many cases, programs are being developed to train observers to create observations and even to collect specimens (also see Box 6.2 for the role of field guides). For example, the Atlantic Canada Conservation Data Centre has developed the five-year Maritime Butterfly Atlas to observe butterflies. By harnessing the combined efforts of conservation scientists and interested naturalists, the program aims to improve information on the numbers, distribution, and status of butterflies in the Maritimes, which will be especially valuable for assessing the conservation status of various species (ACCDC, 2010).

Box 6.2
Field Guides: A Vital Tool Linking Citizen Scientists and Taxonomists

The Canadian public has been enabled to make a great contribution to taxonomic science through the proliferation of natural history guides written by specialists using a wide variety of data, including taxonomic data. Citizens use these guides on birds, plants, insects, and other organisms to identify species in the field for which they compile sightings records and behavioural observations. This kind of field observation data, in turn, aids taxonomists in developing more accurate species distributions that help to better define species.



(Courtesy of the Royal Ontario Museum ©ROM)



(Courtesy of Royal BC Museum)

6.2 ACCESSING BIODIVERSITY INFORMATION

Once data has been created it needs to be published and shared. Only then do researchers, policy-makers, and citizens gain the full value of biodiversity information.

Publishing Data

While the development of consistent approaches would help encourage data development in Canada, gaps in observational and specimen data may in part be attributed to a history in the biodiversity science community of retaining data for individual research purposes. Although there are efforts in place to work more collaboratively and strategically, and to share biodiversity data based on common standards, individual researchers have little incentive to make the additional effort and expend the additional funds required to make their datasets publicly available (Costello, 2009). Data about biodiversity may end up scattered in many databases or remain only on paper, on collection specimen labels, or on other media not amenable to interactive searching or discovery. Without a clear repository built around common standards, data that have been digitized are at risk of being lost.

Stimulating the needed work in discovering species may require a change in how biologists' careers are assessed. In most fields of science the fundamental unit of credit is the publication: the more publications, the more rewards. Scientists' careers are usually promoted best by many small publications rather than a few big ones. In taxonomy, however, the most effective publication compiles many individual discoveries — results on dozens of newly distinguished species — into a large comparative monograph. In addition, the fundamental contributions made by taxonomists are the specimens collected and the data contributed to databases, and not just publications. These contributions, not reflected in publication count, will be an increasingly important part of a taxonomist's work as the field moves to the efficient publishing and sharing of data. To recognize the contributions of taxonomists better, efforts are being made in other research communities (e.g., Howe *et al.*, 2008) to design a uniform system of "micro-attribution" that counts contributions at a finer scale than publications, by measuring specimens deposited, species described, DNA sequences obtained, and entries to databases. Of course, to assist in recognizing taxonomists' contributions, these new metrics will have to be accepted by colleagues and institutional administrators. Emerging institutional policies and clear incentives (e.g., tied to career advancement) will be needed to reinforce the importance of these contributions.

Sharing Data

It is not enough to digitize information: it also needs to be accessible. Access requires that data be captured and shared based on common data standards.

Biodiversity Information Standards (TDWG),[25] an international, not-for-profit, scientific, and educational association affiliated with the International Union of Biological Sciences (which does not have Canadian institutions among its members) has adopted the "Darwin Core" — a simple, extensible data exchange standard. This standard has become a foundation for sharing data, though other challenges remain.

Accurate taxonomic information is fundamental to accessing shared data, and to ensuring information about any one species is not mixed with data from other species. See Box 6.3 for the growing use of the Integrated Taxonomic Information System in Canada. In other cases, data can be sensitive: for example, exposing data about a harvested species that is at risk, such as American ginseng, can put the species at further conservation risk. Sometimes data can be considered restricted rather than sensitive, for example, to allow a researcher to prepare a publication or to respect intellectual property rights. The need to respect such concerns and rights is critical, however, to the sharing of and open access to such data.

