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TRACKING CLIMATE CHANGE EFFECTS

Potential Indicators for Canada's Forests and Forest Sector



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Sylvie Gauthier,[1] Miren Lorente,[1] Laurie Kremsater,[2] Louis De Grandpré,[1] Philip J. Burton,[3] Isabelle Aubin,[4] Edward H. Hogg,[5] Solange Nadeau,[6] Elizabeth A. Nelson,[7] Anthony R. Taylor,[6] and Catherine Ste-Marie[7]

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EXECUTIVE SUMMARY

Introduction

Climate change effects are already being observed in Canada's forests, influencing the provision of goods and services on which the Canadian forest sector relies. Given the magnitude of projected climate change, it is becoming increasingly imperative to explore and implement adaptation measures in addition to mitigation strategies. Proactive adaptation is based on three fundamental pillars: knowledge of potential changes, the will to intervene, and the development and implementation of adaptation actions (Figure 1). In the context of climate change, proactive adaptation of the forest and the forest sector necessitates that each of these three pillars rely on an adaptive management cycle of monitoring, assessing, and adjusting. The development of a tracking system that reports on relevant indicators of climate change is an integral part of such a cycle.

The overarching goal of this report is to provide potential indicators and selection criteria to develop a tracking system for Canada's forests and forest sector. The specific objectives are (1) to present a suite of potential indicators of climate change effects on Canada's forests and forest sector and (2) to provide criteria to select and prioritize indicators to track climate change effects. Indicators of the effectiveness of adaptation actions are not covered in the report as it is a nascent field of investigation. The report is elaborated with a forest sector audience in mind including decision makers in forest industries; federal, provincial, and territorial departments and agencies; conservation agencies; nongovernmental organizations; research scientists; and the public.

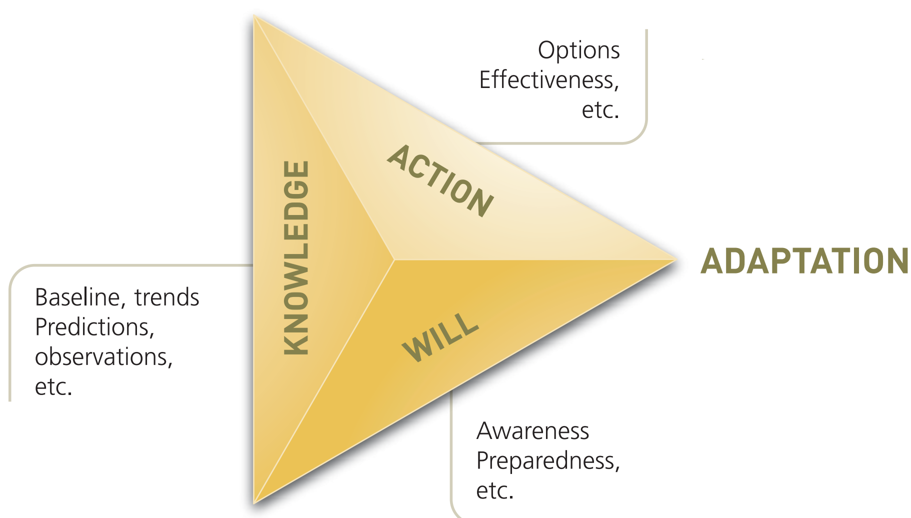


Figure 1. The adaptation triangle has three components that are in constant interaction: knowledge, the will to intervene, and action. Proactive adaptation to climate change effects on the forest and the forest sector requires that each of these three components rely on an adaptive management cycle of monitoring, assessing, and adjusting.

Methodological Approach

To develop a tracking system, a three-step process is proposed in which candidate indicators are first identified, then they are filtered through a set of criteria, and finally selected indicators are incorporated into a tracking system (Figure 2). Over time, some indicators may have to be refined or new ones developed. Technological advances may also allow implementation of indicators that were previously difficult to track.

To identify candidate indicators, two complementary initiatives were undertaken: a broad consultation within the Canadian Forest Service (CFS) research community and a group of forest sector representatives outside the CFS (more than 100 participants), and a comprehensive literature review and website scan searching indicators currently used or in development to track climate change effects on forests and the forest sector in other jurisdictions worldwide (more than 500 documents and websites).

Candidate indicators were assigned to one of three systems: climate, forest, or human, and were then subdivided into several categories and dimensions (Figure 2). Indicators for the climate system focused only on climate drivers that directly affected forest ecosystem structure and function and the human system. Climate drivers were grouped according to temperature, precipitation, extreme weather events, and integrative indicators. Indicators for the forest system looked at structural attributes and functional processes likely to be affected by climate change (landforms and hydrology, natural disturbances, species phenology, species distribution and abundance, forest stand dynamics, and edaphic conditions and processes). Indicators for the human system focused on forest-related dimensions, and comprised potential indicators of impacts and adaptive capacity. They were addressed through eight dimensions: natural capital, forest uses, infrastructure, the economy, social capital, demography, human health, and institutions and governance.

Five criteria for indicators of impacts have been defined for selection among candidate indicators: (1) sensitivity to climate, (2) measurability, (3) feasibility, (4) spatiotemporal scope, and (5) relevance. A preliminary assessment of indicators was undertaken using some of these proposed criteria.

Indicators of Climate Change Effects on the Forest and the Forest Sector

For each of the three systems, we developed rationales describing the fundamental changes hypothesized under a changing climate. We then listed potential indicators and identified linkages among indicators. A preliminary assessment of the indicators was undertaken for the climate and the forest systems only and was limited to indicator sensitivity and feasibility, based on expert judgement and a literature review. For the human system, although indicators of impacts are partially developed, those related to adaptation will and actions and their selection criteria require more investigation.

Perspective: Opportunities and Challenges

An adaptive framework allowing continual evaluation of the effectiveness of adaptation actions through a feedback loop of monitoring, assessing, and adjusting is required to decrease the gaps between observed and desired conditions. As this feedback loop necessitates rapid adjustments when changes and surprises occur, tracking should be an integral part of adaptation. This adaptive iterative process of decision making will likely improve forest management in the face of not only climate change outcomes but also other types of fluctuations.

The identification of potential indicators of climate change effects carried out here provides a basis for prioritizing candidate indicators for future tracking and shows that prioritization of indicators and their tracking are still at the embryonic stage globally. For the climate and the forest systems, a preliminary evaluation of sensitivity to climate and feasibility of implementation was achieved. As the human system will likely respond to climate change in a less deterministic manner than the ecological systems, efforts to define and track the human system's indicators will be key for adaptation. Once indicators have been prioritized, data collection has to be undertaken cost-effectively. Implementing an indicator requires the development of standards allowing systematic data collection and data warehousing schemes to allow data mining and trend analysis by a variety of stakeholders. Knowledge translation and extension services that communicate technical information in an engaging and understandable way to a broad range of users are also needed. Collaboration and coordination among stakeholders are crucial for implementing all of these elements. Globally, a tracking system can contribute to adaptation by providing an understanding of climate change effects and by increasing awareness and preparedness that will promote the development of adaptation options. Options can then be confronted with different scenarios and subsequently be implemented. Monitoring the effectiveness of the implemented adaptive actions is also required for continuous improvement.

