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TERRESTRIAL ECOLOGICAL MONITORING: A Review and Recommendations for Northern Ontario's Ring of Fire

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Executive Summary

Effective ecological monitoring is needed to inform environmental planning and evaluate the success of management efforts to protect biodiversity. While many governments have recognized the need for better monitoring of large-scale cumulative effects, there are few examples of successful, long-term regional monitoring programs. Common shortcomings of monitoring have included a lack of clear objectives, poor design, disengagement between scientists and managers, and lack of sustained funding.

Ontario's Far North is a vast, remarkably intact region representing one of the world's few remaining expanses of relatively undisturbed boreal forest. It supports globally significant, large-scale ecological processes and holds valuable natural resources like timber, minerals, and hydroelectric potential. The Ring of Fire sub-region faces particular development pressure due to recent mineral discoveries, with planning for mine development proceeding in the absence of regional planning. The Ontario government is mandated to protect at least 50% of the Far North and pursue sustainable development with First Nations, and the need for regional monitoring in the Ring of Fire has been recognized.

Devising an effective ecological monitoring program for the Ring of Fire will be challenging due to factors such as the lack of a specific regional land use plan, a paucity of existing ecological data, and logistical challenges associated with accessing this remote region. Nevertheless, the undisturbed nature of the Far North presents a unique opportunity to initiate regional monitoring *before* significant changes have occurred. The purpose of this report is to facilitate progress toward an effective ecological monitoring program for the Ring of Fire by: a) reviewing key themes for ecological monitoring from the scientific literature, b) summarizing examples of other relevant regional-scale monitoring initiatives, and c) making recommendations for further development of a monitoring framework for terrestrial biodiversity in the region.

There is broad agreement in the ecological monitoring literature that it is critical to set clear objectives and questions to be addressed through monitoring, and the use of conceptual models has been emphasized. There has been debate about whether monitoring should be targeted to key stressors or focus on broader surveillance of trends. Recently, hybrid or adaptive approaches have been proposed that attempt to link targeted impact monitoring with regional surveillance of cumulative effects and unanticipated changes. Strong engagement between researchers and managers is essential for effectively linking monitoring to adaptive management, and structured decision making has been proposed as a powerful and transparent approach.

The details of *what* to monitor and *how* to do it flow from the explicit definition of monitoring objectives. Many approaches for choosing monitoring targets have been used, and several multispecies programs have been developed for regional monitoring. Good sampling design is necessary to ensure monitoring data meet their intended purpose and withstand scrutiny. Valid inferences depend on probability-based samples, and sampling scales should be matched to those of the ecological populations and processes of interest. Precision analysis is necessary to ensure adequacy of a sampling

design. Sampling protocols and analytical approaches must contend with imperfect detection and other sources of observation error that could obscure underlying ecological patterns of interest.

An ecological monitoring program for the Ring of Fire region should complement existing or emerging monitoring initiatives in Ontario and learn from the challenges of other programs. Aerial surveys of large mammal occupancy in northern Ontario, conducted by the Ministry of Natural Resources and Forestry (MNRF) and Wildlife Conservation Society (WCS) Canada, could direct conceptual model development and monitoring design for such species in the Far North. Mandated monitoring of woodland caribou ranges is also being developed under Ontario's Woodland Caribou Conservation Plan. Nevertheless, past shortcomings of the mandated Provincial Wildlife Population Monitoring Program serve as a reminder that new programs must be carefully designed, with clear objectives and sufficient funding to achieve success. The Far North Biodiversity Project is currently testing multispecies sampling protocols for inventory and surveillance of a wide range of biodiversity elements in the region, and MNRF is also developing a conceptual framework for more stressor-based cumulative effects monitoring in the Ring of Fire. As soon as possible, documentation for these initiatives should be made available to describe their objectives and design, and thereby demonstrate how they will overcome common shortcomings of ineffective ecological monitoring.

The Alberta Biodiversity Monitoring Institute (ABMI) implements an ambitious regional monitoring program designed to assess cumulative effects by systematically sampling a broad range of species and habitats across multiple stressors. This unique program has been criticized for its reliance on passive trend surveillance without explicit questions, but recently a framework for integrating the long-term surveillance with more targeted, hypothesis-driven sampling has been articulated. The ABMI program continues to evolve, as do related cumulative effects monitoring initiatives in Alberta, such as the Joint Canada-Alberta Implementation Plan for Oil Sands Monitoring (JOSM). ABMI and JOSM represent pioneering efforts to implement coordinated, regional biodiversity monitoring for cumulative effects management in boreal Canada, but the extent to which their results influence management remains to be seen. The Northwest Territories Cumulative Impact Monitoring Plan (CIMP) has taken a more distributed, community-based approach to regional monitoring. To date, the program's effectiveness is unproven, with a 2010 audit indicating it was under-resourced and achieving limited success.

Developing a conceptual model and associated monitoring questions and targets for the Ring of Fire requires an accounting of the ecological components and processes of interest in the region, as well as the activities and stressors expected to impact them, and the management actions that might be applied. Focal species or targets must be chosen in a transparent manner based on management priorities and monitoring objectives, and should address different spatial scales and levels of biological organization. These will likely include coarse-filter measures such as the extent, composition and spatial pattern of natural land covers and disturbances, and fine-filter measures like population responses of species selected for key characteristics such as large area requirements (e.g., caribou) or specialized habitat needs (e.g., yellow rail). Hypotheses linking species and stressors are critical, and potential synergies among stressors should also be considered, such as how mining impacts may interact with timber harvest and altered fire or hydrological dynamics under a changing climate. Land use zones with different management strategies—such as areas designated for more intensive development vs.

protected areas—could be useful for defining management-relevant sampling strata and improving the ability of monitoring to distinguish anthropogenic effects from natural dynamics or other processes (e.g., climate change). Given the considerable uncertainty facing the region, there is likely justification for incorporating surveillance monitoring capable of detecting unanticipated impacts.

Recommendations

We recommend that government commitments to ecological monitoring in Ontario's Ring of Fire be upheld and emphasized as a critical part of adaptive landscape management in the region. Moreover:

- A board of directors and monitoring advisory committee should be established to further guide development of regional cumulative effects monitoring—including advisors experienced in the quantitative, operational, and socio-political challenges of implementing large-scale monitoring—and we recommend scoping workshops to identify and refine key aspects of the monitoring framework.
- A "hybrid" approach to adaptive monitoring should be developed that links targeted monitoring of hypothesized impacts with broader surveillance of cumulative effects, avoiding both narrowly focused piecemeal monitoring and unfocused trend surveillance. However, we stress the importance of involving quantitative experts in ecological sampling design and statistical analysis at the outset of program development.
- The involvement of First Nation communities will be critical to the success of an ecological monitoring program for the Ring of Fire. Integration of scientific monitoring with traditional ecological knowledge and community-based monitoring should be carefully considered.

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Acknowledgements

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About Alberta Innovates – Technology Futures

AITF (www.albertatechfutures.ca) is part of Alberta's research and innovation system, supporting interplay between government, industry and academia. AITF provides research, innovation and commercialization services delivering economic and social benefits to Alberta. The Ecosystem Management team helps build sustainable resource management capacity through research, development and deployment of scientifically rigorous tools in areas such as biodiversity monitoring, ecological conservation, and environmental planning.

About Wildlife Conservation Society Canada

WCS Canada (www.wcscanada.org) was established in May 2004 as a Canadian non-government organization with a mission to conserve wildlife and wildlands. We improve our understanding of, and seek solutions to, critical problems that impact key species and large wild ecosystems throughout Canada. We implement and support comprehensive field studies, particularly in Ontario's Far North, gather information on wildlife and wildlands, and seek to address conservation challenges by working with First Nations, local communities, governments, regulatory agencies, other conservation groups, and industry.

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1.0 Introduction

1.1 Biodiversity decline and the need for ecological monitoring

The Earth's ecological systems face increasing pressure under humanity's growing footprint. As human populations and their consumptive activities expand, anthropogenic influences on the structure and function of natural ecosystems mount, threatening an increasing number of life forms and the ecosystem services they provide (Balmford & Bond 2005; Dirzo et al. 2014; Pimm et al. 2014). For example, Canada's boreal forests were recently considered icons of undisturbed wilderness, providing habitat for an abundance of wildlife and supporting critical functions like carbon storage and water filtration; however, these forests are now among the many natural systems being degraded by rapid rates of industrial development and poor conservation planning (Bradshaw et al. 2009; Schindler & Lee 2010; Venier et al. 2014). Anthropogenic threats range from relatively localized impacts, such as habitat loss due to specific resource extraction projects, to global impacts such as climate change. While different activities have different consequences for various components of natural ecosystems, on the whole, human activities are causing widespread declines in biodiversity (Butchart et al. 2010).

In recognition of the threats to biodiversity, Canada has joined other nations in committing to international agreements like the Convention on Biological Diversity (UNEP 1992), aiming to protect biodiversity and halt or reverse these declines. Ontario and other provinces have also created policies and planning processes for biodiversity protection (e.g., Ontario *Endangered Species Act, 2007*[1]; Ontario Biodiversity Council 2011); for example, the Government of Ontario has committed to protecting at least 50% of the Far North region (*Far North Act, 2010*[2]). Biodiversity protection requires conservation actions that promote well-regulated economic development based on careful land use planning (i.e., limitations on the extent and intensity of human footprint). While indicators of economic activity are widely monitored and reported, having a large influence on public discourse and policy (e.g., Gross Domestic Product; stock market indices), indicators of biodiversity status or ecological "health" are not as well established. This reflects both uncertainty in our understanding of natural ecosystems, and the undervaluing of natural capital—that is, the stock of natural resources creating a vital, long-term supply of ecosystem goods and services (Daily 1997; Costanza et al. 2014). Effective ecological monitoring is needed to both inform environmental planning (e.g., land use, environmental assessment) and evaluate the success of management efforts to ensure an acceptable trade-off between economic development and environmental protection.

[1] *Endangered Species Act, 2007*, SO 2007, c 6, is available at https://www.canlii.org/en/on/laws/stat/so-2007-c-6/latest/so-2007-c-6.html

[2] Ontario's Far North is defined by the *Far North Act, 2010*, SO 2010, c 18, which is available at http://www.ontario.ca/laws/statute/10f18

1.2 Ineffectiveness of many ecological monitoring programs

While many national and regional governments have agreed in principle with the need for better ecological monitoring, there are relatively few examples of successful, long-term monitoring programs (Legg & Nagy 2006; Thompson 2006; Lindenmayer & Likens 2010a,b). Where attempted, monitoring programs have failed or become ineffective for a variety of reasons. Common shortcomings include a lack of clear objectives, poor design, disengagement between scientists and managers, and lack of sustained funding (Lindenmayer & Likens 2010a). In fluctuating financial environments, monitoring programs are often seen as a luxury and are the first to get cut, which is the antithesis of the sustainable long-term funding that is required for effective monitoring. Furthermore, in the context of land use planning and landscape management, monitoring programs have suffered a similar myopia to environmental impact assessment (Duinker & Greig 2006). Assessment and monitoring have often been narrowly focused on particular sites, species and stressors, inadequately considering broader spatio-temporal contexts and the cumulative effects of multiple, interacting impacts (Boutin et al. 2009; Schultz 2010; Burton et al. 2014). Yet, it is an understanding of such large-scale, complex interactions among anthropogenic and natural disturbances, across many components of biodiversity, that is required for effective landscape management and conservation planning (Lindenmayer et al. 2008; Barnosky et al. 2012; Noon et al. 2012).

1.3 Towards regional cumulative effects monitoring and adaptive management

The need to better assess cumulative environmental effects at ecologically relevant scales has been increasingly recognized (Duinker & Grieg 2006; Boutin et al. 2009; Schultz 2010; Burton et al. 2014). Project-by-project environmental impact assessments and the narrowly scoped, mandated monitoring associated with these projects have led to incremental increases in local impacts that collectively represent an increasing risk for species, ecosystems, and human societies—what has been called the "tyranny of small decisions made singly" (Theobald et al. 1997) and "death by a thousand cuts" (Schneider & Dyer 2003).

Land management agencies and environmental non-governmental organizations (NGOs) are increasingly working toward regional land use planning supported by broader assessment tools, such as Regional Strategic Environmental Assessment (Didier et al. 2009; Johnson et al. 2011; Chetkiewicz & Lintner 2014). However, managing at regional scales is difficult, given pervasive uncertainty in our understanding of large-scale ecological patterns and processes, of responses to past, current and future land uses, and of the consequences of management decisions. Such uncertainty cannot be a reason for inaction, but rather provides strong motivation for developing regional cumulative effects monitoring linked to land use management. Management agencies must transparently confront uncertainty in decision making while seeking to reduce uncertainty through monitoring programs capable of linking patterns and processes at relevant scales (Lyons et al. 2008; Haughland et al. 2010). Monitoring should not be seen as a stand-alone activity implemented for its own sake, but rather as an integral component of scientific research and assessment designed to support decision making.

Adaptive management—a systematic approach for improving resource management by learning from management outcomes—is widely recognized as an important approach for managing natural resources in the face of uncertainty (Williams et al. 2009). While frequently invoked, adaptive management has rarely been effectively implemented (Far North Science Advisory Panel 2010; Westgate et al. 2013). In particular, adaptive management requires effective monitoring to provide the learning component necessary to compare alternative management actions, understand system responses, and adjust management practices if they are not reaching their objectives. The need for monitoring itself to be adaptive—to maintain flexibility in the face of evolving understanding and socioecological context—has more recently been articulated as a means of helping monitoring programs confront both current management challenges and unexpected future scenarios (Lindenmayer & Likens 2009; Burton et al. 2014).

1.4 The need for effective ecological monitoring in Ontario's Far North and Ring of Fire

Ontario's Far North is a vast, remarkably intact region representing one of the world's few remaining expanses of relatively undisturbed boreal forest. The 452,000 km^2 Far North planning area supports globally significant, large-scale ecological processes including carbon sequestration and storage, migratory bird breeding habitat, and large mammal predator-prey dynamics (Far North Science Advisory Panel 2010; Chetkiewicz & Lintner 2014). It also holds valuable natural resources, including timber, minerals, and hydroelectric potential. In particular, the "Ring of Fire" sub-region in the McFauld's Lake area (Fig. 1) faces increasing development pressure due to recent mineral discoveries—more than 90% of active mining claims in the Far North are in this area, and planning for mine development is happening faster than regional land use planning (Far North Science Advisory Panel 2010; ECO 2013; Hjartarson et al. 2014). The Far North Science Advisory Panel (2010) recommended immediate designation of the Ring of Fire as a Priority Management Area with an interim sub-regional planning process.