Box 6.3
The Importance of Taxonomic Data Management

The Integrated Taxonomic Information System (ITIS) is an effort to manage taxonomic information about species across North America. Canada has adopted ITIS Taxonomic Serial Numbers (TSN) as a mandatory data element for trade of wild species under the *Convention on the International Trade of Endangered Species* (CITES). Additionally, ITIS is partnering with Species 2000 to produce the *Catalogue of Life.* Published each year, and with over 1.26 million unique species, this catalogue is now used as the authoritative source of taxonomic data by large international projects such as the GBIF and the *Encyclopedia of Life* (EOL). If properly resourced, ITIS has the potential and scalability to become a taxonomic standard in Canada for use by a range of research and other communities who consume such information.

National Networks

Much of the available data on biodiversity are being captured and shared through a handful of networks in Canada. Two of these currently work to capture data systematically across all taxonomic groups for all of Canada: the Canadian Biodiversity Information Facility (CBIF) acts as a focal point for data sharing internationally and within Canada; and NatureServe Canada, a network of provincial and territorial conservation data centres, shares taxonomic and occurrence data on species.

[25] http://www.tdwg.org/

Other key networks that hold Canadian biodiversity data include:

- Canadensys, an affiliation of universities working to unlock and share the specimen information held by university-based biological collections (see Box 6.4);
- Barcode of Life Database (BOLD) (see Box 3.2);
- Fishnet, a network that shares data on fish species from natural history museums and other institutions; and
- eBird Canada, a database of extensive observational data, much of which is available through the Avian Knowledge Network and Bird Studies Canada.

A number of other lesser-known networks also capture and share primary biodiversity data in Canada (e.g., ORNIS, MaNIS, and HerpNet), and include specimen data on specific taxonomic groups, some of which encompass data from Canada. In many cases, these other sources of Canadian specimen data are located outside Canada, and data published to the GBIF are then acknowledged as coming from outside Canada.

Box 6.4
The Montréal Biodiversity Centre (Centre sur la biodiversité), Université de Montréal

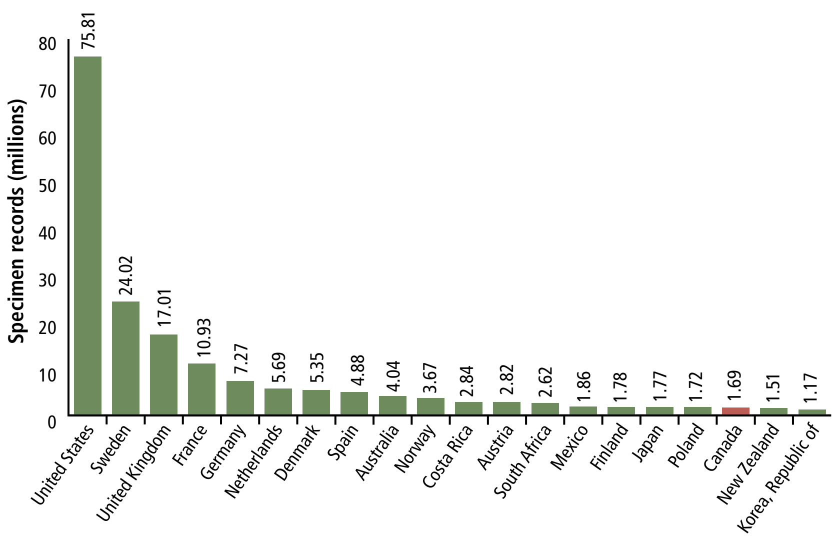
Created as a centre of excellence in the conservation and digitization of natural history collections and in biodiversity research and training, the Montréal Biodiversity Centre is due to open in late 2010 on the site of the Montréal Botanical Garden. The centre will house the natural history collections of the Université de Montréal, the Herbier Marie-Victorin, the Ouellet-Robert Entomological Collection, the Montréal Insectarium, and the Fungarium, a macrofungi collection owned by the Mycologists Society of Montréal, a renowned amateur organization.