Although a broad climate change monitoring and reporting program may seem to be costly in the short term, the cost of not adapting must also be considered as climate change is both a short- and long-term reality, and the effects are likely to be cumulative and far-reaching. This report provides the first step toward a set of indicators of climate change effects on Canada's forests and forest sector and elements for moving forward with adaptation measures under continued climate change.

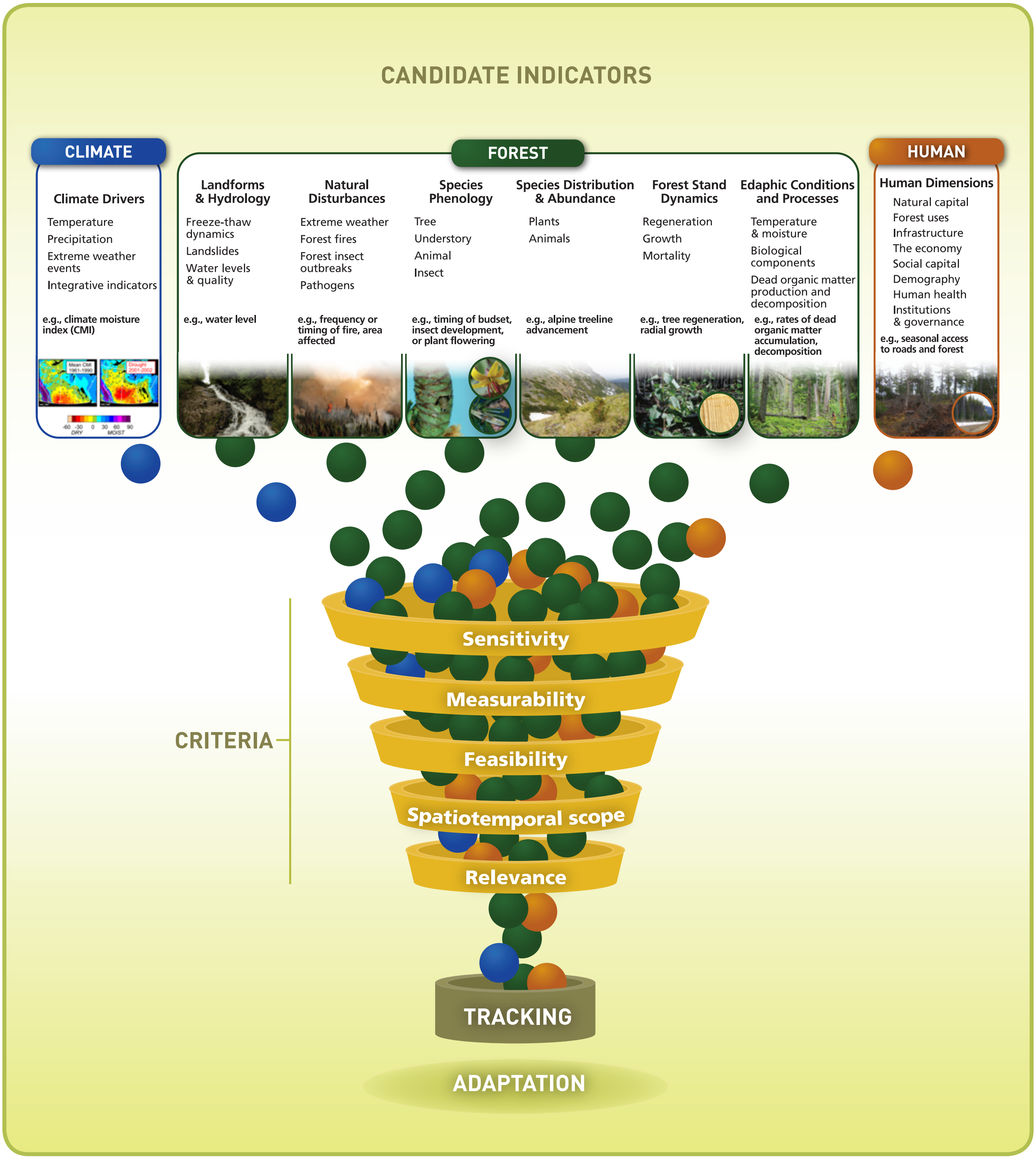


Figure 2. Framework for the identification and prioritization of climate change indicators. Candidate indicators are assigned to one of three systems: climate, forest, or human. These indicators are filtered through five proposed criteria and the ones selected are integrated into a tracking system. After tracking changes over time, some indicators may have to be refined or new ones developed. Such a tracking system is an integral part of the adaptation cycle.

INTRODUCTION

Recent, unprecedented climate change has resulted in a 1.6°C increase in Canada's average air temperature between 1948 and 2010, with shifts in temperature and precipitation varying regionally, both in direction and magnitude (Environment Canada 2011; Mekis and Vincent 2011). Projected climate changes for the coming century are greater than those experienced over the last 100 years (IPCC 2007; Price et al. 2011). Canadian forests are already showing signs of climate change effects, including alteration to ecological processes and natural disturbance regimes (e.g., Caccianiga and Payette 2006; Hogg et al. 2008; van Mantgem et al. 2009) that affect the provision of goods and services on which the Canadian forest sector relies.

Given the magnitude of projected climate change (IPCC 2007), it is becoming increasingly imperative to explore and implement adaptation measures in addition to mitigation strategies (Klein et al. 2005; Swart and Raes 2007). Proactive adaptation is based on three fundamental pillars: knowledge of the occurring changes, the will to intervene, and the capacity to take action (Figure 1). In terms of knowledge of change, monitoring ecosystem responses, modeling, and synthesis of research are used to assess past trends and to project effects. The will to intervene depends on awareness of climate change, perceived risks, and the preparedness of interested parties to act. Lastly, development and evaluation of adaptation options regarding the predicted changes allow for selecting and deploying adaptation actions. These three components of adaptation are constantly interacting. Knowledge of climate change increases the will to intervene (both awareness and preparedness) and supports decisions on where and what actions might be taken. Knowledge also contributes to the mainstreaming of adaptation into routine decision making. By observing previous adaptation experiences, knowledge enables society to take appropriate corrective actions. Together, action and will create a demand for more knowledge as gaps are identified. In turn, action toward reducing climate change effects can positively influence the will of other interested parties to adapt.