Nevertheless, resource development planning in the Far North is proceeding in a piecemeal, project-by-project manner, without due consideration of cumulative environmental impacts at a landscape scale (Far North Science Advisory Panel 2010; Chetkiewicz & Lintner 2014). With the expectation of increased infrastructure, mining and other development, the Ring of Fire and broader Far North region is set to undergo significant changes over coming decades (Carlson & Chetkiewicz 2013; ECO 2013; Chong 2014; Hjartarson et al. 2014). Anticipated mining developments in the Ring of Fire will cause intense localized disturbances to forest and wetland habitats, and will also entail larger disturbances through associated development of infrastructure, particularly for transportation (road, rail) and power transmission (Carlson & Chetkiewicz 2013). Furthermore, environmental impacts attributable to the mining sector will interact with other anthropogenic impacts (e.g., hydroelectric development, hunting and fishing, climate change) and natural disturbances (e.g., forest fires, insect outbreaks). While such cumulative effects are mentioned in the context of land use planning in the Far North (e.g., draft Far North Land Use Strategy and community based land use plans), currently there is no integrated, regional approach to assessing or managing them (Chetkiewicz & Lintner 2014).

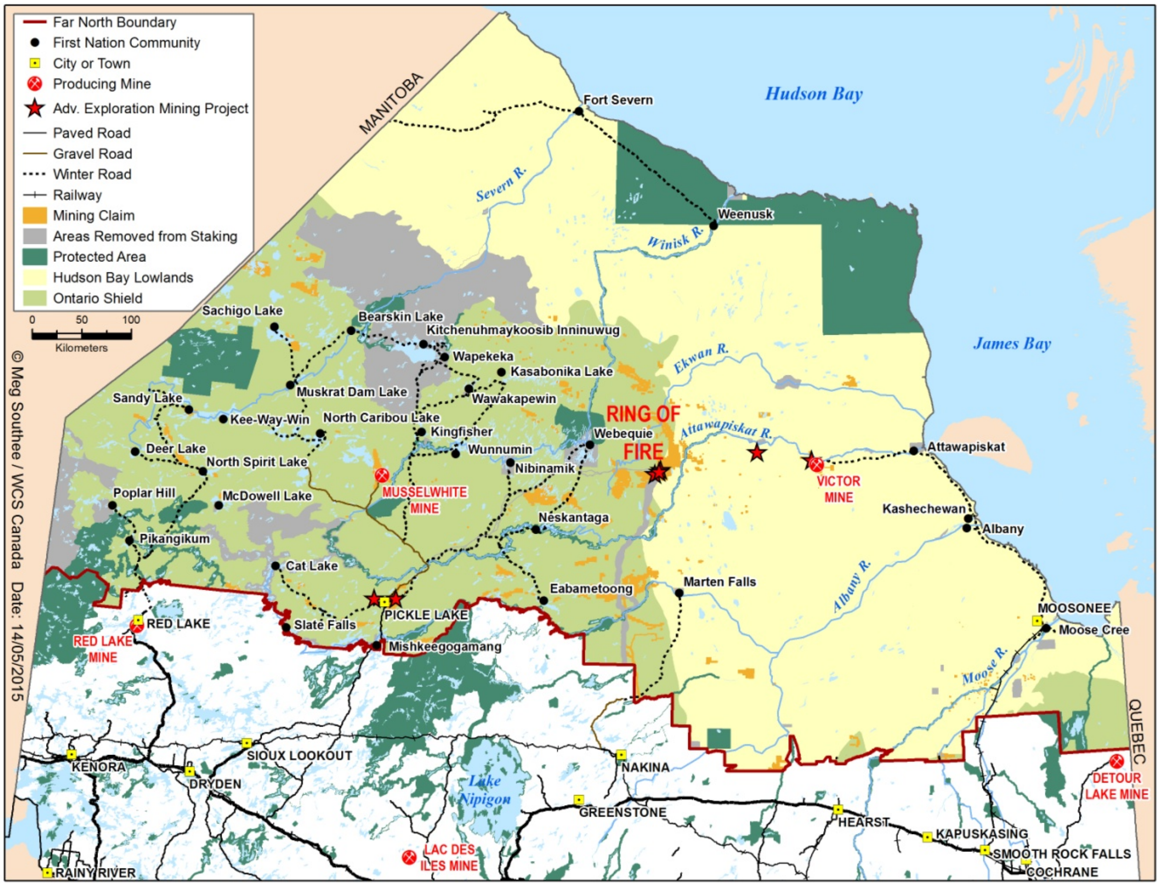

Figure 1. *Ontario's Far North region and the Ring of Fire sub-region, including producing mines, mining claims, advanced exploration projects and areas withdrawn from staking. (Sources: Ontario Ministry of Natural Resources, Ontario Ministry of Northern Development and Mines.)*

The Ontario government has made commitments to protect at least 50% of the Far North from anthropogenic development and pursue sustainable development with First Nations on the remainder (*Far North Act, 2010*). In addition, Ontario has committed to regional environmental monitoring, infrastructure planning, revenue sharing, and enhanced participation of First Nations in environmental assessment in the Ring of Fire (Matawa First Nations, Regional Framework Agreement 2014). However, the means by which these commitments will be implemented, and their success measured, are not yet clear. While there is currently no statutory requirement for ecological monitoring across Ontario's Far North, the need for regional monitoring has been articulated in many contexts. For example:

- The Far North Science Advisory Panel (2010: 106) recommended a comprehensive inventory and enhanced monitoring program, suggesting that "a regional monitoring program and associated database management system should be established to collect and store information efficiently." (2010: 81).

- The Environmental Commissioner of Ontario (ECO) provided an overview of why monitoring is required in the Ring of Fire and recommended that the government "make a statutory commitment to monitoring in the Ring of Fire" (ECO 2013: 72), and that new financial tools be developed to recover costs of environmental monitoring (ECO 2013: 60).
- Federal and provincial environmental assessment processes beginning in 2011 for proposed mining developments in the Ring of Fire (Cliffs Natural Resources' Black Thor Project and Noront Resources Inc.'s Eagles Nest Project) require baseline data. In association with the provincial assessment, Ontario's Ring of Fire Secretariat is considering "long-term monitoring of environmental impacts on a regional basis … to support future regional and cumulative impacts evaluation" (MNDM 2015).
- Nine Matawa First Nations signed a Regional Framework Agreement (2014) with the Government of Ontario that included an objective of long-term environmental monitoring on a regional basis.
- Within the Government of Ontario's mandate letters released in July 2014, key ministries responsible for development planning and approvals in the Ring of Fire were charged with ensuring robust and comprehensive approaches to planning, including regional cumulative effects assessment and long-term monitoring (Ministry of Northern Development and Mines, MNDM[3]; Ministry of the Environment and Climate Change, MOECC[4]; Ministry of Natural Resources and Forestry, MNRF[5]).
- As part of efforts to recover threatened woodland caribou (*Rangifer tarandus caribou*), Ontario's Woodland Caribou Conservation Plan is focused on managing and monitoring cumulative disturbances within caribou ranges, six of which occur in the Far North (MNR 2009; MNRF 2014).

Despite the recognized need for monitoring, devising an effective ecological monitoring program in Ontario's Ring of Fire will be challenging. Firstly, the objectives of a monitoring program should be explicitly tied to management objectives, but the lack of a regional land use plan makes it difficult to develop a robust monitoring framework. Planning is currently proceeding at a variety of spatial and temporal scales, such as for individual mining projects and Far North communities, but appropriate scales for regional monitoring are unclear. To date, the spatial scale of the Ring of Fire has been delineated on the basis of mining claims (e.g., 2000-5000 km^2; ECO 2013; Chong 2014), yet mining projects and associated developments like access roads will affect ecological processes at much larger spatial scales (e.g., watersheds). Furthermore, identifying important monitoring targets is made difficult by a paucity of existing ecological data—the remoteness of Ontario's Far North means that many components of the region's ecosystems are poorly studied (Far North Science Advisory Panel 2010). This remoteness also presents tremendous logistical challenges to accessing the region and thus designing a financially viable and statistically robust sampling design. Finally, there remain no processes for

[3] http://www.ontario.ca/government/2014-mandate-letter-northern-development-and-mines
[4] http://www.ontario.ca/government/2014-mandate-letter-environment-and-climate-change
[5] http://www.ontario.ca/government/2014-mandate-letter-natural-resources-and-forestry

considering the collection and application of traditional ecological knowledge to address planning or monitoring.

Nevertheless, the relatively undisturbed nature of Ontario's Far North presents a unique opportunity to initiate regional cumulative effects monitoring *before* significant changes have occurred. Monitoring provides the means by which to improve understanding of the Far North socio-ecological system over time—particularly the responses of valued ecosystem components to land use changes—and, importantly, to assess the effectiveness of management actions, such as protected areas design, development thresholds, or habitat restoration. Monitoring cumulative effects on biodiversity across large spatial and temporal scales is a complex undertaking, particularly in such a remote and understudied region where development pressures and management plans are uncertain. Crafting a scientifically defensible, financially sustainable, management-relevant, and stakeholder-accepted monitoring program will require considerable effort. Given the ecological and social importance of the Far North, and Ontario's commitments to ecological protection, sustainable development, and regional monitoring in the Ring of Fire, this effort is warranted.

The purpose of this report is to facilitate development of an effective, question-driven ecological monitoring program for the Ring of Fire. We begin by reviewing general recommendations for ecological monitoring from the scientific literature (Section 2), with the aim of identifying key themes for consideration in developing a new program in Ontario's Far North. We then summarize examples of existing monitoring efforts in Ontario, Alberta, and the Northwest Territories (Section 3), in order to identify challenges and lessons from relevant initiatives. Finally, we make recommendations for further development of a monitoring framework and design applicable to the Ring of Fire socio-ecological system (Section 4). Although ecological monitoring is a broad topic that includes monitoring of diverse components of terrestrial and aquatic ecosystems, this report focuses primarily on monitoring terrestrial biodiversity, and particularly on vertebrate wildlife.

2.0 General recommendations for effective ecological monitoring from the scientific literature

2.1 The purpose of monitoring

There has been considerable discussion in the recent scientific literature about the role and effectiveness of ecological monitoring. The value of reliable, long-term data on ecological dynamics and biodiversity responses to human impacts has been highlighted (Butchart et al. 2010; Magurran et al. 2010; Robertson et al. 2012), but so has the paucity of examples of effective monitoring in support of large-scale biodiversity management (Legg & Nagy 2006; Lindenmayer & Likens 2010a,b; Buckland et al. 2012; Noon et al. 2012). In the hope of remedying this situation, many prominent ecologists have provided recommendations for monitoring programs based on their scientific philosophies and practical experiences. An influential paper by Yoccoz et al. (2001) suggested that many programs suffered from a lack of well-articulated objectives and the neglect of important sources of sampling error. These authors argued that monitoring initiatives must pay adequate attention to three fundamental questions: (1) *Why* monitor? (2) *What* should be monitored? and (3) *How* should monitoring be carried out? Echoing proponents of adaptive environmental management (e.g., Walters & Holling 1990), Yoccoz et al. (2001) called for greater integration between monitoring, management and research, and stressed that the strongest inferences on cause-effect relationships come from experimental manipulations (cf. Krebs 1991). However, recognizing that controlled manipulations may not often be feasible, Yoccoz et al. (2001) emphasized that stronger inferences result from the testing of *a priori* hypotheses with monitoring data, rather than relying only on monitoring data to generate *a posteriori* hypotheses (i.e., trying to explain trends after they have been observed).

In another widely-cited paper, Nichols and Williams (2006) advanced similar arguments and specifically criticized the common "omnibus surveillance" approach to monitoring as "an inefficient use of conservation funds and effort". They characterized surveillance monitoring as the passive collection of data on status and trend for a wide variety of species and locations, often for various, poorly defined purposes and without links to management-oriented hypotheses. Lindenmayer and Likens (2010b) similarly contrasted question-driven monitoring with both passive (i.e., surveillance) monitoring, which is devoid of specified questions, and mandated monitoring, where trend data are gathered as a legislative or political requirement, but without an attempt to understand mechanisms influencing trends. Nichols and Williams (2006) argued that the two-step process of using monitoring to identify trends and subsequently develop hypotheses or management actions is inefficient and frequently ineffective. They cautioned that surveillance monitoring "can become a form of political and intellectual displacement behavior, or worse, a deliberate delaying tactic" (Nichols & Williams 2006: 672). They maintained that monitoring should not be seen as a stand-alone activity, but rather as one key element within a framework for informed decision making (i.e., adaptive management), with the other essential elements being clear objectives, potential management actions, models of system response to management actions, and measures of confidence in the models.

Despite such criticisms of passive surveillance or mandated monitoring, other authors have defended approaches focused on trend surveillance. Boutin et al. (2009) acknowledged an important role for targeted or "stress-oriented" monitoring, but argued that it is inadequate for detecting the cumulative ecological effects of a diverse set of environmental stresses on broad suites of indicators (see also Haughland et al. 2010). Johnson (2012) argued that hypothesis-driven monitoring is impractical for long-term, multispecies assessments, and that surveillance monitoring has value for detecting unanticipated changes to ecosystems. Wintle et al. (2010) suggested that either targeted or surveillance monitoring may be appropriate depending on the context—they recommended a decision analytic framework to weigh the expected costs and benefits relative to program objectives. Increasingly, benefits of both targeted and surveillance monitoring have been recognized, and several authors have suggested designing programs that combine elements of the two approaches (e.g., Lindenmayer & Likens 2010a; Environment Canada 2011; Lookingbill et al. 2012; Burton et al. 2014). Such hybrid or adaptive programs are centered on clear objectives and designed to test specific management-oriented hypotheses, while also maintaining a long-term "core" set of broader measures that facilitate detection of unanticipated changes, and around which the hypothesis-driven monitoring can adapt. Lindenmayer & Likens (2009, 2010a) termed their framework "adaptive monitoring" and its key components are shown in Figure 2.