This new facility will coordinate the networking of, and international access to, the databases of the major biological collections of plants, insects, and fungi of Canadensys — the Canadian universities' biodiversity consortium. The centre will have imaging technology to photograph herbarium and insect specimens, scanning electron microscopes, and software for specimen digitization. Databased information and images will be made available through Canadensys and the GBIF, making an important contribution to the availability of Canadian biodiversity data.

International Data Sharing

Canada's data sharing efforts compare poorly internationally. Participation in the GBIF, a focal point for international data sharing, is at the discretion of individual organizations and networks. The lack of investment in the digitization of collections and observational data, and the lack of a strong policy requiring digitization significantly restrict Canada's contributions to global databases, as shown in Figure 6.2, as well as limit Canada's ability to draw useful information from these databases.

The GBIF portal provides basic statistics on its sources of data. In terms of basic taxonomic information, it holds a total of 51,209 species recorded in Canada, though some of these are fossils and others may be duplicates (e.g., there are multiple entries for *Poa pratensis* L., more commonly known as Smooth Meadow-grass, Common Meadow Grass or Kentucky Bluegrass). This would represent about half of the known species in Canada and one third of its estimated species. The GBIF has data on 9,427 species of Canadian insects, equal to roughly one third of the approximately 30,000 species known to occur in Canada, and 17 per cent of the estimated 55,000 insect species thought to exist in Canada (see Table 5.1). These data can be used by researchers to model range, climate change impacts, or to consider species interactions.



(Data Source: GBIF, 2010)

Figure 6.2

Top 20 contributors of specimen records to the Global Biodiversity Information Facility (GBIF)

Specimen databases on GBIF were searched on 25 May 2010 to show the total number of specimen records contributed by each country. Only the top 20 countries are shown.

The GBIF records a total of 6.35 million specimens with latitude and longitude information that indicate they are from Canada, yet the GBIF indicates that only 1.33 million of these records are hosted and administered by Canadian institutions, with the majority (3.80 million) held by the United States. This means that approximately 80 per cent of Canada's publicly accessible digitized biodiversity information is being held and contributed by institutions outside Canada, though it is important to remember that the majority of Canada's information (in collections and field notes) remains undigitized.

In the opinion of the Panel, Canada is not fully engaged in the global effort to develop and exchange biodiversity data. This is due to a lack of funding support, a lack of strong government policy leadership, and the culture of taxonomic research. Embracing, rather than resisting, changes in this direction will be fundamental to the success of the taxonomic community in Canada. Such a culture shift, with investments in collections and basic inventories within Canada, would work to complement efforts to improve databasing. This would enhance our access to knowledge concerning native and invasive species, and lead to more cost-effective support for biodiversity policy and management activities in Canada.

Chapter Key Messages

Digitization of biodiversity collections and investments in basic surveys and inventories is essential for understanding environmental change, identifying and controlling alien species, and identifying and conserving species at risk.

Canada has large geographic and taxonomic gaps in data coverage. Canada's experts are often called upon to provide advice on biodiversity management on the basis of limited data.

There are no strong financial incentives or policies built into biodiversity science to encourage digitization and dissemination of data.

There are international standards for digitization and data sharing. However, internationally, Canada compares poorly in terms of digitization, inventories, and contributions to international data sharing efforts such as the Global Biodiversity Information Facility (GBIF). The majority of Canada's information remains undigitized, and 80 per cent of online information about Canadian biodiversity is being held and contributed by institutions outside Canada.

Chapter 7 Taxonomy in Canada: Creating Opportunity

Canada has strengths in many areas of taxonomy, but also significant gaps, and lacks a strategic plan to exploit the opportunities linked to our biodiversity resources. Canada is not alone in this regard, but there are signs of change, with many nations making substantial investments in biodiversity discovery and documentation. Canada is well positioned to establish itself as an international leader in taxonomy, a status that will bring important environmental benefits and economic opportunities.