In the context of climate change, proactive adaptation of the forest and the forest sector necessitates that each of these

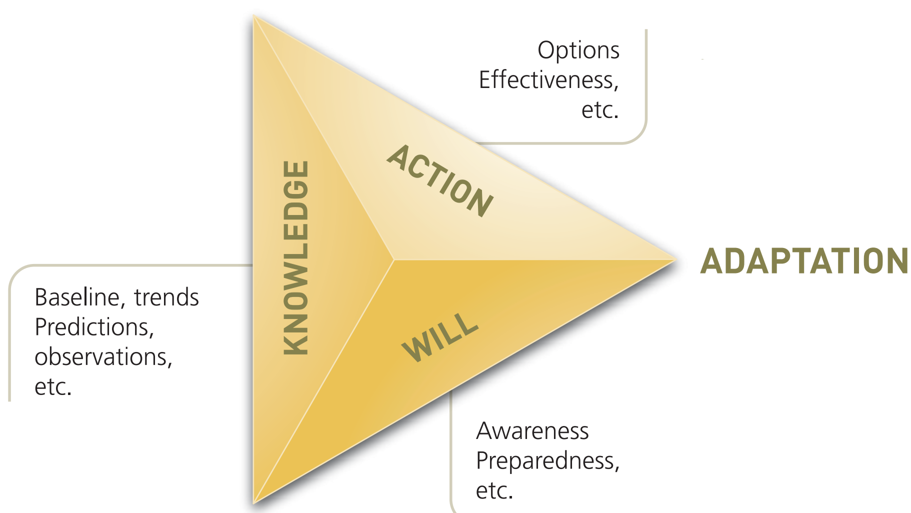
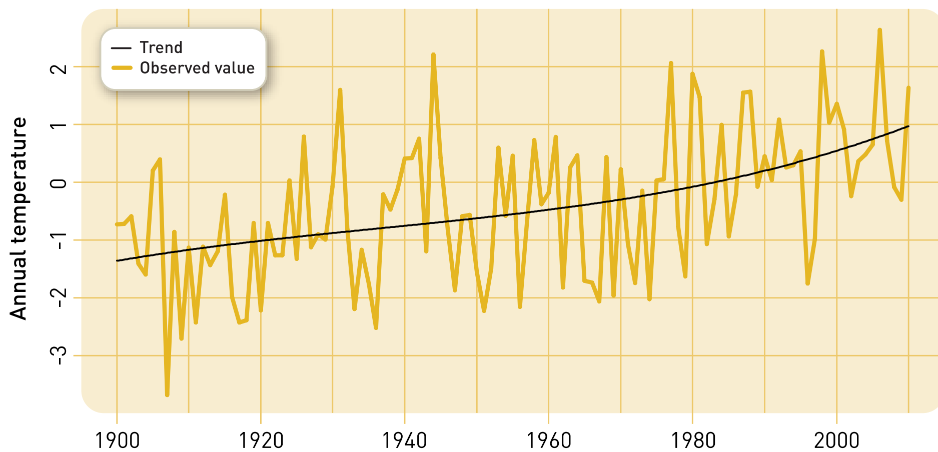


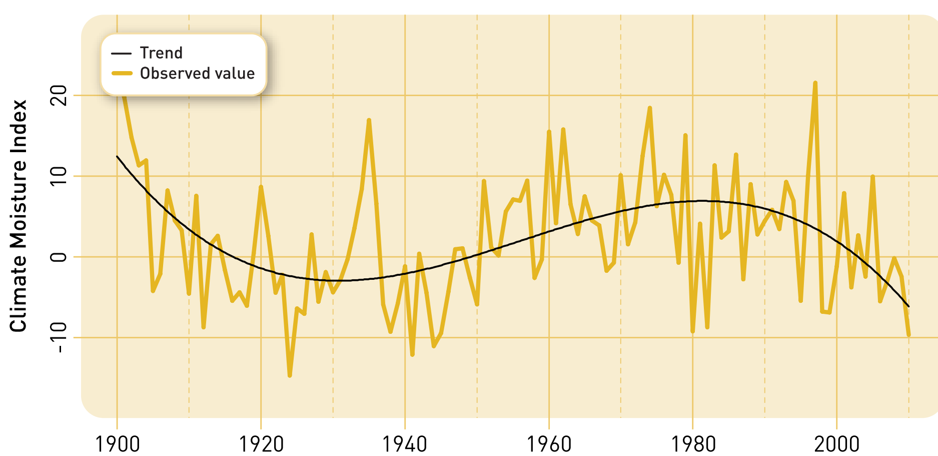
Figure 1. The adaptation triangle has three components that are in constant interaction: **knowledge**, the **will to intervene**, and **action**. Knowledge is increased by monitoring ecosystem responses, modeling efforts, and scientific research. The will to intervene relies on awareness of climate change effects, perceived risks, and the preparedness of the interested party. Adaptation actions depend on specific effective implementation options. Knowledge of potential climate change effects increases the will to intervene and informs where and how to take action. Knowledge is mainstreamed into adaptation decision making and also enables society to improve efficiency of future efforts by learning from previous adaptation action experiences. Action and will create a demand for more knowledge as gaps are identified. Action toward reducing climate change effects can positively influence the will of other interested parties to adapt. Proactive adaptation to climate change effects on the forest and the forest sector requires that each of these three components rely on an adaptive management cycle of monitoring, assessing, and adjusting. A tracking system that reports on relevant indicators of climate change effects on the forest and the forest sector is the first step of this cycle.

three pillars rely on an adaptive management cycle of monitoring, assessing, and adjusting. The development of a tracking system that reports on a series of relevant indicators of climate change effects on the forest and the forest sector (Box 1) is an integral part of such a cycle. When assessed periodically, indicators can show the direction and magnitude of change, and help detect instances of change in quality and quantity of goods and services provided by the forest. Although significant progress has been made in forecasting future climate conditions and the effects of these changes on forest ecosystems (e.g., Program for Climate Model Diagnosis and Intercomparison; Price et al. 2011), uncertainties still exist, mainly because of the underlying complexities of forest ecosystems (Lawler et al. 2010). This highlights the need to monitor and better understand changes. In this context, indicators may provide evidence of differences between predicted and observed changes. Indicators can also help monitor awareness and preparedness over time. These two elements provide a measure of the perception of risk related to climate change effects, and may help us better understand how risk perception enables or constrains the overall system's ability to adapt to climate change. Finally, indicators may be used to measure and report on the effectiveness of implemented actions, which in turn informs future efforts as well as efforts undertaken by other parties. By providing vulnerability assessment, and implementing effective adaptation, indicators offer a useful framework for identifying information and knowledge gaps. This understanding may lead to new options and directions for supplemental monitoring activities and research on causal relationships. This iterative approach is also used to optimize the relevance and efficiency of tracking systems through time as information needs and data availability change.