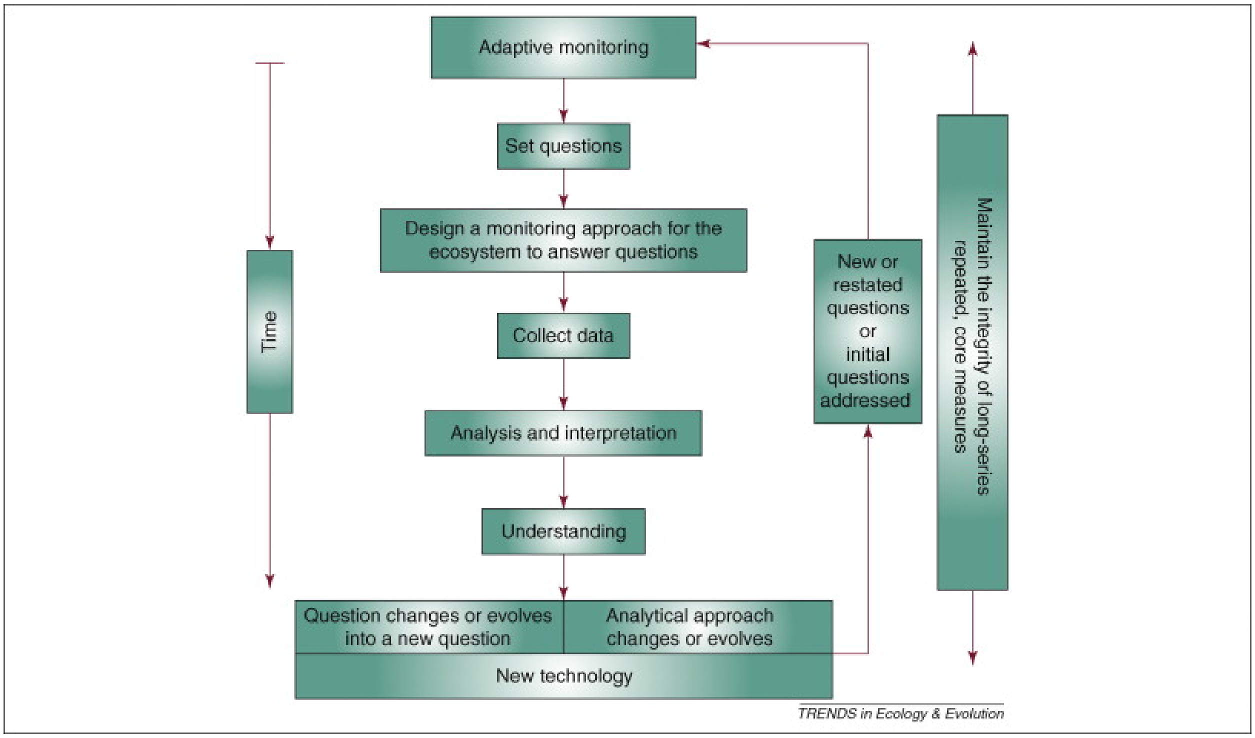

Figure 2. *Components of an "adaptive monitoring" framework, following Lindenmayer and Likens (2009, reprinted with permission from Elsevier).*

2.2 Monitoring objectives and conceptual models

Despite debate over the degree to which monitoring should be focused on testing specific hypotheses vs. surveilling trends, there is broad agreement that it is critical to set clear objectives and questions to be addressed through monitoring. Explicit objectives provide a focus for monitoring—i.e., determining the details of what and how to monitor (Yoccoz et al. 2001)—as well as a basis for assessing a program's effectiveness. Lindenmayer and Likens (2010a:55) stress that "good questions must be scientifically tractable and test real policy and resource management options", and they recommend the use of conceptual models to clarify thinking about monitoring objectives, targets and outcomes. Similarly, the US National Park Service's Inventory & Monitoring Program emphasizes that effective monitoring objectives need to be realistic, specific and measurable (NPS 2012). Devising explicit questions or objectives and conceptual models can be a difficult task and is often overlooked, given the daunting complexity and uncertainty associated with most ecological systems. For instance, responses of wildlife to the effects of human development activities can be complex, variable, and scale-specific, including localized behavioural or physiological effects on individuals and large-scale influences on population dynamics, species distributions, and community structure (Johnson & St-Laurent 2011).

A conceptual model is a visual or narrative summary of the important components of a system and the interactions among them; it can be specified in many different ways, including tables, schematics, or flow charts (e.g., Gross 2003; Margoluis et al. 2009). Conceptual models are important at all stages of monitoring: from structuring thinking at the early stages of program development, through learning about system dynamics when models are confronted with data, to helping communicate understanding generated by monitoring (NPS 2012). Pathways-of-effects models may be particularly useful in the context of cumulative effects monitoring, representing expectations of how human activities produce stressors and the pathways by which stressors impact components of an ecosystem (Clarke Murray et al. 2014; Fig. 3).

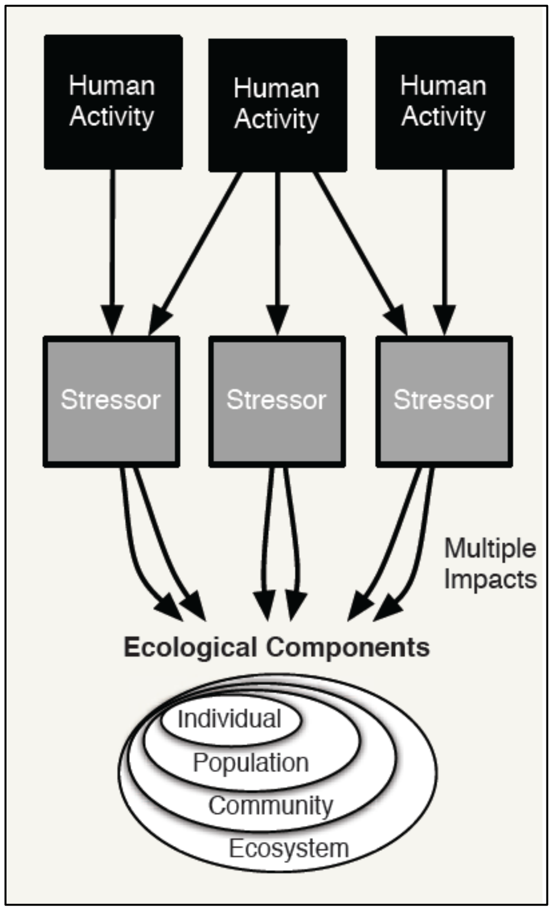

Figure 3. *General approach to a conceptual model of the cumulative effects of multiple human activities and stressors on valued ecosystem components at multiple scales of ecological organization (Source: Clarke Murray et al. 2014).*

Noon (2003) recommended the following sequential approach to characterizing anticipated stressors and disturbances and forming a conceptual model:

- list ecological processes and resources likely to be affected by identified stressors;

- rank stressors according to their degree of impact and/or degree of irreversible consequences; and
- outline pathways from stressors to ecological effects on one or more resources (see also Environment Canada 2011).

While conceptual models of multiple stressors acting on diverse ecological communities can be highly complex, Lindenmayer and Likens (2010a,b) suggest that simple, general models are likely to be more useful. Burton et al. (2014) provided a general conceptual model for biodiversity monitoring in Alberta, describing the *overarching hypothesis* that changes in human "footprint" (i.e., physical habitat disturbance) are the primary driver of biodiversity changes and are under the influence of management decisions, but that other interacting natural and human disturbances may also be important to consider (e.g., fire, hunting; Fig. 4).

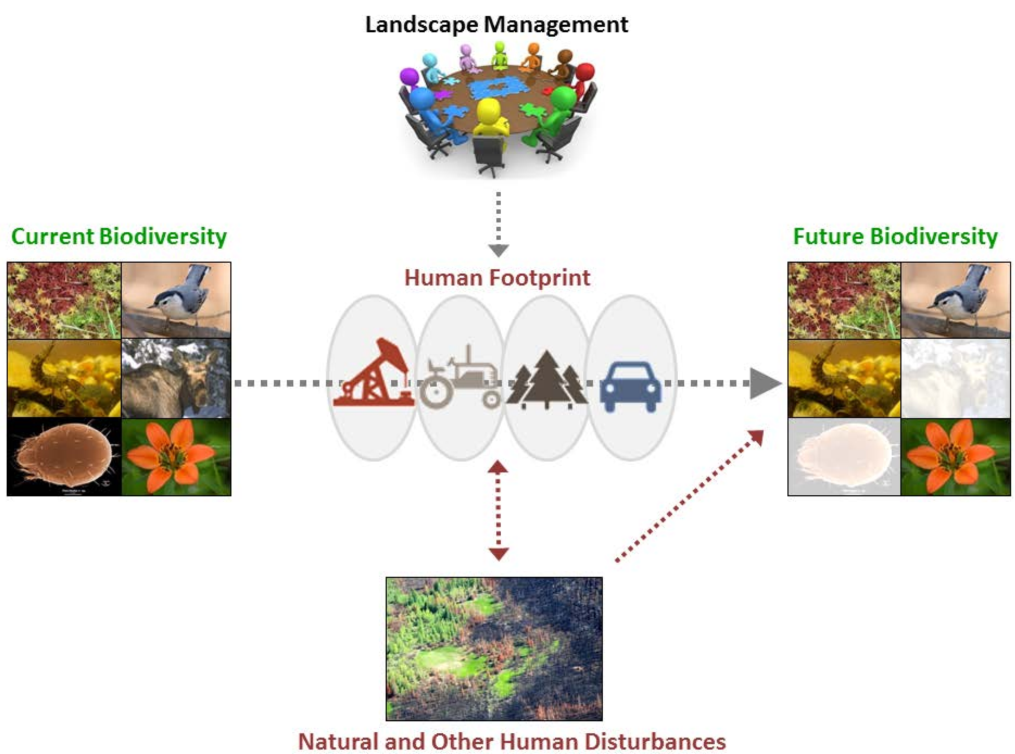

Figure 4. *Example of a general conceptual framework guiding regional monitoring of cumulative effects on biodiversity in Alberta (see Burton et al. 2014 for details; reprinted with permission from Springer).*

Regardless of the specific details of a given conceptual model, it should be useful in framing the main monitoring hypotheses and targets (e.g., focal species, ecosystem attributes, stressors, response variables). It should also be general or flexible enough to allow a program to adapt as understanding improves or questions change; it is thus important to periodically re-examine a conceptual model during the course of monitoring. For example, Irvine et al. (2015) conducted an empirical evaluation of the conceptual model used in a long-term, regional aquatic surveillance monitoring program and found that it inadequately captured drivers of observed changes. As a result, they suggested the program move beyond a primary focus on biological status and trends, and adjust the design to better address questions about mechanisms of change (such as by including environmental contextual variables underlying natural heterogeneity). It is important to remember that there will not be any single, correct conceptual model, and that constructing alternative models may help articulate competing hypotheses that form the basis of an effective adaptive management program (Nichols & Williams 2006; NPS 2012). Multiple, hierarchical models may also be necessary to represent important details of particular components of the larger management context, which will likely encompass ecological, social, economic, and political subsystems relevant at multiple spatial and temporal scales (NPS 2012).

2.3 Linking monitoring to management priorities and decisions

A key challenge in devising objectives and conceptual models for management-oriented monitoring lies in creating explicit linkages to management hypotheses (Nichols & Williams 2006). Scientists need to play a primary role in developing a scientifically rigorous monitoring design (Gitzen & Millspaugh 2012), but the involvement of resource managers, policy-makers, and other stakeholders will be critical for setting objectives that are relevant to management goals and higher-level policy commitments. For example, a conceptual model specifying management actions that will not be considered by managers will likely be of limited value. Strong engagement between researchers and managers or policy-makers is therefore essential for effective monitoring in support of adaptive management (Lindenmayer & Likens 2010a,b; Gitzen & Millspaugh 2012; Westgate et al. 2013; Nichols et al. 2015). Broader consultation across key stakeholders (e.g., industry, First Nations, general public) is also important for identifying monitoring priorities and building support for the monitoring program; however, achieving consensus among diverse interests may not be possible or necessary in some cases (Boivin et al. 2014).

Structured decision making has been proposed as a powerful and transparent approach for linking monitoring to management decisions (Williams et al. 2002, 2009; Lyons et al. 2008; Martin et al. 2009; Kendall & Moore 2012; Nichols et al. 2007, 2015). This systematic approach can help shift debate from an emphasis on ecological uncertainty—which often results in delaying action to gather more information—to one on objectives and management alternatives. Resource managers, working with other stakeholders, determine objectives for biodiversity management (e.g., minimize extinction risk, maximize area of high quality habitat) and identify potential actions designed to meet the objectives (e.g., location and intensity of development, impact mitigations). In doing so, they formulate explicit hypotheses (models) about the consequences of alternative actions that facilitate evaluation of trade-offs (i.e., management costs vs. biodiversity benefits). Within structured decision making, the critical role for ecological monitoring lies in estimating variables describing biodiversity status (e.g., species abundance, distribution), thereby testing the hypotheses of biodiversity responses to management actions. Understanding is improved over time as alternative hypotheses are weighted based on comparisons between model predictions and monitoring observations (Nichols and Williams 2006; Lyons et al. 2008; Burton et al. 2014). A structured decision analysis provides a quantitative way of choosing the management option that has the best cumulative effect on focal biodiversity resources

(Williams et al. 2002; Sauer et al 2012). As an example, structured decision making has been successfully applied to the adaptive management of North American waterfowl harvest (Nichols et al. 2007, 2015). More generally, decision analysis may be important in determining optimal allocation of monitoring effort given economic constraints and management priorities (Field et al. 2005; Possingham et al. 2012).