The prior chapters of this report have assessed Canada's capacity in taxonomy — research that discovers, distinguishes, classifies, and documents living things. This concluding chapter begins with a gap analysis. This is followed by a section considering the ways in which nations around the world are building capacity in taxonomy. The third section considers recent developments that have strengthened our nation's preparedness to mount a major initiative in this area of science. The final section considers both a way forward to energize taxonomy in Canada and the benefits of such action.

7.1 ASSETS AND GAPS IN CANADIAN TAXONOMY

The Panel's assessment has revealed important strategic assets in Canadian taxonomy. Canada has substantial natural history collections conservatively valued at one quarter of a billion dollars. There are world-class researchers and research programs. The knowledge held by Canada's Aboriginal populations and non-governmental sector represents a significant addition to the biodiversity capacity within the government and university sectors. Young Canadians are strongly attracted to taxonomy as a career opportunity, reflecting their life in a nation with magnificent wild lands; the nation should take advantage of that. Canada also has world-class analytical capacity in three fields — informatics, genomics, and remote sensing — that underpin a new approach to the discovery, documentation, and evaluation of biodiversity.

Although Canada has key assets, the Panel's analysis has revealed that certain strengths are under threat or that potential benefits are not being fully realized (Figure 7.1), and that, to directly answer the question posed to the Panel by the Minister, **Canada is not yet equipped to fully understand the challenges of our biodiversity resources**. Many, possibly most, species in Canada's ecosystems are as yet unknown, and we have not yet developed rapid means of identifying most of the known species. Canada is home to many impressive specimen collections, but most specimen information is trapped in cabinets rather than ranging free and accessible on the web. This deficit needs resolution, not just for the sake of taxonomy, but for the well-being of other disciplines in biology that depend upon this information. There are huge geographic gaps in accessible information about Canada's biodiversity that require the capture of

Current Gaps

- Canada has gaps in species description and geographic distribution data, and lags behind other countries in digitization, systematic inventories, and support for national contributions to international biodiversity data-sharing efforts.
- There is an absence of national collections strategy and standards.
- Many collections are housed in outdated and inadequate facilities with little capacity for growth.
- Highly qualified personnel are being lost because of low job prospects and stagnant research funding levels.
- Taxonomists and naturalists are aging and not being replaced.
- Traditional and community knowledge is at risk.

Consequences

- Insufficient capacity to adequately manage, conserve, and utilize Canadian biodiversity.
- Limited capacity to evaluate the response of Canadian biodiversity to global change, and its value for mitigation and adaptation.
- Limited ability to respond to the risk of invasive species and the spread of pests.
- Limited capacity of taxonomy to provide fundamental support to other elements of biodiversity science.
- Limited ability to identify components of biodiversity in a Canadian context.
- A loss of interest, particularly on the part of young Canadians, in biodiversity and ecosystems.

Outcomes

- Diminished capacity to understand biodiversity, its loss, and erosion of associated ecological services that provide economic, health, and cultural benefits to Canadians. Biotechnology and resource industries, such as forestry, agriculture, and fisheries are particularly vulnerable.

(Council of Canadian Academies)

Figure 7.1

Gaps in Canadian taxonomy, the consequences of those gaps, and potential long-term outcomes

legacy field data, extensive fieldwork, and long-term monitoring to fill. There is a critical need to strengthen the recruitment of young taxonomists because many of Canada's current leaders in this field are close to retirement and our international research contribution is diminishing. There is no national strategy or program to build cohesion and interactivity among the biodiversity science workforces in the government, private, and university sectors.

7.2 TAXONOMY: A SCIENCE IN TRANSITION

The science of taxonomy is in flux — recent advances, especially in the fields of genomics and computer science, are revolutionizing both access to biodiversity information and the pace of biodiversity documentation. A growing number of nations are making major investments in response to these opportunities.