Temperature trends in northern Alberta



Moisture trends in northern Alberta



The temperature has been increasing in northern Alberta since 1900. The composite Climate Moisture Index for the same region suggested dry conditions between 1920 and 1940, although records are less reliable notably for precipitation. Recent years show a dryness condition similar to that of 1920–1940. Is this an early sign of climate change? Tracking this indicator will help answer this question. (Based on BioSIM climate interpolations by Michael Michaelian, Natural Resources Canada)

The overarching goal of this report is to provide potential indicators and selection criteria to develop a tracking system for Canada's forests and forest sector. Its specific objectives are (1) to present a suite of potential indicators of climate change effects on Canada's forests and forest sector (including indicators of interest that may need further development) and (2) to provide criteria to select and prioritize indicators to track climate change effects. Indicators of the effectiveness of adaptation actions are not covered in this report as it is a nascent field of investigation. Finally, the climate change issue is much larger than any single agency or stakeholder group can manage, and monitoring it will require new levels of participation and collaboration among forest sector players. This report is therefore elaborated with a forest sector audience in mind including decision makers in forest industries; federal, provincial, and territorial departments and agencies; conservation agencies; nongovernmental organizations (NGOs); research scientists; and the public.

Box 1. What is an indicator?

An indicator is a quantitative or qualitative attribute that can indicate whether changes are occurring, if measured periodically (FAO 2011). At the most fundamental level, the effects in which we tend to be most interested (e.g., natural communities or human health) often cannot be measured directly or in a timely manner, so indicators provide a set of practical measurements that are correlated with these attributes, or warn of their change. Indicators require the development of shared understanding about complex systems and significant resources for continual gathering and reporting of data.

Gudmundsson (2003) suggests the following common traits inherent to indicators employed in environmental and performance evaluation sectors; they

- condense large amounts of information;
- are sensitive to signals of change in the identified element or system;
- describe states, flows, or changes within systems;
- can be descriptive or normative (evaluating performance relative to standards or goals); and
- may ascribe "agency" (i.e., cause and effect).

The computation and communication of environmental indicators (in the broadest sense) are common features of modern life. Examples we encounter daily include weather and stock market reports. We use daily weather reports (e.g., air temperature and precipitation levels) to get a sense of how seasons are progressing, and to decide what clothes to wear and what outdoor activities can proceed. The current level and recent trends in the Dow-Jones Industrial Average and the NASDAQ Composite Index guide investors in their decisions to buy or sell stock market holdings. Furthermore, these reports, trends, and projections differ among cities and regions (in the case of weather) and among markets and countries (in the case of stock prices). Statistics Canada provides various census and survey results to indicate temporal trends and geographic differences in employment, economic activity, demographics, and education that help inform government and private policies and investment. Indicators currently in use or under development in the forest sector include those assessing sustainable forest management (http://www.ccfm.org/english/coreproducts-criteria_in.asp) and ecological integrity as well as climate change indicators. Forest management must be sustainable under climate change, and protecting a desired level of ecological integrity is challenging under increasing pressures of resource use and a changing climate.

METHODOLOGICAL APPROACH

To develop a tracking system, a three-step process is proposed in which candidate indicators are first identified, then they are filtered through a set of criteria, and finally selected indicators are incorporated into a tracking system (Figure 2). Over time, some indicators may have to be refined or new ones developed. Technological advances may also allow implementation of indicators that were previously difficult to track.

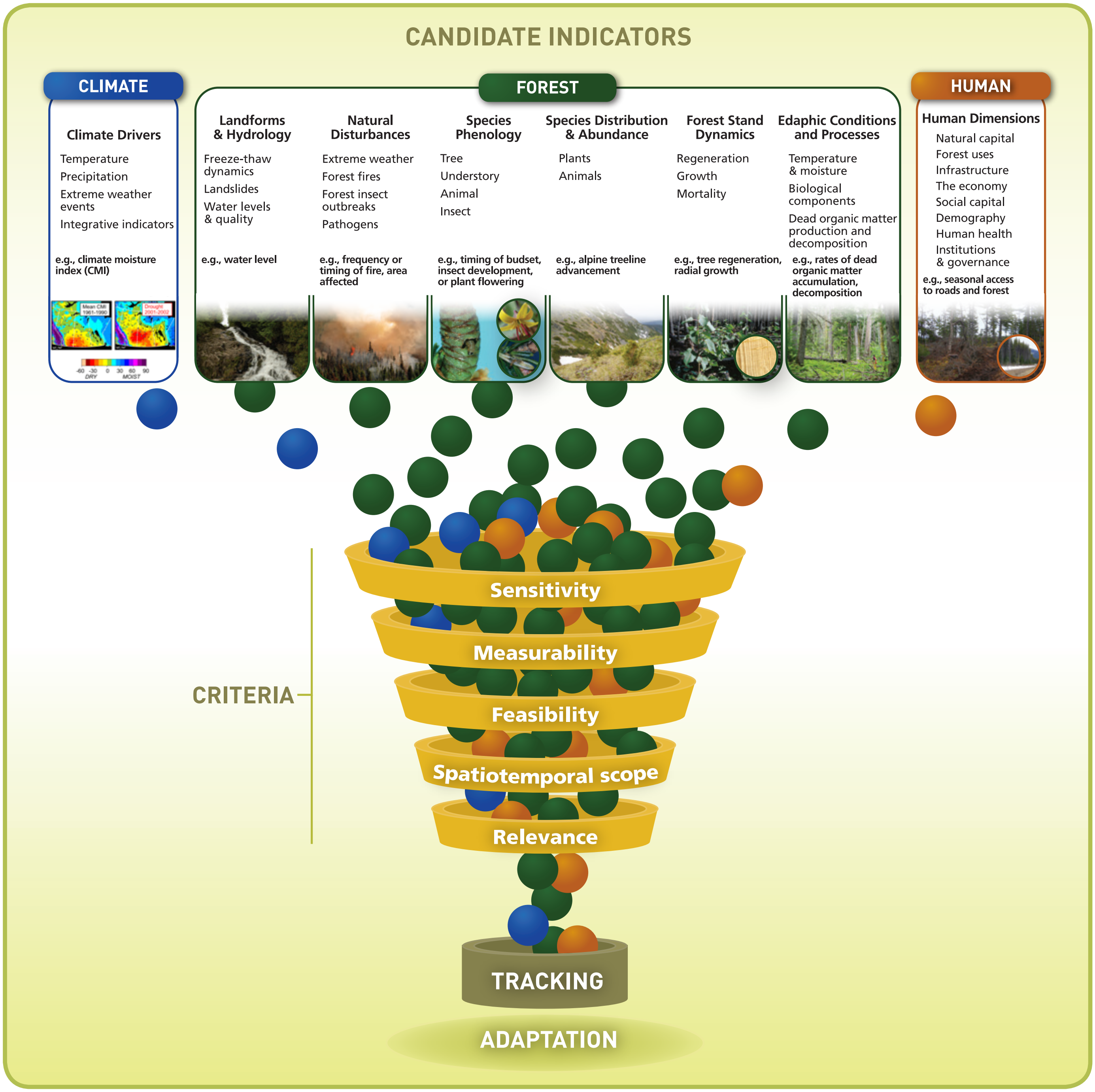


Figure 2. Framework for the identification and prioritization of climate change indicators. Candidate indicators are assigned to one of three systems: climate, forest, or human. These indicators are filtered through five proposed criteria and the ones selected are integrated into a tracking system. After tracking changes over time, some indicators may have to be refined or new ones developed. Such a tracking system is an integral part of the adaptation cycle.