2.4 What to monitor: defining monitoring targets

The details of *what* to monitor and *how* to do it flow from the explicit definition of monitoring objectives and questions (Yoccoz et al. 2001; Lindenmayer & Likens 2009, 2010a,b). There are a great many potential foci of ecological monitoring programs, and choosing a manageable number of monitoring targets is not a trivial task. Many different approaches for choosing targets have been used by monitoring programs and there is no one standard method (NPS 2012). Many large-scale monitoring programs have relied on coarse filter approaches for monitoring landscape changes (Noon et al. 2012). Environmental data collected by remote sensing are likely to be an important part of regional monitoring initiatives, and there are many promising examples (e.g., Pettorelli et al. 2005, 2014; Coops et al. 2014). Nevertheless, coarse filter landscape metrics (e.g., land cover, vegetation indices, fragmentation metrics) are likely to be inadequate on their own as they may not reliably reflect dynamics of finer scale components of the monitored system, such as species distribution and abundance (e.g., Schlossberg & King 2009; Noon et al. 2012).

Given a common need to include species as targets for regional cumulative effects monitoring, there is some tension between trying to avoid a narrow focus on a small number of species and diluting effort across too many species (a “laundry list”, Lindenmayer & Likens 2010a). The former may give an incomplete picture of ecological changes in the region of interest, while the latter may render the explicit formation of questions, hypotheses, and a conceptual model too complex and intractable. Several multispecies survey and monitoring programs have been developed for the purpose of managing regional landscapes and cumulative environmental effects (e.g., Manley et al. 2004, 2006; Schwenk & Donovan 2011; Erb et al. 2012; Burton et al. 2014; Furnas & Callas 2015). Such programs may work effectively when groups of species are linked by common management issues (e.g., sensitivities to habitat disturbance, harvest management) and can be surveyed effectively using standardized methods (e.g., camera traps, breeding bird point counts). Multispecies programs may also be well-suited where aggregate indices of biodiversity are desired (e.g., species richness, biodiversity “intactness”; Buckland et al. 2005, 2012; Nielsen et al. 2007). However, aggregate indices can be difficult to interpret in terms of underlying drivers of change, and multispecies monitoring methods may not yield the strongest inferences for individual species of particular management concern (Fleishman et al. 2006).

Noon et al. (2012) suggest that for pragmatic reasons monitoring efforts should be focused on a small number of species chosen on the basis of specific management objectives, their ecological roles, their sensitivity to current or expected future impacts, or their conservation importance. For example, in Canada’s boreal forests, woodland caribou are increasingly a focus of management and monitoring effort due to their observed declines and federal listing as a species at risk, their sensitivity to industrial and cumulative disturbance, and their large-scale habitat requirements (MNR 2009; Festa-Bianchet et al. 2011; Environment Canada 2012; Hervieux et al. 2013). Mandated monitoring may be primarily focused on such threatened species for which there are political or legal requirements for monitoring or other management attention.

Aside from regulatory requirements, many justifications have been advanced for choosing particular species as targets for monitoring. Approaches to prioritizing species for conservation planning and monitoring have included indicator species (Carignan & Villard 2002; Thompson 2006), umbrella and focal species (Lambeck 1997; Hannon & McCallum 2004; Roberge & Angelstam 2004), landscape species (Coppolillo et al. 2004), and keystone or strongly interacting species (Power et al. 1996; Soule et al. 2003). At the same time, many of these approaches have been critiqued (e.g., Simberloff 1998; Andelman & Fagan 2000; Lindenmayer et al. 2002). Lindenmayer and Likens (2010a) argue that while a wide range of biota have been deemed to be key monitoring “indicators”, explicit links between such indicators and other components of the ecosystem are often poorly articulated or supported. They contend that there are limitations to relying on indicator or surrogate species as proxies for unmonitored components of the system, and suggest that trade-offs in choosing focal species for monitoring should be made explicit (e.g., rare vs. common, societal value vs. ecological role). Krebs (2012) recommends constructing a food web for the targeted ecosystem and focusing on strongly interacting species central to monitoring objectives (cf. Simberloff 1998; Soule et al. 2003). Even when target species are identified, decisions must be made as to what levels of ecological organization are important to monitor (e.g., population dynamics, individual behaviour, genetic diversity; Johnson & St. Laurent 2011; Fig. 3).

Ultimately, a monitoring program may choose a range of target species linked to different objectives or characteristics of the monitored system. For example, the Far North Science Advisory Panel (2010) identified potential focal species for land use planning in Ontario’s Far North based on traits such as specialized habitat requirements (e.g., yellow rail), breeding aggregations (e.g., sharp-tailed grouse), large ranges (e.g., caribou, wolverine), movement routes (e.g., migratory waterfowl), and sensitivity to disturbance (e.g., marten. See Section 4 for more discussion specific to the Far North).

2.5 Where and when to monitor: sampling design

Effective monitoring programs must produce scientifically credible results. Good sampling design is necessary to ensure monitoring data meet their intended purpose and withstand scrutiny (NPS 2012). Sampling design is inherently a statistical issue, with a good design yielding unbiased and precise estimates at a reasonable effort (Thompson 2002). Explicit monitoring objectives and targets will define the desired scope of inferences to be made, and sufficient attention needs to be devoted to developing a sampling design that will deliver robust inferences. Monitoring programs are almost always limited by funding, particularly for large-scale multispecies initiatives, so it is critical that data collected at a limited number of sampling locations permit inferences to the larger region(s) of interest. Gitzen & Millspaugh (2012) emphasized that quantitative issues of design and analysis are of fundamental importance to the success of long-term monitoring programs. They warned against thinking simply that something useful will come from any data collected (“hope for the best”), and suggested thinking carefully beforehand about “worthlessness” in the context of monitoring—e.g., what is the low-end threshold of statistical precision below which results would not be useful for management. Such explicit thinking shifts the focus from rushing to implement *any* monitoring to acknowledging that if a monitoring program can't meet its objectives, monitoring capacity must be increased or the limited resources may be better spent on other endeavours (e.g., biodiversity protection, public education).

There are many useful references detailing valid approaches to ecological sampling design (e.g., Krebs 1999; Thompson 2002; Williams et al. 2002; McDonald 2012). Assuming the goal of a monitoring program is to make inferences for an entire region of interest—as opposed to only specific sites—valid inferences depend on probability-based samples. Nevertheless, Yoccoz et al. (2001) argued that many monitoring programs use inappropriate sampling designs that do not deal effectively with spatial variation, relying instead on subjective samples of "representative" sites. A key first step is to specify a target population of potential sampling sites (i.e., "statistical" population) from which samples can be selected following a probability-based design, such as random sampling, systematic sampling with a random start, or stratified random sampling (McDonald 2012). Probabilistic designs occur when each potential sampling unit has a known, non-zero probability of being selected, and they always include a random component. In defining the statistical population and potential sampling units, it is important to link sampling scales to ecological scales. In other words, the spatial and temporal scales of measurement should be matched to the spatial and temporal scales at which the ecological populations and processes function. It is likewise important to define the state variables to be monitored; for example, sampling designs may differ between monitoring focused on estimating population abundance and occupancy (Burton et al. 2015). Such differences can create particular challenges for multispecies programs that sample a wide-range of taxa, requiring careful consideration of whether multiple sampling designs may be required.

Cumulative effects monitoring programs are likely to operate across large, complex landscapes, and to target multiple, interacting species and stressors. As highlighted above, making strong inferences from monitoring data will require clear objectives and targets, but may also require more complex approaches to sampling. When monitoring is focused on assessing the impact of a particular disturbance, such as an industrial development, a Before-After-Control-Impact (BACI) design is a powerful approach for making causal inference (Stewart-Oaten et al. 1986; Underwood 1992; Schwarz 1998). The BACI design isolates a disturbance as an experimental treatment, measuring pre-treatment reference conditions and matching the treatment with an ecologically similar control area not affected by the disturbance of interest. However, in the context of monitoring the cumulative effects of multiple disturbances, some having already occurred and others unplanned, and all within complex and poorly understood ecosystems, a classic BACI design is unfeasible. Enhanced BACI designs have been proposed (Underwood 1992; Schwarz 1998), but may only be suitable in cases where specific, planned disturbances can be monitored in advance and matched with a sufficient sample of control sites to adequately account for natural variability over space and time.

While a BACI approach is not likely to be appropriate for regional cumulative effects monitoring, relying instead on a sampling design that ignores spatial and temporal variation in key stressors and other factors of interest (including potentially confounding variables) would make it difficult to assess drivers of observed changes and link monitoring results to management applications (Nichols & Williams 2006; Lindenmayer & Likens 2010a; Irvine et al. 2015). Therefore, some form of stratified or unequal probability sampling may be important to ensure sufficient samples with characteristics of primary interest. Stratification attempts to combine sampling units into homogenous groups which are sampled independently. Potential strata of interest may include areas of expected industrial impacts, protected areas or ecological benchmarks (Schmiegelow et al. 2008), rare habitats of management importance, administrative units, and remote vs. accessible areas. However, in the context of long-term regional monitoring, it may be difficult to stratify across the many variables of interest and importance over time, and care should be taken to avoid strata that are likely to change over the monitoring time frame (e.g., boundaries of dynamic vegetation communities). McDonald (2012) suggested that stratification and unequal probability sampling (a form of stochastic stratification) are unlikely to achieve a goal of reducing variance in estimates in most ecological monitoring situations, since too little is usually known about the response of interest to construct proper strata. Using spatial distribution as a basis for probabilistic selection of a representative set of sampling sites is another option—the US National Parks Service uses a spatially balanced Random Tessellation Stratified (GRTS) approach to developing sampling designs for monitoring within national parks in the United States (Fancy & Bennetts 2012; Olsen et al. 2012).

Where important factors are not explicitly included in a sampling design, they should still be adequately sampled and included as covariates to improve estimates, although large sample sizes may be necessary to statistically estimate effects while controlling for other variables. Model-based design and inference may be important to consider in the context of monitoring dynamic processes over time, such as cumulative environmental effects (Reynolds 2012). Nevertheless, achieving reliable model-based inferences also requires careful planning, as well as an assumption that the model is an adequate description of the population of interest. Generally speaking, model-based inference requires more complicated analysis and better knowledge of the system being monitored (Reynolds 2012). Stokes et al. (2010) provided an example of landscape-scale monitoring and the challenges of model-based estimation relative to a stratified design-based approach. Ultimately, a probabilistic sampling design is preferred as it not only provides a basis for design-based inferences, but also an ability to compare with model-based estimates and thus avoid relying on an assumption that the underlying model is unbiased.

Hybrid or adaptive sampling designs show promise for combining elements of trend surveillance and targeted, question-driven monitoring. Lookingbill et al. (2012) describe a hybrid approach to monitoring that combines a probability-based sampling framework for unbiased estimation of long-term regional trends (i.e., permanent sampling plots selected using GRTS) with dynamic, model-based samples to address more local, shorter-term management needs. Burton et al. (2014) articulated an approach to cumulative effects monitoring in Alberta that combines a systematic surveillance grid with more targeted, model-based sampling. Environment Canada (2011) described a similar approach focused on monitoring cumulative effects in Alberta's oil sands, whereby representative sampling of key gradients is achieved by cross-classifying variation in expected habitat suitability for target species with variation in disturbance footprints (see also Danz et al. 2005 and Kimmins et al. 2007; more discussion of cumulative effects monitoring in Alberta is provided in section 3.2).

Whatever approach is used to create a spatial sampling design for monitoring, it is important that an analytical approach is appropriately matched to the sampling, and complex sampling designs will require complex analyses (McDonald 2012; Reynolds 2012). It is also important to carefully consider the temporal component of sampling—that is, how frequently sites should be sampled. For long-term monitoring, permanent sampling plots are generally recommended over selecting new sites through time, since trends estimated from repeated observations at permanent sample points typically have better precision and higher likelihood of detecting significant changes over time (Scott 1998 in Environment Canada 2011; Fancy 2000; Urquhart 2012). It is not necessary to visit all plots in each year of monitoring, as rotating panel designs have been used (e.g., Stadt et al. 2006; see section 3.2.1), but such designs can increase the complexity of analysis.

The key to ensuring the adequacy of a spatio-temporal sampling design is to conduct formal precision analysis (a.k.a. power analysis; Nielsen et al. 2009; Reynolds et al. 2011; Skalski 2012; Garman et al. 2012; Ellis et al. 2015). This in turn requires characterization of expected levels of variance and survey effort, and specification of intended approaches to analyzing monitoring data. Precision analysis can be a challenging undertaking and is frequently overlooked or done superficially, but it represents a crucial component of rigorous survey design and is needed to ensure a monitoring program can meet its objectives (Gitzen & Millspaugh 2012). Precision analysis can also be used to optimize sampling efficiency, which is often an important consideration given the typical situation of limited resources for monitoring. Hooten et al. (2012) recommended an adaptive sampling approach to increase the cost-efficiency of monitoring, optimizing sampling design while maintaining flexibility if program funding is likely to vary over time. Their approach fuses monitoring and modelling, identifying the subset of total potential monitoring sites that should be monitored to minimize variation in the estimate of interest (e.g., trend in abundance), given an available budget for sampling.

2.6 How to collect data: sampling methodologies and protocols

Once an adequate sampling design has been determined –that is, the specification of sampling locations and frequency—suitable data collection protocols must be developed. Sampling methods will be driven by monitoring objectives, targets, and response variables, and they must produce reliable data for making inferences. Several authors have argued that many existing monitoring programs fail to adequately deal with important sources of observation or measurement error that could obscure underlying ecological patterns of interest (e.g., Anderson 2001; Yoccoz et al. 2001). The problem of detectability, or imperfect detection, has received particular attention—that is, the fact that not all entities of interest (e.g., species, individuals) will be observed during most ecological sampling processes, resulting in observations that may be significantly biased (Pollock et al. 2002; MacKenzie et al. 2006). It is therefore important to consider and control for significant sources of potential detection bias during design and implementation of survey protocols (e.g., Banks-Leite et al. 2014; Matsuoka et al. 2014). Carefully evaluated and standardized sampling protocols are critical, and collection of sampling covariates that may explain heterogeneity in detection processes can be important (e.g., weather, time of day, observer experience; Matsuoka et al. 2012). Methodological standardization is important both in space and time; any methodological changes through time must be carefully calibrated to avoid losing the integrity of the long-term dataset (Lindenmayer & Likens 2010a).