In the United States, the National Science Foundation (NSF) has several programs that target taxonomy. The Partnerships for Enhancing Expertise in Taxonomy (PEET) program has already disbursed US$30 million focused on training the next generation of taxonomists (NSF, 2010b). A second program, Assembling the Tree of Life (AToL), has provided more than US$115 million towards large-scale research collaborations that aim to clarify phylogenetic relationships within major groups of organisms (e.g., all fish, all worms). A third undertaking, the Planetary Biodiversity Inventory (PBI) Program, has so far distributed US$15 million to projects focused on comprehensive biodiversity surveys for particular lineages of life (e.g., all catfishes). Finally, there is the National Ecological Observatory Network (NEON), involving the NSF and many other departments and agencies. NEON is a US$300 million effort to monitor biodiversity at 20 sites across the United States over a 30-year period; it couples collection programs with DNA-based identification and remote sensing (NEON, 2010).

Other countries are also actively investing in taxonomy. The Swedish Taxonomy Initiative, a 20-year program with an overall budget of US$200 million, is building a publically accessible compendium for all multi-cellular species in that nation (ArtDatabanken, 2010). The Atlas of Living Australia, an AU$30 million endeavour launched in 2008, has a different orientation. This partnership between government and museums is building the informatics and data management system needed to provide all Australians with online access to information about their biodiversity (CSIRO, 2010). And the European Distributed Institute of Taxonomy is a 12 million Euro initiative to build a network of excellence linking 28 major biodiversity science institutions across Europe (EDIT, 2008).

Canadian funding agencies have not been on the sidelines — they have invested more than C$50 million to advance phylogenetic studies and to build a DNA-based system for species identification. Nevertheless, Canadian funding opportunities to support general taxonomic efforts, collections, and databasing have been lacking. These diverse research initiatives all rest upon a solid foundation of classical taxonomy, and benefit from the use of digital technologies, molecular analysis, or remote sensing. Viewed from a "big science" perspective, these investments of $15 million to $300 million are modest, and mean that no nation has yet established a program that takes full advantage of new opportunities. However, it is certainly the case that these research endeavours have greatly expanded collaborations among researchers in the fields of taxonomy and biodiversity analysis. Such collaboration is also essential to revitalizing basic taxonomic work, such as identifications and descriptions, that remains a necessary foundation for biodiversity science.

7.3 BIODIVERSITY SCIENCE IN CANADA: GAINING MOMENTUM

As noted earlier in this report, Canada has long had strength in ecology, evolution, and taxonomy, disciplines that are central to biodiversity science. However, until recently, Canada's capacity in this field has rested largely upon the capabilities of single researchers or small teams. The past decade has seen some important change; researchers have joined forces to build larger alliances that make use of the new technologies described in this report. The Biodiversity Institute of Ontario, the Biodiversity Research Centre at the University of British Columbia, and the Quebec Centre for Biodiversity Science, all represent research alliances that have had major investments since 2005. Interactions across the entire university-based community of biodiversity scientists have been further stimulated by the establishment in 2007 of Canadensys, a network of university-based taxonomic databases. Federal departments and agencies with involvement in biodiversity science similarly gained a new level of coordination following the establishment of the Federal Biodiversity Information Partnership in 2003. There is also an increasingly vibrant dialogue with non-governmental organizations (NGOs) active in Canada, such as the International Union for the Conservation of Nature (IUCN), which produces species red lists, the Global Biodiversity Information Facility (GBIF), which aims to mobilize biodiversity data, and NatureServe, which uses biodiversity data to empower conservation action.

This growing cohesion of human resources has been accompanied by major investments in research facilities. The Universities of British Columbia, Guelph, and Montréal have collectively received more than $80 million from the Canada

Foundation for Innovation (CFI) and other agencies to build new biodiversity science facilities over the past decade. Multi-million dollar investments have also occurred at the Canadian Museum of Nature, the Canadian National Collection and the Royal Ontario Museum. In addition to this new infrastructure in urban centres, Canada's capacity to support long-term monitoring programs in remote areas has been reinforced by the recent commitment of $85 million to refurbish stations in the Arctic and imminent plans to direct $250 million towards a High Arctic station. Further investment in field stations would not only build training capacity, but would also provide an opportunity for novel research programs and long-term monitoring of ecosystem changes.