To identify candidate indicators, two complementary initiatives were undertaken (see Process for Information Collection): a broad consultation within the Canadian Forest Sercvice (CFS) research community and a group of forest sector representatives outside the CFS (see Appendix 3. Workshop Participants), and a comprehensive literature review and website scan (Kremsater 2012) to explore indicators currently used or developed in other jurisdictions worldwide to track climate change effects on forests and the forest sector.

Candidate indicators were assigned to one of three systems: climate, forest, or human (Figure 2). Indicators for the climate system focused only on climate drivers that directly affected forest ecosystem structure and function and the human system. Climate drivers were grouped according to temperature, precipitation, extreme weather events, and integrative indicators. Indicators for the forest system looked at structural attributes and functional processes likely to be affected by climate change (landforms and hydrology, natural disturbances, species phenology, species distribution and abundance, stand dynamics, and edaphic conditions and processes). Indicators for the human system focused on forest-related dimensions, and comprised indicators of potential impacts and adaptive capacity. They were addressed through eight dimensions: natural capital, forest uses, infrastructure, the economy, social capital, demography, human health, and institutions and governance.

Five criteria for indicators of impacts (Landres et al. 1988; Dale and Beyeler 2001; Steenberg et al. 2011) have been defined for selection among candidate indicators (Figure 2): (1) sensitivity to climate, (2) measurability, (3) feasibility, (4) spatiotemporal scope, and (5) relevance. A preliminary assessment of indicators was undertaken using some of the proposed criteria (see Indicators of Climate Change Effects on the Forest and the Forest Sector).

1) Indicators should be sensitive to climate, and exhibit a strong signal-to-noise ratio (Kenney et al. 2011). Tree phenology indicators, for example, are particularly sensitive to climate, notably to spring and fall temperature fluctuations (e.g., Cleland et al. 2012; Fridley 2012). Conversely, some indicators, such as those involving complex interactions, are sensitive to many confounding factors. For instance, climate change may affect human health and well-being through increased frequency and intensity of heat waves, floods, droughts, and smoke from fires; however, similar health problems can also be caused by nonclimatic factors.

2) Indicators should be empirically and objectively measurable. Soil temperature is easily measured with portable or permanent digital thermometers and can be repeatedly measured over time to observe trends. In contrast, soil biodiversity is more difficult to measure due to lack of adequate and standardized techniques to identify species (e.g., Kirk et al. 2004). One gram of soil may harbor over 10 billion microorganisms (Roselló-Mora and Amann 2001) and less than 1% may lend themselves to being cultured and characterized (Torsvik and Øvreås 2002).

3) Measurement and use of an indicator should be feasible. This determines the level of financial and human resources needed. For example, an indicator for which baseline information already exists can be implemented more easily than one for which new data need to be collected. Baseline data should cover at least 30 years (the traditional standard for reporting climate normals) when possible. Such baseline information can be readily acquired for some indicators (e.g., see Climate Drivers), but for others, such as forest fire regime characteristics, longer baseline data may be needed. For some indicators, useful data may have already been collected, but for other purposes or by different agencies (e.g., tree planting dates or periods for which forest access is restricted due to fire hazard). These data are often not standardized across jurisdictions, which can obstruct data usefulness and applicability.

The criteria of sensitivity, measurability, and feasibility rely on current scientific knowledge and methodological standards. A particular indicator could be discarded due to low sensitivity to climate signals, or because the signal cannot be separated from confounding factors. Other indicators may be discarded because they require information that is currently unavailable or cannot be gathered efficiently. However, because science and technology are quickly evolving (e.g., remote sensing technology for monitoring; use of smart phones), we suggest indicators not be dismissed based solely on these criteria. Moreover, as our understanding of climate change progresses and our knowledge of socioecological systems develops, indicators may also evolve in response to growing or changing needs, capacity, and knowledge.

Once indicators are ranked according to these three criteria, considerations related to tracking system objectives should be taken into account (Figure 2). Tracking considerations are largely related to (4) spatiotemporal scope and (5) relevance.

4) Spatiotemporal scope is particularly important in the context of Canada's forests. Given the sheer size of Canada's forested land base, climate change effects are unlikely to be uniform. Therefore, a national tracking system of climate change indicators must account for regionality. Observations must be collected at multiple locations across different forest regions, and preferably over long time periods. Some indicators that are regionally specific and are not measured across Canada may deserve to be included in a national tracking system if outcomes have national influence. A recent example is the mountain pine beetle (*Dendroctonus ponderosae*) outbreak,

which is unique to western forests but has a national economic impact. When scaling up measurements nationally, valuable local information can sometimes be lost. Beckley (2009) suggests adopting a multipronged approach that considers three groups: one including indicators that are identical across all spatial scales, another with indicators related to similar themes, and a third one with local indicators that reflect the unique character of a given place or forest management approach. Such an approach may help balance indicator representation across a range of environments, governance types, and institutional levels.

5) The relevance of indicators describes how well they inform the objectives of a particular tracking system (e.g., informing citizens or informing decision makers). Some indicators may be highly relevant to detecting changes occurring in the forests, whereas others will help raise awareness of the risks of climate change effects, and increase society's will for action. Some indicators may provide more than one tracking service; for instance, measurements of fire weather indices, which begin three days after snow disappearance, can provide not only an estimation of wildfire risk but also the period of (absence of) snow cover in the forest.

The criteria defined above are well suited for indicators of the climate and the forest systems. However, knowledge of linkages between society and the forested environment and the ability to measure these links have not yet yielded a consensus on meaningful human system indicators. Significant efforts have been devoted to better understand relationships between people and forests through various lenses (cultural, economic, ethical, institutional, political, psychological, sociological, spatial, etc., e.g., Harshaw et al. 2007; Stedman et al. 2007; Rayner 2012). Indicators of impacts on social and economic spheres are partially developed, while those related to adaptation will and actions require more investigation. In fact, much work is still needed to settle on indicators that might be used to assess these constructs. Several key constructs have been proposed to describe characteristics of the socioecological system (e.g., community capacity, forest dependency, forest values; Doak and Kusel 1996; MacKendrick and Parkins 2005; Stedman et al. 2007; Moyer et al. 2008; Flint et al. 2009) and recommendations have been proposed to improve social indicators related to the forest generally or to climate change effects. Beckley et al. (2002) suggest focusing on how forests contribute to well-being, and avoiding solely forest-related indicators. Experts brought together to assist the US National Climate Assessment team in developing societal indicators also stressed the need to find a balance between links to climate change effects and what people value, including how this will impact their families, communities, institutions, and society (Kenney et al. 2011). Indicators should allow us to describe not only the current state but also past and future changes (Kusel 2001). Since there is still considerable debate on the relative importance of various elements and functions of social systems in relation to the forested environment, criteria for selection of indicators in this field require additional investigation.