In designing data collection protocols and considering subsequent analyses, efforts should be made to directly estimate detection probabilities or test assumptions of equal detectability over space or time. Several analytical approaches have been developed to explicitly account for detectability (e.g., distance sampling, Buckland et al. 2001; capture-recapture, Royle et al. 2014; occupancy estimation, MacKenzie et al. 2006). However, it is important to consider that all such statistical models also involve important assumptions and must be carefully matched to the observational and ecological processes being measured (Johnson 2008; Efford & Dawson 2012; Welsh et al. 2013; Burton et al. 2015; Miller et al. 2015). Ultimately, there are no "silver bullets" to fix poorly designed or implemented sampling methods after data have been collected.

Explicitly defining response variables for monitoring targets is a key prerequisite for designing sampling protocols. For instance, if an objective is to monitor the abundance of particular focal species, robust abundance estimation methods such as distance sampling or capture-recapture may be necessary. Such methods may be challenging to apply over large areas and multiple species, so other options such as abundance indices or occupancy may need to be considered (Johnson 2008; O'Brien et al. 2010; Noon et al. 2012). Monitoring that targets community-level response variables, such as species diversity, also needs to adequately account for species detectability (Cam et al. 2000; Buckland et al. 2012; Iknayan et al. 2014). Methods focused on estimating detection probabilities or ensuring rare species are adequately detected may require additional protocol considerations, such as double-observers or repeated sampling over short time periods (Pollock et al. 2002; Thompson 2004; MacKenzie et al. 2006; Poley et al. 2014).

There are many references detailing potential sampling methods for plant and animal populations (e.g., Thompson et al. 1998; Krebs 1999; Bibby et al. 2000; Sutherland 2006). Canada's Ecological Monitoring and Assessment Network (EMAN; Vaughan et al. 2001) produced a series of recommended protocols for monitoring different components of terrestrial biodiversity (Environment Canada 2014b), and monitoring protocols have also been prepared as part of the Ontario Parks Inventory and Monitoring program (OPIAM; see section 3.1.3 below). Newer automated technologies and non-invasive sampling techniques—such as acoustic recorders, camera traps, fecal DNA sampling—hold considerable promise for standardizing wildlife monitoring methods across large spatial scales (e.g., Long et al. 2008; O'Connell et al. 2011; Noon et al. 2012; Rempel et al. 2013; Burton et al. 2015; Furnas & Callas 2015). Large-scale monitoring programs will also likely need to develop sampling protocols that span multiple spatial and temporal scales, such as annual field plots and multi-year updates of remote sensing datasets (e.g., Burton et al. 2014).

Cost is often a key factor in sustaining large-scale monitoring programs, and alternative, cost-effective approaches to collecting data should be considered. For example, citizen science monitoring (a.k.a. participatory or community-based monitoring) may provide a viable, cost-effective means of collecting data on some resources in certain areas (e.g., Danielsen et al. 2009, 2014; Wiersma 2010; Conrad & Hilchey 2011; Hochachka et al. 2012). It may also be possible to combine monitoring and education programs, whereby students contribute to data collection during the course of training (e.g., McGill University 2015). Traditional Ecological Knowledge is a fundamental source of information on ecological status and change, particularly in remote northern areas such as Ontario's Far North, and many efforts are being made to combine local and traditional knowledge with scientific surveys (e.g., Polfus et al. 2014; Service et al. 2014). Nevertheless, citizen science and traditional knowledge have different strengths and weaknesses relative to standard scientific approaches in the context of ecological monitoring, and they may be expected to meet multiple purposes (e.g., stakeholder engagement, public education). If such alternative approaches are being used to collect data for scientific inferences, sufficient attention must be devoted to accounting for potential sources of bias and ensuring resulting data are reliable (e.g., Burton 2012).

Regardless of the ultimate choices in data collection methods, protocols must also be developed for careful and transparent data management, including metadata necessary for understanding the context of ecological data (Michener et al. 2011; Michener & Jones 2012). It is also critical that monitoring data be continuously analyzed and disseminated, including both peer-reviewed publications and material for policy-makers and the broader public, in order to maintain the credibility and relevance of data collection methods and the broader monitoring program (Lindenmayer & Likens 2010a).

3.0 Examples of ecological monitoring initiatives in Ontario, Alberta, and the Northwest Territories

There are a large number of ecological and biodiversity monitoring programs in North America and around the world. These vary enormously in purpose, design and scale (both spatio-temporal and ecological), as well as in effectiveness (Lindenmayer & Likens 2010a). The creation of a new ecological monitoring program for Ontario's Ring of Fire will obviously need to carefully consider the unique characteristics of the Far North region—such as its remoteness, emerging policy and planning frameworks (*Far North Act 2010*, Regional Framework Agreement 2014), existing and anticipated stressors (e.g., mining), and large-scale ecological dynamics (e.g., fire) spanning two major ecozones (Boreal Shield and Hudson Bay Lowlands; see sections 1.4 and 4.1 for more details on the Ring of Fire context). Nevertheless, consideration of the strengths and weaknesses of existing monitoring programs is also important in the development of new programs. In this section, we briefly review several initiatives focused on large-scale monitoring of biodiversity in Ontario and other northern boreal regions, particularly Alberta, where regional cumulative effects monitoring has been ongoing for over a decade.

3.1 Ecological and biodiversity monitoring in Ontario

An ecological monitoring program related to Ontario's Ring of Fire region, and Ontario's Far North in general, should ideally complement successful existing programs in Ontario (or those soon to be implemented) and learn from programs that have not been successful. It is clear that there is momentum to further develop and implement biodiversity monitoring in Ontario and the Far North (e.g., Ontario Biodiversity Council 2011; draft Far North Land Use Strategy[6]; Regional Framework Agreement 2014; Far North Science Advisory Panel 2010). For instance, Ontario's Biodiversity Strategy (Ontario Biodiversity Council 2011) has a goal of establishing and operating a "long-term monitoring and

[6] https://dr6j45jk9xcmk.cloudfront.net/documents/3627/fnlus-discussion-paper-2014-09-23-english.pdf

reporting system for assessing the state of Ontario's biodiversity" by 2015, and the Far North Science Advisory Panel (2010) recommended adaptive management and decision support for the region and provided a list of inventory and monitoring needs (see also section 1.4 above). The draft Far North Land Use Strategy (mandated under the *Far North Act, 2010*) aims to assist community-based land use planning and guide integration across individual plans for key management foci such as biodiversity, cumulative effects, and climate change. However, despite recognizing the importance of long-term monitoring for cumulative effects, the Strategy offers no prescriptive guidance on the What, Why, Where, and How of monitoring (see section 2).

Here we briefly review several existing efforts or guiding documents of relevance to ecological monitoring in Ontario's Ring of Fire region. We note that this is not an exhaustive review and that there are other programs, projects and resources worthy of consideration (including some under development). For instance, we have not included a review of mandated monitoring conducted as part of federal or provincial environmental impact assessments in the Far North (e.g., requirements under the *Canadian Environmental Assessment Act, 2012*[7] include effects monitoring plans for pre-construction, construction, and operational phases, as well as monitoring to assess mitigation and compensation plans), nor have we detailed existing or planned efforts related to monitoring climate change (e.g., monitoring of peatland, permafrost, water, and carbon flux through the Far North Monitoring Network). In many cases, our ability to review emerging initiatives in the Far North was limited by a lack of publicly accessible documentation.

3.1.1 Survey and monitoring of caribou and other large mammals

Ontario's Ministry of Natural Resources and Forestry (MNRF) is responsible for managing wildlife and undertakes or facilitates research and monitoring of several wildlife species of management importance[8]. Recent publications have detailed the methods and results of large-scale aerial surveys to assess the occupancy of multiple large mammal species (e.g., woodland caribou, wolverine, wolf, moose, white-tailed deer) across much of Ontario's northern boreal forests (Bowman et al. 2010; Poley et al. 2014; MNRF 2014). This application of large-scale aerial surveys and advanced statistical modelling of occupancy is well-suited to assessing such wide-ranging species across this large and remote region. As such, these surveys may serve as a useful template around which to develop a standardized, long-term monitoring framework for large mammals. Furthermore, the results of completed surveys may be useful in developing a conceptual model focused on these species. However, the particular monitoring objectives and management questions to be addressed, as well as the relative benefits and costs of this approach and these focal taxa, would need to be carefully evaluated.

A range management focus on woodland caribou has been clearly established in Ontario and the rest of Canada (Environment Canada 2012). Caribou are a species of conservation concern in Ontario's boreal region and the focus of a detailed conservation plan (MNR 2009). As such, caribou will be an important focal species for large-scale monitoring to support regional assessment in the Ring of Fire, and a number

[7] *Canadian Environmental Assessment Act, 2012*, SC 2012, c 19, s 52. Available online at: http://laws-lois.justice.gc.ca/eng/acts/c-15.21/index.html
[8] https://www.ontario.ca/environment-and-energy/wildlife-research-and-monitoring

of monitoring and assessment activities have been undertaken in recent years across caribou ranges in Ontario (MNRF 2014). Wolverine is another species of management concern targeted by the large-scale, multi-mammal aerial surveys conducted in northern Ontario (Magoun et al. 2007; Bowman et al. 2010; Poley et al. 2014). The Wolverine Recovery Strategy (Ontario Wolverine Recovery Team 2011) highlights the need for further information and long-term monitoring of wolverine status to assess the success of recovery efforts. Some wolverine-specific monitoring protocols and recommendations have been developed (Koen et al. 2008), although these remain to be tailored to specific monitoring questions in the Ring of Fire.

In developing a regional monitoring program that includes large mammals and other terrestrial wildlife, it is important to learn from the past shortcomings of Ontario's Provincial Wildlife Population Monitoring Program (PWPMP). The program was established as a legal requirement in 1994 to "monitor population trends of representative terrestrial vertebrate species within the Area of the Undertaking (AOU) of commercial timber harvesting, in order to understand the effects of forestry on wildlife at the provincial scale" (O'Malley et al. 2013). Reporting on an assessment conducted through the office of the ECO, O'Malley et al. (2013) concluded that "the program has failed to achieve its own objective and is unable … to adequately inform government policy and/or management decisions". They report that the PWPMP lacked a consistent list of species monitored and collected very limited long-term trend information. The program appeared to suffer from many of the problems highlighted by critiques of ecological monitoring in the literature (e.g. Lindenmayer & Likens 2010a; see section 2 above), including a lack of clear objectives and severe underfunding (the program received only 6.3% of recommended funding; O'Malley et al. 2013). Following the ECO assessment, the wildlife monitoring program for the AOU has been redesigned by MNRF, building on multispecies monitoring methods developed by the US Forest Service (Manley et al. 2006), and documentation describing the updated approach is being prepared (D. Phoenix, personal communication, April 2015).

3.1.2 Far North Biodiversity Project

The Far North Biodiversity Project (FNBP) is part of the Far North Information and Knowledge Management Plan and has a general goal of providing life science information at multiple spatial scales across Ontario's Far North region (Phoenix et al. 2013). At a broad scale, the project aims to "provide information on the occurrence and distribution of selected terrestrial biodiversity components (birds, mammals, reptiles and amphibians, invertebrates, and plants) across community planning areas. It will also provide information on specific areas (finer scales) of high natural heritage value which may be considered for some level of protection through land use planning exercises" (Phoenix et al. 2013: 1). Further, the project intends to "aid in the protection and recovery of [species at risk] by contributing to knowledge on their range, distribution and habitat associations".

The FNBP appears to have broad goals for inventory and surveillance monitoring of a wide range of biodiversity elements. However, it is difficult to thoroughly review this program due to a general lack of available documentation. For example, a summary report by Phoenix et al. (2013) provides details on numbers of plots and sampling protocols for program activities in 2013, but gives little rationale as to why particular plots or protocols were chosen. It is not clear that the FNBP is driven by explicit questions or conceptual models, nor that a rigorous survey design has been developed and adequately evaluated (e.g., precision analysis). Our understanding is that the program has thus far focused primarily on gathering basic ecological inventory data to inform evolving land use planning in the Far North, as well as evaluating the logistics of biodiversity sampling in this remote region—for instance, determining how to adapt multispecies protocols from wildlife monitoring in the AOU to much less accessible areas (D. Phoenix, personal communication, April 2015). Such information will be valuable in guiding development of long-term, cumulative effects monitoring in the region. However, the "Why, What and How" (cf. Yoccoz et al. 2001) of the FNBP, or other monitoring initiatives in the Far North, must be thoroughly articulated and reviewed to provide evidence that common shortcomings of ineffective ecological monitoring will be overcome (e.g. Lindenmayer & Likens 2010a; Gitzen et al. 2012; see section 2 above). Encouragingly, MNRF is working to develop a new cumulative effects monitoring program in the Far North based on conceptual models detailing causal pathways between human activities and ecosystem components (R. Rempel, personal communication, April 2015). We hope that details describing this program will soon be available for broader review.

3.1.3 Ontario Parks Inventory and Monitoring

The Ontario Parks Inventory and Monitoring program (OPIAM) is an initiative led by Ontario Parks, in collaboration with several other organizations, designed to promote "consistent collection, storage, and dissemination of inventorying and monitoring information (life science, recreation, and earth science) collected in protected areas and adjacent landscapes across Ontario" (McCaul & Kingston 2012). It has broad and general intended uses, such as biodiversity lists, planning information, and status reporting for parks, as well as contributing to other related efforts (support other species monitoring or modelling exercises; McCaul & Kingston 2012). The OPIAM manual provides details of what information to collect for consistent recording of incidental observations, and describes inventory and monitoring protocols for various target features (e.g. vegetation, birds, amphibians). Broad adoption of OPIAM protocols could promote standardization and coordination across existing and new monitoring data sources in Ontario; however, protocol standardization and data management pertain more to the "How" of monitoring, but do not provide specific direction for the key questions of "Why" and "What" to monitor (i.e., program objectives, conceptual model, sampling design, focal species; see section 2). The OPIAM manual (McCaul & Kingston 2012) includes general recommendations for creating project-specific sampling designs in Ontario (e.g., stratifying a study area, selecting sampling sites, establishing plots; pages 32-42), but again, these need to be matched to specific objectives for monitoring in the Ring of Fire and Far North (see section 4).