The biodiversity science community has also obtained substantial support from NSERC's Strategic Research Networks Program, with $15 million since 2005 to support networks on DNA Barcoding, pollination biology, and invasive species. Each of these networks represent major research achievements, but the level of funding ($1 million/year), its brief duration (five years), and the necessity for a thematic focus has meant that the broader integration of biodiversity science has not been achieved. On a positive note, these networks and biodiversity centres have played an important role in establishing scientific linkages and in building administrative capacity, all of which has better prepared Canada's biodiversity science community to manage a significant investment in a major endeavour.

7.4 THE ROLE OF TAXONOMY IN CANADA'S KNOWLEDGE-BASED FUTURE

The Panel believes that Canada is well positioned to gain international leadership in taxonomy and biodiversity science. In part, this conclusion rests upon the accomplishments of the past decade highlighted in the prior section. However, it also reflects the fact that no other nation has developed a program that fully integrates emergent technologies and a strong taxonomic foundation. Canada could be the first — with bold vision from its scientific community, policy leaders, Traditional Knowledge holders, NGOs, and industry.

Proposing the detailed mechanisms and funding models for this effort is beyond the mandate of the Panel, however the Networks of Centres of Excellence (NCE) Program and derivatives of the Canada Research Chair Program have enabled Canada to rise to international prominence in other areas of national interest, such as Arctic science.[26] A similar funding strategy could transform Canada's taxonomy and biodiversity science capacity with manifold benefits to our nation.

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26 http://www.arcticnet.ulaval.ca/

Scientific capacity is rarely the most important factor in provoking major investments in a particular branch of science; cost-benefit analysis often takes central stage. There will be financial costs to preparing Canada to fully understand and manage its biodiversity resources, but the benefits will be many. The final section of this chapter considers three of the ways in which a strengthened capability in taxonomy would contribute to Canada's economic well-being, to its status as a responsible world citizen, and to the protection of its natural resources.

Innovation: Probing Biological Solutions to Complex Problems

Innovation requires the exploration and testing of novel ideas. While humans have been doing this for millennia, nature has been practicing it for billions of years: each species has explored novel solutions to its survival problem, and then tested these "ideas" through natural selection. This trial and error process has occurred in millions of species over millions of years, resulting in diverse solutions to diverse problems. Birds evolved flight, and humans were inspired by it. Burdock plants evolved "velcro," and humans mimicked it. Fungi evolved chemicals to control bacteria, and humans now exploit them as antibiotics. Plants evolved chemical defences to deter herbivores, and humans now use them for varied purposes from medicines to crop protection.

Each species represents an unbroken chain of billions of years of survivors — an encyclopaedia of proven innovations that enabled its survival. Different species hold different innovations, provoking a need for species identification if one wishes to properly explore biological innovations. The features that species have invented and hold encoded in their genes are their "intellectual property," their unpatented innovations, ready for discovery and exploitation. Humans have been "bioprospecting" for millennia — many of the painkillers and stimulants in plants were first identified by Traditional Knowledge. However, the pace of discovery of these ready-made solutions is accelerating as we become more adept in cell biology, and more effective at copying biological solutions through advances in chemistry, genetic engineering, and nanotechnology. Other nations have begun to develop strategic plans that include bio-discovery as a core element of their biodiversity strategy. For example, Norway has established a program that is isolating bioactive compounds from arctic species, leading to a flow of patents. A strong research effort in taxonomy would enable Canada to focus on the discovery of compounds and biochemical pathways for multiple fields of endeavour: from the generation of bio-fuels, to the protection of human health and the development of new manufacturing processes.