PROCESS FOR INFORMATION COLLECTION

The core team* of the CFS Climate Change Indicators Initiative included at least one member from each CFS centre. The team hosted a series of workshops, collected and interpreted information gathered in each workshop, supervised and synthesized the literature review and web scan of existing indicators, and helped write this report.

Listing Potential Indicators by Consulting with Scientists and Stakeholders

The first phase of this initiative consisted of five workshops, one held at each CFS regional centre from November 2011 to January 2012. The participants at these sessions were CFS experts in a wide range of subject areas, mainly from the biophysical fields. The workshop format was designed to solicit and assemble a logical and cohesive set of indicators on the effects of climate change on Canada's forests and forest sector. A blank template and a completed example were sent to participants before the workshop. The completed template provided background information and initiated the thinking process on the development of meaningful indicators. Participants were asked to complete at least one template before the workshop. Core team members provided context and background at the beginning of each workshop. Participants were then invited to introduce their proposed indicators, and Sylvie Gauthier and Miren Lorente presented results from workshops held at other CFS centres. The remainder of the workshop was spent brainstorming additional indicators and discussing those already presented. Mean duration of the workshops was three hours.

The second phase of consultation took place on February 29, 2012, in Ottawa. The CFS brought together forest industry, university, and provincial government representatives, and climate change researchers to gain insight on how to improve the inclusion of climate change into forest management. Sylvie Gauthier presented the combined results from the regional CFS workshops, and participants discussed the type of indicators that are needed and how the broader forestry community could contribute to tracking them. Discussions focused on five basic themes: forest climate indicators, forest ecosystem indicators, forest economic indicators, forest community indicators, and adaptive capacity of the forest sector. Although only a few socioeconomic indicators were suggested during the regional CFS workshops, this second phase of consultation was particularly useful in identifying potential indicators in this area.

* Sylvie Gauthier, Miren Lorente, Laurie Kremsater, Louis De Grandpré, Philip J. Burton, Isabelle Aubin, Edward H. Hogg, Solange Nadeau, Elizabeth A. Nelson, Anthony R. Taylor, and Catherine Ste-Marie

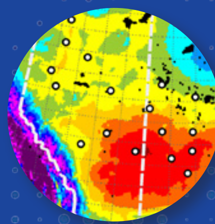
Literature Review and Web Scan of Existing Initiatives Related to Indicators of Climate Change Effects

To review information on indicators currently used to assess climate change, Laurie Kremsater conducted a comprehensive literature review and website scan from January to March 2012, mostly of jurisdictions in the Northern Hemisphere that have boreal or temperate forests. Searches were carried out using Google, Google Scholar, and Web of Science with the following keywords: "climate change" or "global warming" and "forests" or "forestry", and "indicators" or "monitoring" or "assessment". For each jurisdiction, searches returned thousands of hits, but examination was limited to the first 200 and we retrieved only the most relevant among more than 900 papers initially retrieved. Government websites for each province, territory, state, and country, and websites from known organizations were also scanned using the keywords "climate change" or "global warming" and "forests" to find government publications. Globally, approximately 500 papers and 150 websites were inventoried. Particular attention was paid to existing or proposed monitoring and reporting frameworks in different provinces, states, and countries, including any criteria for ranking and prioritizing indicators. Searching by jurisdiction and key words yielded information on government programs but also returned numerous journal articles on studies of climate change in forests. In most cases, it was not possible to achieve a full view of the jurisdiction's approach to climate change indicators in forests without including the refereed journal papers, many of which are authored by agency scientists. Hence, the review also includes information from many journal papers concerning impacts and indicators of climate change effects on forests. Many indicators are those proposed by researchers, or that have been used locally or regionally or over a limited period of time, not necessarily implemented operationally by a government jurisdiction.

INDICATORS OF CLIMATE CHANGE EFFECTS ON THE FOREST AND THE FOREST SECTOR

For each of the three systems, climate, forest, and human, we developed rationales describing the fundamental changes hypothesized under a changing climate. We then listed potential indicators and identified linkages among indicators. Although we acknowledged a broad set of considerations when evaluating indicators of climate change effects (see Methodological Approach), our preliminary assessment was undertaken for the climate and forest systems only and was limited to indicator sensitivity and feasibility, based on expert judgement and a literature review. Further indicator assessment will be needed before a complete set of indicators can be compiled. Moreover, there is still limited understanding of the web of relationships between the forested environment and social systems (Beckley et al. 2002; McCool 2003; Mitchell and Parkins 2011). Literature regarding observed changes in socioeconomic indicators in response to climate change remains scarce (Rosenzweig et al. 2007). Hence, rather than listing currently used indicators and assessing their potential use for the human system, elements for which indicators may be further developed were identified.

CLIMATE SYSTEM



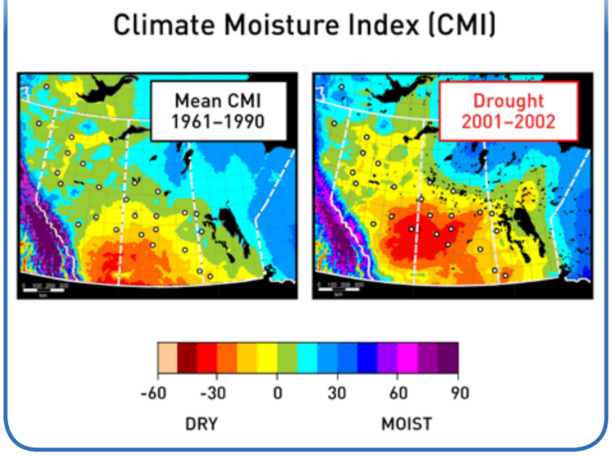
CLIMATE DRIVERS

What are climate drivers and how are they organized?

Climate drivers refer to the main elements of climate and weather that affect forest ecosystems and the forest sector. This category focuses on temperature, precipitation, extreme weather, and derived indicators that have important influences on forest ecosystem processes and structure. It also includes integrative indices (e.g., drought indices, fire weather indices) that are likely to be useful in forecasting climate-related changes in our forests. Indicators in this category are thus grouped according to temperature, precipitation, extreme weather events, and integrative indicators (Table 1).

Why are climate drivers relevant to climate change?