3.2 Biodiversity and cumulative effects monitoring in Alberta

3.2.1 Alberta Biodiversity Monitoring Institute (ABMI)

There has been considerable recent attention focused on cumulative effects assessment and monitoring in Alberta. This has been driven in large part by the growing documentation of environmental impacts of rapid expansion of the oil and gas industry, and how such impacts interact with other anthropogenic disturbances like timber harvest (Schneider et al. 2003; Schneider & Dyer 2006). The Government of Alberta has recognized the importance of improving assessment and management of the cumulative effects of resource development at regional scales, moving toward Regional Strategic Assessment implemented through a Provincial Land Use Framework (Government of Alberta 2008; Johnson et al. 2011). Mandated monitoring has often been implemented by industrial operators to meet conditions of regulatory approval (e.g., under Alberta's *Environmental Protection and Enhancement Act*[9], EPEA), with monitoring programs focused on specific impacts or mitigations at the level of individual project leases. These programs are often poorly integrated with others in the region, resulting in an inefficient project-by-project design and correspondingly weak inference on cumulative effects at ecologically relevant scales (with notable exceptions, such as regional caribou monitoring; Sorensen et al. 2008; Hervieux et al. 2013). Furthermore, industrial mitigation and monitoring have frequently focused on rare species (e.g., federally or provincially listed species), yet these are by nature often difficult to detect, resulting in small sample sizes and correspondingly weak inferences for directing protection and mitigation efforts. In response to such monitoring shortcomings, the Alberta Biodiversity Monitoring Institute (ABMI; initially called the Alberta Biodiversity Monitoring Program, ABMP) was developed in the late 1990s and early 2000s to fill this gap through systematic, representative sampling of multiple taxa over large spatial and temporal scales (Farr et al. 1999; Stadt et al. 2006; www.abmi.ca).

The ABMI monitoring program is designed to assess cumulative effects by tracking a broad range of species and habitat elements across multiple, interacting stressors on the landscape (Boutin et al. 2009; Burton et al. 2014). Its core approach centres on regional surveillance of trends in species and land cover through repeated, standardized sampling of a range of taxa at 1656 permanent sites distributed evenly across the province (Table 1; www.abmi.ca). Sites are situated along a systematic 20 km grid that was chosen to coincide with the National Forest Inventory grid (Gillis et al. 2005) and provide a representative sample of Alberta's biodiversity features. The ABMI design specifically avoided stratification schemes that may be subject to change over time (e.g., political units, vegetation communities, disturbance gradients), although more recently the program has been considering complementary stratified sampling to address shorter-term management questions (see below).

A series of field-based sampling protocols (ABMI 2012b; www.abmi.ca) are implemented at each site on a proposed 5-year monitoring cycle, generating a time series for trend analysis. The original design was estimated to have 90% power to detect 3% annual declines over 20 years in regional prevalence of common species (Nielsen et al. 2009). Focal taxonomic groups are surveyed at different spatial scales (Table 1) and were chosen to cover a range of ecological roles, social values, and potential sensitivities to anthropogenic disturbances (Stadt et al. 2006; Boutin et al. 2009). Species-level monitoring is complemented by monitoring other components of ecosystem structure and function, including site-level measures of habitat complexity and remotely sensed measures of landscape composition (Table 1). A key aspect of the ABMI is characterization of human footprint at site and regional scales through field sampling, remote sensing, and synthesis of existing government and industry data sources (ABMI 2012a). Currently the ABMI collects data on more than 2000 species, 200 habitat elements, and 40 human footprint variables (Table 1; www.abmi.ca). The program has developed an aggregate index of

[9] *Environmental Protection and Enhancement Act*, RSA 2000 c E-12 (CanLII), [2000]. Available online at: http://www.canlii.org/en/ab/laws/stat/rsa-2000-c-e-12/latest/rsa-2000-c-e-12.html

biodiversity "intactness" (Nielsen et al. 2007) and produces reports summarizing the status of biodiversity in different parts of the province (e.g., ABMI 2012c).

Table 1. Taxonomic groups and land cover elements monitored by the terrestrial program of the Alberta Biodiversity Monitoring Institute, as an example of multi-target monitoring within a cumulative effects framework (from Burton et al. 2014).

Monitoring Target	Method [a]	Scale [b]	Example variables [c]
Mammals	Snow track surveys [a]	100 km^2 (10 km transect)	Species occupancy per transect (25 species)
Birds	Unlimited radius point counts [a]	1 km^2 (9 stations)	Species occupancy per point count (>200 species)
Vascular plants	Timed plot searches	1 ha (4 x 250 m^2 quadrants)	Species occupancy per plot (>1100 species)
Bryophytes	Timed plot searches	1 ha (4 x 375 m^2 plots)	Species occupancy per plot (>300 species)
Lichens	Timed plot searches	1 ha (4 x 375 m^2 plots)	Species occupancy per plot (>200 species)
Soil mites	Soil cores	1 ha (4 cores)	Species occupancy per core (>200 species)
Habitat structure	Plot sampling Surface substrate transects Soil cores	1 ha (4 x nested plots 25-625 m^2) 1 km^2 (9 x 7 ha plots)	Ecosite type, % vegetation cover, slope, tree DBH and age, woody debris, depth of organic soil
Land Cover	Air photo and satellite interpretation	21 km^2 (3 x 7 km plot around site) Province-wide (2 ha minimum mapping unit)	Proportion of area covered by vegetation type (e.g. grassland, shrubland, coniferous forest)
Human Footprint	Field plots Air photo and satellite interpretation	1 km^2 (9 x 7 ha plots) 21 km^2 (3 x 7 km plot around site) Province-wide	Proportion of area covered by e.g. forestry cutblocks; residential development; industrial infrastructure; roads and other linear features; cultivation

[a] Further details on ABMI sampling protocols are available at www.abmi.ca (e.g., ABMI 2012a,b). Mammal snow track transects have recently been replaced by camera trap surveys (Burton 2014), and bird point counts are transitioning to sampling with Automated Recording Units.

[b] Approximate scale over which sampling methods are applied. Sampling sites cover the entire province of Alberta and can be aggregated at multiple spatial scales (e.g., management planning regions).

[c] Examples of variables used in species-land cover models. The approximate number of species being sampled by ABMI protocols is given, although the program is not yet at full implementation, and not all species are currently modeled (further details at www.abmi.ca).

3.2.2 Challenges and changes in Alberta biodiversity monitoring

The ABMI is a unique and ambitious monitoring program, and may serve as a model for other cumulative effects monitoring initiatives, but it is not without challenges and criticisms. For example, Lindenmayer and Likens (2010a) reviewed available information on the ABMI and outlined their concerns that the program suffered from:

- a paucity of clearly defined, tractable questions and lack of conceptual model;
- an unusual statistical design;
- a passive approach lacking explicit links to mechanisms or management actions;
- effort spread across too many monitoring foci; and
- reliance on a complex, aggregate index to track biodiversity (the "intactness" index).

Based on their experiences with ecological monitoring, these authors worried that the systematic sampling design would be inefficient (preferring a design using contrasts in key variables and control sites), poorly sample rare environments and species of management significance, and miss important ecological phenomena on the 5-year rotation. They were further concerned that the broad emphasis would dilute effort that could be concentrated on fewer key targets, and that the "one-size-fits-all" design might entail scale mismatches for some species or ecological processes. Lindenmayer and Likens (2010a) were also uncertain that the ABMI program could be financially tenable, although they commended its multi-stakeholder governance structure.

Proponents of the ABMI did not agree with Lindenmayer and Likens' 2010 assessment (e.g. Boutin et al. 2009; Haughland et al. 2010; see also Lindenmayer and Likens' own "rejoinder" 2010a:98), and it is important to note that the program continues to evolve. For instance, while earlier documentation of the ABMI indicated a passive approach removed from specific management questions or ecological hypotheses (e.g. Stadt et al. 2006; Shank et al. 2002 in Lindenmayer & Likens 2010a), Burton et al. (2014) recently articulated how the ABMI could better integrate long-term surveillance with more targeted, hypothesis-driven sampling. In this approach, trend monitoring across the ABMI's systematic grid is complemented by sampling additional sites targeted to increase coverage of important landscape gradients—these "off-grid" sites are sampled in an adaptive manner reflecting hypotheses about drivers of biodiversity change, with a goal of improving empirical models describing change (Burton et al. 2014). For example, targeted sampling has focused on improving resolution of gradients in human footprint by sampling heavily disturbed sites within regions with relatively low overall footprint, and sampling less disturbed sites within regions where overall footprint is high. Nevertheless, explicitly linking ABMI monitoring to management questions and activities remains difficult, due in part to the fact that the ABMI program was designed to be arms-length from government in order to avoid a perception of political interference in monitoring. The Government of Alberta is developing a Biodiversity Management Framework for the Lower Athabasca region and has proposed the ABMI's biodiversity intactness index as a key monitoring indicator that can trigger management action (Government of Alberta 2014). However, to date it is not clear whether or how ABMI monitoring results have been incorporated into decision making. The future relationship between the ABMI and government is also not clear as the provincial monitoring landscape evolves (see below).

Another area of management interest pertains to the status and trend of rare species of conservation concern—species that are not typically monitored adequately by the ABMI's long-term, systematic surveillance design. To address this gap, the ABMI has been a partner in the Ecological Monitoring Committee for the Lower Athabasca (EMCLA), a collaborative initiative involving the energy industry, provincial and federal governments, and other scientists pursuing approaches for improving rare species monitoring (www.emcla.ca). This has led to new monitoring developments, such as using automated recording units to monitor rare birds[10], and model-based adaptive sampling to detect rare plants[11]. However, it remains a challenge to incorporate new methods into the ABMI's long-term program, or better integrate long-term surveillance with shorter-term needs related to regulatory requirements.

Securing adequate and sustainable funding also remains a key challenge for the ABMI, particularly when considering the desire to address gaps such as rare species and "off-grid" sampling. Despite annual budgets on the order of $10 million, the program has not attained full implementation and is thus not yet able to cover the full systematic grid at the desired 5-year sampling interval[12]. Full sampling coverage is beginning to be reached in sub-regions where more management attention and funding are directed, such as the Lower Athabasca region that contains much of Alberta's oil sands resources, and thus the program has had to stratify effort despite an initial intent to avoid stratification. Such changes—driven by a lack of secure, sustainable funding—may affect the quantitative objectives tied to the full monitoring design (e.g., Nielsen et al.'s 2009 power analysis). Although the program has been collecting data for more than 10 years, partial implementation has precluded resampling of sites on the expected interval, making reliable reporting of trends not yet possible. An inability to follow the planned 5-year rotating panel design has also complicated model-based inferences due to confounding of sampling covariates in space and time.

Evolution of the ABMI program has been accompanied by other recent developments pertaining to environmental monitoring in Alberta. Criticisms of monitoring programs in the oil sands region, such as the Regional Aquatics Monitoring Program (RAMP), were made in peer-reviewed publications (e.g., Kelly et al. 2009, 2010) and helped prompt Federal and Provincial review panels on environmental monitoring (Federal Oil Sands Advisory Panel; Alberta Environmental Monitoring Panel). As a result, the governments of Canada and Alberta undertook the Joint Canada-Alberta Implementation Plan for Oil Sands Monitoring (JOSM; Government of Canada and Government of Alberta 2012) to enhance monitoring efforts through creation of a comprehensive, integrated cumulative effects monitoring program (see next section). The Government of Alberta has also now established a new monitoring agency, the Alberta Environmental Monitoring, Evaluation and Reporting Agency (AEMERA)[13]. These initiatives continue to evolve, along with the ABMI, reflecting the complexity and challenges of implementing large-scale, management-oriented ecological monitoring programs. The development of a new program in Ontario's Far North may benefit from further consideration of the history and evolution of cumulative effects monitoring in Alberta.

[10] http://abmi.ca/home/projects/applied-research-projects/rare-animal-monitoring.html
[11] http://abmi.ca/home/projects/applied-research-projects/rare-plant-monitoring.html
[12] See ABMI 2013-14 Annual Report available for download at: www.abmi.ca
[13] See information and updates on the website at: www.aemera.org

3.2.3 Joint Canada-Alberta Implementation Plan for Oil Sands Monitoring (JOSM)

As noted in the previous section, the governments of Canada and Alberta initiated a new monitoring effort to try to improve ecological monitoring of the cumulative environmental effects of industrial development in Alberta's oilsands region. The goal of the 3-year JOSM program was to build on existing status-and-trend monitoring such as the ABMI's surveillance program, while expanding the approach to include cause-and-effect monitoring. Environment Canada (2011) produced a detailed plan for the terrestrial biodiversity monitoring component of JOSM, and its consideration of both regional surveillance monitoring and more directed cause-effect monitoring represents a novel attempt to combine these approaches. The plan focused on two key types of impacts of oil sands activities on terrestrial biodiversity: the effects of oil sands-related contaminants and the impacts of habitat disturbance. In designing the approach, Environment Canada (2011) considered direct and indirect effects of oil sands development—such as vegetation disturbance; noise, air and water pollution; facilitation of invasive species—as well as other related and unrelated anthropogenic activities in the broad region encompassing oil sands activities. They also recognized calls in the literature for good evolving questions drawn from a conceptual framework of the system, an adaptive approach with monitoring as a key part of adaptive management, and the importance of considering processes at multiple spatial and temporal scales (including different scales for different species). Environment Canada (2011) outlined a process for designing a monitoring program and criteria for selecting monitoring targets. They proposed a two-tier sampling approach, with "one tier comprising a general purpose sample frame for distributing points broadly across the landscape and a second tier of sampling frames that addresses a relatively small number of target species that require more precise status and trend estimates". The proposed sampling approach was based on defining strata for *a priori* predictors (and covariates) of effects, in order to ensure that factors of interest are adequately represented in the sample. They also proposed incorporating ecological benchmarks as means of measuring impacts, and they recognized the value of using predictive models to compare observed vs. predicted trends (cf. Burton et al. 2014). The JOSM program is currently being implemented by Environment Canada and AEMERA, and the success of the approach will be evaluated in the coming year (Environment Canada 2014a).