Meeting Our National Commitments to Biodiversity Conservation

We live on a planet where biodiversity is increasingly under threat. This fact has been demonstrated most dramatically by the recent decision of the United Nations to establish an Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services. Canada has diverse policies that signal our national commitment to the protection of biodiversity including, amongst others, the *Canada Wildlife Act*, the *Canada National Parks Act*, the *Species at Risk Act*, the *Fisheries Act*, and the *Canadian Environmental Assessment Act*. Canada is also a signatory to international agreements such as the *Convention on the International Trade on Endangered Species (CITES)*, the *Ramsar Convention on Wetlands*, the *United Nations Convention on the Law of the Sea*, and, most comprehensively, the *Convention on Biological Diversity (CBD)*. The achievement of the objectives in these accords depends on biodiversity science, underpinned by basic taxonomic information. Therein lies a harsh reality. Canada's constrained capacity to analyze biodiversity information impedes the nation's ability to achieve the goals set out in these policy instruments. This is old news — the *Canadian Biodiversity Strategy* (1995) first recognized the need for a proper catalogue of life in our nation. The development of a national program in taxonomy that takes full advantage of new technologies is needed to fill this gap, bringing capacity to commitment.

Protecting Canada's Natural Resources

Amongst the world's nations, Canada is one of the leading exporters of agricultural and forestry products. This position will only be sustained if Canada has a strong scientific capacity in taxonomy and other biodiversity sciences, to facilitate the development of new cultivars, and to ensure that land-use practices are sustainable. There is also a need for strong bio-surveillance programs to ensure that crops and forests are protected from both resident pest species and new invaders. The economic benefits linked to the interception of a single invasive species can be huge. The zebra mussel first reached Canadian waters in 1987; since that time, its presence has cost Canadians dearly — over $5 billion has been spent by the United States and Canada in the Great Lakes basin alone (Pimental *et al.*, 2000). One of Canada's most important hardwood trees is now threatened with decimation by another invader, the emerald ash borer, reliving a situation that saw earlier invaders wipe out the elms and chestnuts that were once important components of Canada's deciduous forest belt. A strong capacity in taxonomy, including field work and inventories, promises the interception or early eradication of invaders before they establish the population density that makes their control impossible. Strong and vibrant taxonomy is central to realizing the promise inherent in biodiversity itself.

Chapter Key Messages

Canada is well positioned to establish itself as an international leader in taxonomy, a field that is being transformed worldwide by a shift in the scale of collaborations, and by the adoption of new technologies.

Canada can lead by investing in our strengths and building stronger linkages among the varied organizations with involvements in biodiversity science including universities, governments, industry, Traditional Knowledge holders, and NGOs. There is also a requirement for bold investigation of new technologies that promise to transform our ability to document and monitor biodiversity.

If Canada fails to act, it risks ill-informed policy decisions on pressing issues such as climate change, conservation, and natural resource management. In contrast, action will unlock opportunities for economic development in the traditional renewable resource sector and the emergent field of bio-products and processes.

Glossary

Biodiversity
The variability among living organisms from all sources including, *inter alia*, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems.[1]

Conservation
The management of human interactions with genes, species, and ecosystems so as to provide the maximum benefit to the present generation while maintaining their potential to meet the needs and aspirations of future generations; encompasses elements of saving, studying, and using biodiversity.[2]

COSEWIC
The Committee on the Status of Endangered Wildlife in Canada (COSEWIC) is a committee of experts that assesses and designates which wildlife species are in some danger of disappearing from Canada.[3]

Cultural diversity
Variety or multiformity of human social structures, belief systems, and strategies for adapting to situations in different parts of the world.[2]

Digitization
The process of recording information in a digital form.[4]

Ecology
A branch of science concerned with the interrelationship of organisms and their environment.[2]

Ecosystem
A dynamic complex of plant, animal, fungal, and microorganism communities and their associated non-living environment interacting as an ecological unit.[2]

Endangered
As of a wildlife species facing imminent extirpation or extinction.[3]

Extinct
As of a species that no longer exists.[3]

Extirpation

As of a species that no longer exists in a particular area.[3]

Federal Biodiversity Information Partnership (FBIP)