All aspects of forest ecosystems are influenced by climate and weather events, which in turn are affected by climate change. Monitoring climate drivers is useful for tracking climate change and evaluating the causes of changes in biological processes, ecological communities, and the physical environment. In some cases, these primary variables can provide direct, useful measures of climate-related effects on forested ecosystems. For example, permafrost thawing, which affects northern forests and transportation infrastructure, relates directly to mean annual temperature and number of days above freezing; the phenology, growth, and distribution of many organisms can be predicted using simple indicators of daily temperature (e.g., growing degree-days, timing of frost). Additional indices have been developed that are specifically tailored to physiological responses of trees and other organisms, such as birch (*Betula* spp.) dieback following thaw–freeze events during winter and spring (Bourque et al. 2005). Climate-related range expansion models of forest insects such as mountain pine beetle typically rely on a combination of climate driver inputs and species responses (Safranyik et al. 2010), although there are inherent difficulties in predicting climate effects on forest insect outbreaks and range expansions. Integrative indicators such as drought exert direct effects on forest growth and can lead to increases in tree mortality and regeneration failure. Furthermore, drought can have indirect impacts on forests by reducing the ability of trees to defend themselves against forest insects and diseases. Similarly, fire plays a major role in the function of Canada's forested ecosystems, and also poses a major threat to public safety and to the forest sector. Thus, among climate drivers, those affecting fire danger and risk are particularly important.



How will climate change affect climate drivers and how these effects can be measured?

Temperature

Temperature changes will likely affect many forest attributes such as vegetation growth, the speed of insect development, and overwinter survival. Most areas in Canada have experienced significant increases in average annual temperature since 1950 (Zhang et al. 2011) and continued warming is expected during this century (IPCC 2007). Relatively greater warming is expected during winter than during summer. Extreme maximum temperature events are predicted to increase somewhat, while there will likely be an even greater reduction in the number of extreme minimum events (e.g., Kharin et al. 2007). Temperature drives the length of the growing season, which is usually defined as the period between the last springtime frost and its first occurrence in the autumn (Schwartz et al. 2006). Many weather stations in Canada show that the growing season has started earlier in recent years (Zhang et al. 2011). The longer growing season, in combination with its warmer temperatures, has resulted in significant increases in growing degree-days. There is also evidence of a reduction in the frequency of frost days and killing frost days during the growing season (Zhang et al. 2011). A longer growing season can lead to both positive and negative effects on forests. Temperature patterns are important for many other indicators (e.g., drought indices, insect population models, and permafrost thawing).

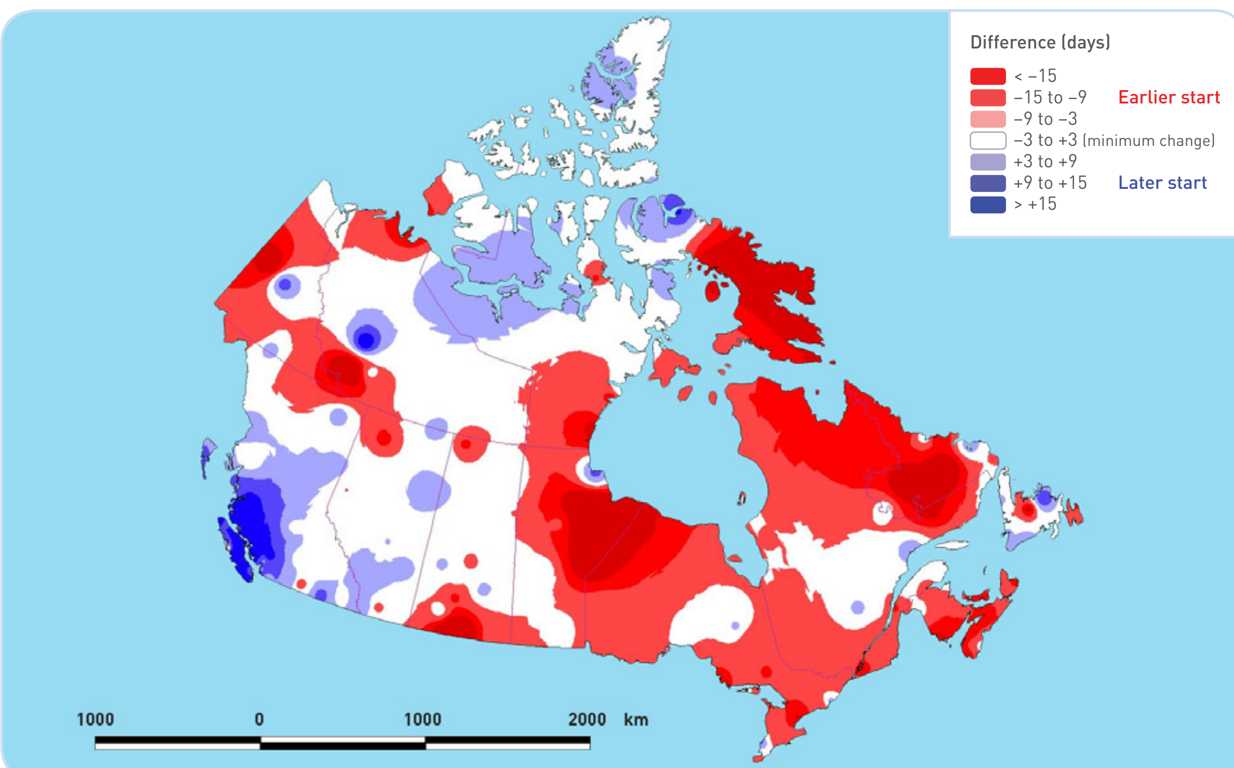
Precipitation

Precipitation changes will almost certainly have significant effects on forest ecosystems, and monitoring these changes will be important to inform management. However, forests respond indirectly to precipitation through its effect on soil moisture, snow depth, and other factors. Also, precipitation projections are not as reliable as temperature projections. Generally, more frequent wet years, greater year-to-year variability, and more extreme precipitation events are expected. Snowpacks are expected to decrease, with more precipitation likely to fall as rain and less as snow. Freezing rain is expected to increase in some parts of the country and can have very damaging effects on vegetation (Catto 2010). In some areas of the country, climatic warming is expected to lead to an increase in summer droughts (soil moisture deficits). Given that projections are recognized as highly uncertain, continuing to track actual precipitation patterns is important. In some areas, historical winter precipitation has already decreased while summer precipitation has increased (e.g., most of British Columbia; Rodenhuis et al. 2009); in other areas of the country, the reverse is true. Note that even if summers have more precipitation, it can be concentrated so that periods of extended drought are still possible; also, the evaporative demand associated with higher temperatures will likely exceed any increases in precipitation.

Reduced snowpack is anticipated as the snow line in mountainous areas is forecast to rise. Changes in the timing of accumulation and loss of snowpack are uncertain but could have considerable effects on forest ecosystem processes and on forestry operations. Also, these changes are important in determining the start and end of the forest fire season. Seasonal patterns of snow accumulation and snowmelt are highly sensitive to changes in temperature and precipitation; rapid snowmelt during periods of extreme spring warmth may lead to widespread flooding. Snowmelt runoff contributes to a substantial portion of the total water flow in basins dominated by snowmelt, and thus is an important hydrologic variable for recharge and sustenance of baseflow conditions.