3.3 Northwest Territories Cumulative Impact Monitoring Plan

The Northwest Territories Cumulative Impact Monitoring Plan (NWT CIMP) was initiated in 1999 and coordinates, supports and conducts monitoring-related initiatives in the NWT. The monitoring of cumulative impacts is a constitutional obligation contained in the Sahtu, Gwich'in and Tlicho land claim agreements and a statutory requirement of the *Mackenzie Valley Resource Management Act*[14]. The CIMP strives to incorporate both scientific and traditional knowledge and follows a community-based approach, with northern residents involved in design, monitoring, analysis, interpretation and reporting of traditional knowledge or science-based activities.

[14] *Mackenzie Valley Resource Management Act,* SC 1998, c. 25. Available online at http://laws-lois.justice.gc.ca/eng/acts/m-0.2/

Monitoring targets (termed Valued Components, VCs) were identified through a working group and community consultations, and include: water quality and quantity; snow, ground ice and permafrost; fish habitat, population and harvest; fish quality; caribou, moose and other terrestrial mammals; birds; marine mammals; vegetation; climate; air quality; and human health and community wellness. However, through a priority-setting exercise the initial focus limited to water, fish and caribou.

The monitoring is implemented through a variety of programs developed by different groups, including NWT communities, governments, industry and other organizations and individuals. Programs are reviewed and selected by the multi-party NWT CIMP Working Group through an annual competitive process. A web-based information repository has been created to collate and distribute monitoring results and other environmental information from the various projects[15]. Such a distributed approach to implementation may present challenges in delivering a coordinated and focused long-term monitoring program. To that end, the NWT CIMP has created a general guide for designing northern monitoring programs (Pathway to Better Monitoring in Canada's North) which is intended to “provide a framework for partnerships, bring consistency and focus to a diversity of projects, and ensure that efforts yield relevant and accessible information”[16] .

We expect that the focus, quality and ultimate application of monitoring results from this type of decentralized program will vary with individual projects, and may thus vary over time, space and VCs. It will therefore be important to carefully assess effectiveness of the monitoring program. The NWT CIMP Working Group will track program outcomes using a Performance Measurement Strategy tool[17], and the program will be subject to an independent evaluation every five years as part of the NWT Environmental Audit, a requirement of the Sahtu, Gwich'in and Tlicho final agreements and the *Mackenzie Valley Resource Management Act*. Two Environmental Audits have been conducted to date, and the 2010 audit concluded that the CIMP was not effective, being both underfunded and under-resourced, with community capacity building and environmental monitoring programs largely occurring on a one-off basis (SENES 2011). The audit indicated that CIMP data are rarely relied upon by participants in the regulatory system. The 2015 audit is scheduled for completion in January 2016, so it remains to be seen if the effectiveness of CIMP is improving.

The CIMP approach provides an example of engaging northern communities, promoting multi-stakeholder collaboration, and combining scientific and traditional approaches to monitoring—all of which are very relevant to Ontario’s Far North. However, the information we reviewed suggests that the program suffers from several common shortcomings of ecological monitoring highlighted in the literature and reviewed above (section 2), such as a lack of clear, tractable questions and conceptual framework, and inadequate attention to quantitative considerations of appropriate sampling design and statistical inference. Addressing such challenges up front should be a key task in designing a monitoring program for the Ring of Fire.

[15] Descriptions can be found on the NWT Discovery Portal available online at: http://nwtdiscoveryportal.enr.gov.nt.ca/geoportal/catalog/main/home.page
[16] www.enr.gov.nt.ca/programs/nwt-cimp
[17] www.enr.gov.nt.ca/programs/nwt-cimp

4.0 Recommendations for ecological monitoring in Ontario’s Ring of Fire.

In designing an ecological monitoring program for the Ring of Fire region in Ontario’s Far North, it is important to carefully consider recommendations from the literature on the components of effective ecological monitoring (Section 2), and to learn from the experiences of other programs in Ontario and elsewhere (Section 3). Time and again, it has been stressed that developing clear objectives is a key first step in designing an effective monitoring program. Monitoring targets, sampling design, and data collection protocols should not be defined until the overarching goals and guidelines of a program are determined, ideally within a broader regional planning framework. We make the following assumptions and recommendations regarding the guiding context within which a new program for the Ring of Fire should be developed:

- The monitoring program will have an overarching objective of informing Ontario’s biodiversity managers, First Nations, and stakeholders (including industry and the general public) about the status of key species and ecosystem components in the region, and particularly about their responses to cumulative anthropogenic stressors and management actions that unfold over time.
- As a management-oriented monitoring program, it will be linked to objectives and hypotheses about the extent, nature and management of anthropogenic impacts on particular components of the targeted ecosystems.
- Given that not all components of Far North ecosystems can be monitored, the program must choose particular species, ecosystems and processes on which to focus. These should be chosen in a transparent manner based on management priorities and linkages to monitoring objectives.
- The program will be expected to inform management over multiple spatio-temporal scales, including short-term and long-term time horizons (e.g., from 5 to ≥ 30 years), and from local to regional spatial scales (e.g., from individual development projects and communities to entire watersheds).

To define specific objectives within this context, there is a need to develop a conceptual framework that identifies key components of the monitoring system and their interrelationships. In the following sections, we provide general recommendations for further developing the conceptual framework, objectives, and implementation plan for a terrestrial ecological monitoring program in Ontario’s Ring of Fire.

4.1 Key characteristics of the Far North to be considered in developing a conceptual model for monitoring in the Ring of Fire

Developing a conceptual model and associated monitoring questions and targets requires an accounting of the ecological components and processes of interest in the Ring of Fire, as well as the activities and stressors that might impact them. It is important to bear in mind that there will not be a single “correct” conceptual model. It can be insightful to explore alternative ways to represent a focal system, with such alternatives helping to identify key management hypotheses and areas of uncertainty to direct monitoring effort (NPS 2012). More detailed “sub-models” may also be necessary to further articulate details within a general conceptual framework, and the use of results chains can help identify explicit linkages between conservation targets and potential management actions (Margoluis et al. 2013). It is also important to accept that there will not be a "one-size-fits-all" program for ecological or biodiversity monitoring in Ontario's Far North. There are many species and ecological components of interest to decision-makers (government, First Nations), the public, and other groups such as industry and academia (Far North Science Advisory Panel 2010; cf. Boivin et al. 2014). Taxonomic groups as dissimilar as large mammals and soil mites play important ecological roles and could be justifiable foci of monitoring (as in the ABMI; Table 1), but different species and groups will be associated with different questions, spatio-temporal scales, and sampling methods. It may thus be necessary to develop multiple monitoring sub-programs to meet all objectives; however, we see merit in carefully coordinating sub-programs to the extent possible. Given that different components of an ecosystem are ultimately interconnected, there is value in developing a coordinated framework that considers linkages from the outset, even while making sure specific details of implementation are appropriate for the questions asked. Below we address some of the key issues relevant to designing a monitoring program in the Far North.

4.1.1 Impending changes to relatively intact ecosystems

The Far North Science Advisory Panel (2010) highlighted ecological connectivity as a key process to be maintained within the large, interconnected, and relatively undisturbed Far North ecosystems. They further suggested that the potential for reaching ecological thresholds should be carefully considered—that is, levels of impact at which further small disturbances could result in disproportionately large ecosystem responses or "state shifts" (Folke et al. 2004; Huggett 2005). In addition, the *Far North Act, 2010*, mandates that land use planning maintain "biological diversity, ecological processes and ecological functions" in the region. A monitoring program in the Ring of Fire must therefore be capable of demonstrating that biodiversity and ecological processes and functions are being sustained in light of new economic development and other influences such as climate change.

While there are currently low levels of human impact in Ontario's Far North, the government is committed to developing mineral, energy and other natural resources in the region, particularly with respect to the significant mineral resources in the Ring of Fire (Chong 2014; Hjartarson et al. 2014). The Far North is also home to approximately 40,000 First Nations in 34 remote communities, who are engaging in natural resource uses such as hunting, trapping and fishing, as well as considering opportunities for economic development (e.g., access roads, industrial development, tourism). Under the *Far North Act, 2010*, First Nations are engaged in planning for both development and protection of their traditional territories.

The cumulative effects of regional development will interact with other forces impacting northern ecosystems, most notably climate change. Climate models and recent trends indicate that the Far North will likely be considerably warmer and facing altered precipitation patterns by the middle of this century (Far North Science Advisory Panel 2010). The consequences of climate change to the region's plants and animals are highly complex and uncertain, but likely to be profound. Ecological monitoring targets in the Far North should be chosen to consider the current state and value of ecological intactness and integrity, based on linkages between species, ecosystems, and processes articulated in the conceptual framework.

In developing the conceptual framework, it will be important to consider potential synergies, such as how disturbances associated with mining may interact with timber harvest and altered fire or hydrological dynamics under a changing climate. Potential linkages between monitoring targets and anticipated stressors should be delimited to identify possible thresholds and establish precautionary objectives around limits to stressors. Given the considerable uncertainty facing the region, there is likely justification for "expecting the unexpected", and thus incorporating surveillance monitoring capable of detecting unanticipated impacts to ecosystems (e.g. disease outbreaks, invasive species, cascading effects).

4.1.2 The context for decision making and land use planning

In the Far North, decision making about the spatial and temporal extent of conservation and development is largely government-led. The general public may be consulted on environmental planning issues through the Environmental Registry, while First Nations are consulted on activities that may impact their Aboriginal and treaty rights. In addition, planning processes mandated under the *Far North Act, 2010* offer an opportunity for First Nations to be engaged in land use planning, while the Regional Framework Agreement (2014) creates an opportunity to consider environmental monitoring with First Nations on a regional basis. However, there remain no decision-making structures that explicitly address First Nations input to planning or monitoring. Similarly, there are no structures that consider advisory, technical, or co-management roles for environmental planning processes in the Far North (with a notable exception for caribou management through the Provincial Caribou Technical Committee). We do not anticipate that the development of regional monitoring programs will be any different. Nevertheless, a key consideration in developing a conceptual model to guide monitoring should include identification of potential management actions, policy windows, or other decision-making "levers" which the monitoring results can inform. This ensures that monitoring objectives and implementation are embedded in pathways that are relevant to management decision making. For example, biodiversity protection in Ontario's Far North may be influenced by many government-led management decisions and activities, such as:

- designation and enforcement of protected areas emerging from community-based land use planning (e.g., provincial parks);
- designation and protection of critical habitat for species at risk (e.g. caribou, wolverine, polar bear);
- approval of exploration permits, mines and other development projects and related footprints, including roads and transmission lines (e.g., Wataynikaneyap Power[18]);
- mitigation, reclamation or offsets associated with industrial development approvals;
- the location, extent, and practice of timber harvesting for communities applying for Sustainable Forest Licenses under their community-based land use plans (e.g., Whitefeather Forest[19]);

[18] See the Terms of Reference and preferred routes for the power line proposal to provide power to Musselwhite Mine, remote communities and, potentially, the Ring of Fire at http://www.wataypower.ca/node/28

- management of caribou, moose and white-tailed deer in the Far North[20], and other forms of wildlife population management (e.g., translocation, augmentation, reducing mortality risks from human-wildlife conflict);
- regulation of tourist operations and recreational activities (e.g., off-road vehicles);
- regulation of air and water pollution;
- creation or expansion of reservations or settlements and associated infrastructure;
- access management for roads and other transportation corridors.

The degree to which such management actions are known, expected, or influenced by First Nations involvement, and can be incorporated into a conceptual model and results chains[21], the greater the probability that monitoring results will directly inform management. For example, if protected areas emerging in land use planning are designated to maintain the richness and abundance of valued species, monitoring can be directed at those species and measures to assess the effectiveness of such a management strategy.

There are currently no regional planning frameworks in the Far North within which to embed a monitoring program that addresses the issues highlighted in our literature review (Section 2). While the Far North Science Advisory Panel (2010) recommended a Conservation Matrix Model for land use planning as a framework for addressing ecological connectivity and resilience in the Far North (see also Carlson & Chetkiewicz 2013), Ontario has not yet taken up this recommendation. Absent an explicit regional planning framework, the general concept of land use zones or sub-regions with different management strategies could be useful for framing a regional monitoring design and defining management-relevant sampling strata. For example, areas designated for more intensive mining development could be considered a “treatment” stratum, with ecological responses compared to those from a “control” or benchmark stratum represented by emerging protected areas. Such a design could improve the monitoring program’s ability to separate effects of anthropogenic activities from natural dynamics or other processes (e.g., climate change), and thus feed into management decision making. Responses pooled across all strata would indicate whether or not regional objectives were being met.

4.1.3 Spatial and temporal scale of monitoring

Determining appropriate spatial and temporal scales for a monitoring program will depend on the scales of ecological processes and functions and their overlap with management objectives, policy commitments (e.g., species at risk), and other management levers such as development approvals. The Far North Science Advisory Panel (2010: 90-91), recommended that both coarse-filter and fine-filter approaches be used for conservation planning in the Far North. They identified key coarse-filter

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[19] See the Whitefeather Forest Management Plan for Pikangikum First Nations online at https://whitefeatherforest.ca/enterprise/whitefeather-forest-community-resource-management-authority/
[20] Information on how Ontario manages ungulates in the Far North can be found online at: http://www.ontario.ca/document/cervid-ecological-framework
[21] Margoluis et al. 2013 describe results chains as "an important tool for helping teams clearly specify their theory of change behind the actions they are implementing." The Miradi adaptive management software, created by the Conservation Measures Partnership, enables teams to develop and monitor results chains based on a conceptual model of the system or region of interest.

components of natural environmental variation that should be a focus of management attention, including peatlands, permafrost terrain, major rivers and estuaries, remote forested uplands, headwaters, and concentrations of fish and wildlife (e.g., areas for breeding, staging, migrating, calving). With respect to fine-filter conservation, the Panel recommended that focal species be identified based on the following characteristics:

- space-demanding;
- vulnerable to human disturbance (e.g. habitat loss and degradation) and other threatening processes (e.g. climate change);
- low reproductive capacity (i.e., slow life histories);
- high socio-economic or cultural importance.