A collaborative endeavour of Agriculture and Agri-food Canada, the Canadian Museum of Nature, Fisheries and Oceans Canada, Environment Canada, Health Canada, the Canadian Food Inspection Agency, Parks Canada and Natural Resources Canada to ensure that the importance of biosystematics is recognized, emphasized, and supported, and that biosystematics is used effectively in Canada.[3]

Genetic diversity

The variety of genes within a particular species, variety, or breed.[2]

Invasive species

An invasive species is a species that has successfully colonized regions new to it. The spread of invasive species populations may cause economic and/or environmental problems.[4]

Inventory

On-site collection of data on natural resources and their properties.[2]

Micro-organisms

Also called microbes. Loosely, those organisms too small to be seen with the naked eye. Some animals and plants are microbial but in general the designation is used for bacteria, archaea, protozoa, some fungi (including yeasts), many algae, and viruses.[4]

Morphology

The form and structure of organisms, or a branch of biology that deals with the form and structure of organisms.[4]

Phylogenetics

Study of the evolutionary history of organisms, with focus on their ancestory-descendant branching pattern.[4]

Species

A classification of a plant, animal, or micro-organism within a group that has distinct characteristics and reproductive processes.[5] Often used to refer to groups that are capable of interbreeding freely with each other but not with members of other species.[2]

Species diversity
The number and variety of species found in a given area in a region.[2]

Systematics
The scientific study of the kinds and diversity of organisms and of any and all relationships among them.[2] (This report, following common usage, treats "systematics" as primarily concerned with phylogenetic relationships and classification, in contrast to taxonomy which focuses primarily on species discovery and distinction.)

Taxonomy
A science that discovers, distinguishes, classifies, and documents organisms.[4]

Taxonomic monograph
Systematic treatment of a group in the most complete detail possible, usually including, along with full descriptions, whatever is known of the biology, ecology, and distribution of a group.[6]

Taxonomic revision
Restudy of a group to correct or improve its diagnosis, description, or phylogeny.[6]

DEFINITIONS ARE TAKEN OR ADAPTED FROM THE FOLLOWING SOURCES:

[1] Convention on Biological Diversity, Article 2, Use of terms. Retrieved July 2010, from http://www.cbd.int/convention/articles.shtml?a=cbd-02
[2] United Nations Environment Programme. World Conservation Monitoring Centre. Retrieved July 2010 from http://sea.unep-wcmc.org/reception/glossaryS-Z.htm
[3] COSEWIC. Operations and Procedures Manual. Appendix C.
[4] Panel-derived definition.
[5] Invasive species, Government of Canada. Retrieved July 2010, from http://www.invasivespecies.gc.ca/english/View.asp?x=501
[6] Winston, J. E. (1999). *Describing Species. Practical Taxonomic Procedure for Biologists.* New York: Columbia University Press.

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Assessments of the Council of Canadian Academies

The assessment reports listed below are accessible through the Council's website (www.scienceadvice.ca):

- Canadian Taxonomy: Exploring Biodiversity, Creating Opportunity (2010)
- Honesty, Accountability and Trust: Fostering Research Integrity in Canada (2010)
- Better Research for Better Business (2009)
- The Sustainable Management of Groundwater in Canada (2009)
- Innovation and Business Strategy: Why Canada Falls Short (2009)
- Vision for the Canadian Arctic Research Initiative: Assessing the Opportunities (2008)
- Energy from Gas Hydrates: Assessing the Opportunities and Challenges for Canada (2008)
- Small is Different: A Science Perspective on the Regulatory Challenges of the Nanoscale (2008)
- Influenza and the Role of Personal Protective Respiratory Equipment: An Assessment of the Evidence (2007)
- The State of Science and Technology in Canada (2006)

The assessments listed below are in the process of expert panel deliberation:

- Approaches to Animal Health Risk Assessment
- The Integrated Testing of Pesticides
- Science Performance and Research Funding
- Women University Researchers