Examples of candidate species mentioned by the Panel include: yellow rail, woodland caribou, sharp-tailed grouse, wolverine, marten, black spruce, gray wolf, and boreal passerine birds (rusty blackbird, Nelson's sparrow, Smith's longspur, Connecticut warbler, orange-crowned warbler, palm warbler and white-crowned sparrow; see Panel report Table 6). Similarly, examples of dynamic ecological processes that derive from intact boreal ecosystems include: large mammal predator-prey interactions; migratory songbird breeding; forest stand dynamics mediated by wildfire and insect outbreaks; flooding and water filtration; and carbon sequestration and storage (Far North Science Advisory Panel 2010).

Ecological monitoring targets in the Far North could therefore include high-profile species of management concern (e.g., caribou, wolverine, moose); strongly interacting species (e.g., wolf, snowshoe hare); functional groups indicative of valued habitats (e.g., old-growth forest songbirds, waterfowl); species expected to be sensitive to specific stressors (e.g., marten, bryophytes, bats); or coarse-filter measures such as the extent, composition and spatial pattern of natural land covers and disturbances (e.g., burned areas, wetland extents, forest stand age).

The selection of a feasible number of monitoring targets, with clear linkages to a conceptual framework for the Ring of Fire, is not straightforward and requires considerable deliberation. Other spatial scales of importance may include:

- Localized development projects or management features, such as:
    - advanced exploration projects, current and proposed mining operations;
    - forestry cutblocks;
    - hydroelectric dams and zones of influence along rivers;
    - infrastructure such as roads, railways, and transmission corridors;
    - hunting areas and trap lines;
    - human communities;
    - natural heritage sites.

- Broader units of industrial and management planning, such as:
    - mineral deposits and claims;
    - forestry management areas;

- Caribou Ranges (Fig. 5), Wildlife Management Units, Cervid Management Zones;
  - Ring of Fire sub-region and Far North region.

- Ecologically-based planning or sampling units, such as:
  - tertiary, secondary and primary watersheds (Fig. 6);
  - ecodistricts, ecoregions, and ecozones (Fig. 7);
  - other biological “units” (e.g. populations, subpopulations, home ranges, breeding sites).

Temporal scales of relevance to monitoring in the Ring of Fire may include:

- annual changes in wildlife populations (e.g., for range management);
- short-term requirements for planning, reporting or political commitments (e.g., 5 years);
- industrial project lifespans (e.g., decades from pre-development to decommissioning or reclamation);
- time series for estimating population trends or assessing changes in conservation status of focal species (e.g., 10-30 years);
- multiple human generations (e.g. 50-100 years).

A cumulative effects monitoring program should have large-scale and long-term horizons (e.g. multiple watersheds over multiple decades), but be scalable so that results are useful at the level of individual sampling units (e.g., annual occupancy of forest sampling plots or animal home ranges) and can be "rolled up" into hierarchical levels of interpretation (e.g., multi-year changes in the proportion of occupied plots within watersheds). For example, monitoring of large mammals might consist of sampling units to estimate occupancy at a smaller scale approximating individual home ranges (e.g., 10-100 km^2), with units distributed at an intermediate scale across gradients or strata of hypothesized impacts or management actions (e.g., mining developments within ecodistricts or tertiary watersheds), and results ultimately summarized at the larger regional scale (e.g., ecoregion or ecozone, primary or secondary watershed).

Variation and interactions among spatial, temporal and taxonomic scales are also critical to consider in the context of cumulative effects. For example, creation of a new road would result in immediate, localized impacts (e.g., loss and fragmentation of habitat along the road), but could be expected to lead to much larger and longer-term impacts by opening up new access for hunting, recreation, industrial development, invasive species, and other potential stressors (e.g., Forman & Alexander 1998; Cameron & Bayne 2009). Biodiversity responses to roads and other impacts can also be expected to vary, both in terms of scale (e.g., from site-level behaviour to population dynamics) and direction (e.g., disturbance-sensitive vs. adapted species; Fahrig & Rytwinski 2009; Bowman et al. 2010).

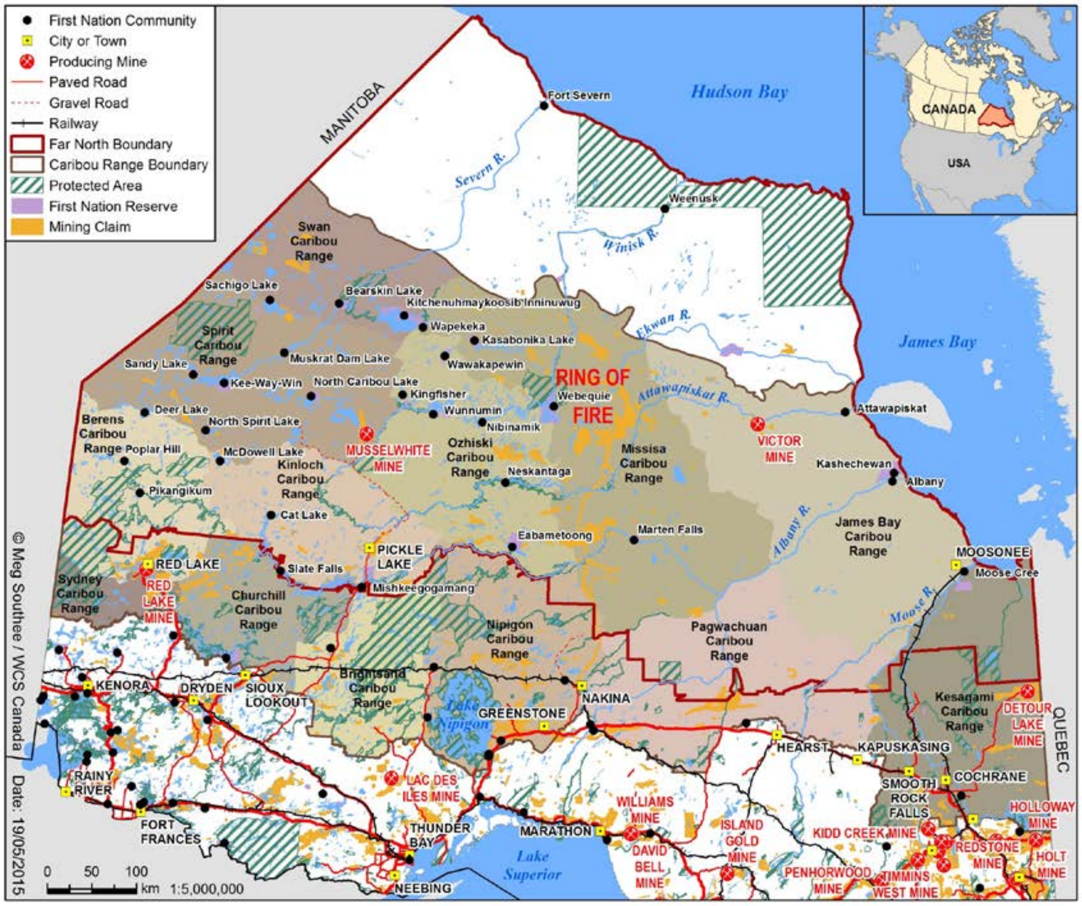

Figure 5. *Woodland caribou ranges delineated in Ontario's Far North. These are one example of a spatial scale of relevance to management in the region, and thus one potential foci for cumulative effects monitoring.*

Figure 6. *Secondary watersheds in Ontario's Far North, representing a spatial scale of ecological relevance to be considered in defining scales for cumulative effects monitoring.*

Figure 7. Ecoregions in Ontario's Far North, representing a spatial scale of ecological relevance to be considered in defining scales for cumulative effects monitoring.

4.2 Recommendations for developing a monitoring program in Ontario's Ring of Fire

In this report we have reviewed concepts and recommendations from the ecological literature on designing effective ecological monitoring programs. We have also summarized several monitoring efforts in Ontario and elsewhere, and identified potential components of a conceptual framework for terrestrial monitoring in the Ring of Fire region. Monitoring cumulative effects on biodiversity across large spatial and temporal scales is a complex undertaking, particularly in a remote region with considerable uncertainty regarding ecological dynamics and land use planning. Crafting a robust, sustainable, relevant, and broadly accepted monitoring program will require considerable effort. Here we provide further recommendations to facilitate this process.

- We recommend that government commitments to effective ecological monitoring in Ontario's Ring of Fire be upheld and emphasized as a critical part of adaptive landscape management in the region. Monitoring should not be considered a luxury or an addendum to management, but rather an integral means of helping to focus management priorities, test management outcomes, reduce uncertainty, and resolve potential land use conflicts. As such, it should be recognized that adequate funding and expertise will be required to ensure that monitoring is effective.

- We recommend that government and First Nations define a regional planning framework and vision for the Far North within which to develop monitoring goals and objectives for the Ring of Fire.

- Funding and operational constraints will be critical to the success of a regional monitoring program, but rather than let those dictate monitoring from the outset, it is important to develop a vision for a program that will effectively inform critical management decisions. It can then be determined whether this program is feasible, and, if not, whether it could be made so (e.g. by obtaining more funding or restricting the focus).

- Currently, monitoring approaches in the Far North are government-led and generally have limited amounts of publically-available information (with some exceptions, e.g., MNRF 2014). It remains to be seen how results from these programs will be applied to government decision making in concert with First Nations. We recommend establishment of a board of directors and advisory committee to guide development of ecological monitoring in the Ring of Fire and Far North. The board should include broad representation of stakeholder groups with interests in the region. We recommend that the advisory committee include quantitative scientists with expertise in monitoring design and analysis, ecologists familiar with Far North ecosystems, resource managers, and representatives from other groups that may be involved in designing, collecting or interpreting monitoring data (e.g. community-based monitors, industry scientists).

- Initial scoping workshops are recommended to identify important monitoring questions and objectives for the Ring of Fire, develop a conceptual model(s), and identify monitoring targets. Several organizations have recommended specific processes and tools for developing monitoring frameworks (e.g., NPS 2012; see also section 3 above). Planning software such as Miradi can support the development and communication of conceptual models in a participatory approach (e.g., Margoluis et al. 2009). Further synthesis of existing information on Far North ecosystems and development pressures will be important for developing the conceptual model (e.g. Far North Science Advisory Panel 2010); however, uncertainty should not be used as an excuse to delay monitoring, but rather a motivation to pursue adaptive monitoring (cf. Lindenmayer & Likens 2009; see section 2.3 above).

- To the extent possible, a holistic view of monitoring should be considered at the outset, combining aspects focused on terrestrial biodiversity monitoring (such as considered in this report) with aquatic biodiversity and other components of the broader socio-ecological system, potentially including human health and welfare. Separate sub-programs can always be designated during the process as needed, but it is generally harder to link programs after they are developed if they do not share higher-level objectives and approaches.

- The Ring of Fire monitoring program should draw on experiences of other ecological programs, both those that have been successful and those that have had limited or mixed success (programs mentioned in this report provide a useful selection of examples). Since the monitoring literature is full of examples of ineffective monitoring, if a new program wishes to adopt an approach that has been criticized in the literature (e.g. lack of questions or conceptual model, non-probabilistic sampling design), the burden should be on the program to explicitly defend why they think that approach will be successful in their case. Monitoring practitioners who have been involved in other relevant programs, such as the ABMI, JOSM, and NWT CIMP (section 3), should be invited to share lessons learned during the evolution of their programs.

- We recommend avoiding a reliance on piecemeal monitoring that focuses too narrowly on individual species or development projects (e.g., mandated monitoring stemming from typical Environmental Impact Assessments). We also recommend avoiding an unfocused surveillance monitoring program that lacks management-oriented questions. Instead, we suggest that a new program consider a "hybrid" approach to monitoring that links targeted, question-driven monitoring of hypothesized impacts, with broader regional surveillance of cumulative effects and unanticipated changes (cf. Environment Canada 2011; Lookingbill et al. 2012; Burton et al. 2014; see sections 2.1 and 2.5). However, we recognize that such an approach may entail considerable complexity in achieving a rigorous and defensible sampling design and analytical framework. We therefore stress the importance of involving quantitative experts in ecological sampling design and statistical analysis at the outset of program development. The chosen sampling design must provide valid inferences, and sampling protocols must adequately contend with common sources of sampling error (Yoccoz et al. 2001). Statistical analysis should be linked to the monitoring design, and frequent analysis and reporting of monitoring results will be critical (Lindenmayer & Likens 2010a; Gitzen et al. 2012). If there is doubt at the outset that a complex program will be analytically or financially tenable, it likely won't be, and a simpler program should be considered.

- Given that there are several existing or planned environmental monitoring initiatives in Ontario, an early step in developing monitoring for the Ring of Fire should be to determine what needs might be met by existing initiatives, and where new programs are needed (i.e., gap analysis). For instance, caribou monitoring is proposed under the MNRF's Caribou Conservation Plan (MNR 2009), and several activities have been initiated regarding assessing caribou populations, habitat, and cumulative disturbances at the large spatial scale of caribou ranges (MNRF 2014). While this could be treated as a stand-alone program focused only on meeting Caribou Recovery Strategy objectives, potential synergies with other monitoring objectives should be explored in order to capitalize on the mandated requirement for, and considerable investment in, caribou monitoring (without diluting its main objectives). For example, while the caribou program entails specific focus on indicators of caribou population viability (e.g., trends in abundance and vital rates), it will also collect data on indicators of broad relevance to other components of the socio-ecological system (e.g., interacting species like wolves, moose, white-tailed deer; forest cover and quality through remote sensing and sample plots; extent of human and natural disturbances; MNRF 2014). Ontario's caribou monitoring may thus provide a useful basis on which to build a more integrated monitoring framework.

- Input from, and involvement of, Far North communities will be critical to the success of an ecological monitoring program for the Ring of Fire. This will be particularly important during the development of objectives, conceptual framework, and monitoring targets. Given the relative paucity of scientific studies in the Far North, traditional ecological knowledge will play a key role in elucidating system dynamics. There will also likely be an important role for community-based monitoring as part of broader efforts to improve understanding and promote collaboration. However, given that monitoring programs developed to date in the Far North are government-led, it remains unclear how First Nations will be engaged. Any approach to monitoring, community-based or otherwise, that is being used for scientific assessment of ecological change must be sufficiently well-designed to provide valid inferences. "Comfort" monitoring that is primarily intended to improve community-industry relations often does little to support effects-based management (Noble & Birk 2010).

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