Extreme weather events

Extreme weather events are likely to increase (Easterling et al. 2000). During periods of climate adjustment, there is a strong likelihood of unseasonable or unexpected weather. This may include late or early frosts, extreme snowfalls, ice storms, hail, droughts, high winds, lightning that causes fire, and extreme heat or cold. Many of these can have major effects on forests because forests respond more quickly to weather events than to climate averages. Extreme heat is tracked under the temperature indicator, as are early and late frosts. This dimension considers wind, thunderstorms, lightning, and drought. High winds affect forests directly through the blowdown of trees, and indirectly through enhancing fire activity. Climate change effects on thunderstorms and lightning are not modeled well; tracking actual changes in lightning timing and density will be important for fire management. Drought can be considered an extreme event, but we consider it under some of the integrative indicators below.



Example of an integrative index (FWI) in which Canadian fire season start dates (Julian days) over the last 10 years are compared with those from 1970 to 2002. (Richard Carr, Natural Resources Canada, in preparation)

Integrative indicators

Integrative indicators to track drought severity and extent combine temperature and precipitation effects. These indicators are highly relevant to forests; there are already indications that forest dieback episodes, which are often ascribed to several damaging agents, have increased at the global scale in response to recent severe droughts (Allen et al. 2010). Drought effects on forests are largely a result of reductions in soil moisture within the tree rooting zone. Soil moisture in turn is driven by both water inputs (rain and snow) and outputs (water use by the vegetation, runoff, lateral water movement within the soil, and infiltration beyond the rooting zone). Although not as complete as soil moisture mapping, drought indices that require only simple inputs (e.g., temperature and precipitation) provide a more feasible approach for assessing spatial–temporal variation in moisture conditions relevant to changes in forest ecosystem function across large areas. In the agricultural sector, drought conditions are commonly reported using the Palmer Drought Severity Index (PDSI), which integrates precipitation, temperature, moisture-holding capacity of the soil, and local infiltration. Other indices such as the Climate Moisture Index (CMI) and the Canadian Forest Fire Weather Index (FWI) System are used as drought or dryness indicators in Canada's forests. The ratio of precipitation to potential evapotranspiration is also sometimes reported.

Climate drivers that affect fire severity and extent include temperature, wind, relative humidity, and precipitation patterns. The FWI System integrates these factors to provide various indicators of weather effects on fire behavior (e.g., risk of ignition, rate of fire spread, fuel consumption, and fire intensity), including changes in moisture content of woody material and flammable organic matter on the forest floor. The FWI System components are very sensitive to climate change.

Table 1. Indicators for climate drivers.

DIMENSION	INDICATOR[a]	SENSITIVITY[b]	FEASIBILITY[c]	KEY CONSIDERATIONS
Temperature	*Daily mean, maximum, and minimum temperature and derived values (monthly, seasonal, and annual mean temperature)*	H	H	- Historical observations of daily temperature and precipitation date to the late 1800s at some climate stations, but spatial coverage is sparse before the 1940s in most of Canada's forested areas. Hourly observations dating to the 1950s are available at some climate stations. - Several computer systems (e.g., ANUSPLIN (Australian National University Splines) and BioSIM (biosimulation)) are widely used for spatial interpolation and historical mapping of climatic variables across Canada's land base (McKenney et al. (Planning Tool for Resource Integration, Synchronization, and Management) 2006; Régnière and Saint-Amant 2008). Other examples include PRISM and the ClimateWNA (Climate Western North America) tool used in the United States and in mountainous regions of western Canada (Daly et al. 2002; Wang et al. 2006), and global products such as the Climate Research Unit gridded historical data sets of temperature (Jones et al. 2012). These are also used for generating maps of projected future climate changes as downscaled from General Circulation Models. - Since the 1990s, automation of weather measurements and closure of long-term climate stations have posed an increasing challenge for continuity and spatial coverage of climate monitoring in Canada. - Summary statistics commonly used to track temperature (such as annual or monthly averages, minima, and maxima) do not necessarily provide the most relevant information for assessing temperature-related effects on forests and the forest sector. - Derived indicators such as length of growing season and dates of first frost and last frost may provide more useful measures for tracking effects on tree regeneration and establishment, primary productivity, and fire season length. These attributes can be derived from data made available daily. - Caution is warranted when applying weather station data (often located at airports and other developed areas) to the relevant microclimatic conditions of interest in forests and other vegetation types. Where available, on-site measurements will provide much greater reliability as to the occurrence of temperature-related events such as summer frost. - **Jurisdictions**: Environment Canada (EC) manages Canada's national climate archive, and data are available free. Other climate networks such as provincial fire weather stations provided greater spatial coverage, but methods of observation, reporting, and data access vary. Most jurisdictions report daily or hourly temperature measurements that may be summarized monthly, seasonally, or annually (see Appendix 1; New et al. 1999; Lemieux et al. 2010). Reporting of frost and growing season length is less common.
	Annual growing degree-days: cumulative sum of positive daily mean temperature greater than 5°C or alternative temperature threshold	H	M	
	Annual cold degree-days: cumulative sum of negative daily mean temperature less than 0°C or alternative temperature threshold	H	M	
	Number of days with temperatures above or below a given threshold value (may vary according to the biophysical process of interest)	H	M	
	Date of last frost, date of first frost, number of frost-free days	H	M	
	Other temperature-related indicators such as length of the growing season (*and freeze–thaw events*)	H	M	

(*Continued*)

[a] Regular font indicators are from the workshops, italic indicators are from the scan, bold indicators are from both the workshops and the scan.
[b] Sensitivity of indicator to climate change: High (H), Medium (M), Low (L).
[c] Feasibility of measuring in a regional or national tracking program: High (H), Medium (M), Low (L).

Table 1. (*Concluded*)

DIMENSION	INDICATOR[a]	SENSITIVITY[b]	FEASIBILITY[c]	KEY CONSIDERATIONS
Precipitation	*Daily total precipitation (rain and water content of snow) and derived values (monthly, seasonal, and annual total precipitation)*	H	H	- Total precipitation is routinely measured at most climate stations; some stations separately report precipitation as rain and snow. In most cases, the period of record for precipitation is the same as for temperature (see above). Records of precipitation input as snow are highly sensitive to the method of measurement and some instruments (e.g., tipping bucket rain gauges) do not reliably measure snowfall. Snow depth measurements are made at fewer climate stations starting in the 1950s or later. EC's Water Survey Branch records snowpack information, usually supplemented with provincial and local industry data. - As for temperature, interpolation among weather stations is necessary to cover Canada's vast area. Precipitation tends to be patchy because of convective storms and topographic effects which pose problems for the accurate interpolation of precipitation across the landscape from climate stations that are often sparsely distributed in remote forested regions. - **Jurisdictions**: Generally the same as indicated above for temperature measurements. Most climate networks (see Appendix 1) report on total precipitation (hourly or daily), and snowpack is reported in some cases. Reporting on freezing rain is less common.
	Daily total rainfall	H	H	
	Daily total snowfall (depth or water equivalence)	H	M	
	Derived indicators such as number of days without rain	H	M	
	Occurrence of freezing rain (number of days and/or amount)	M	M	
	Snow cover, snow depth, snowpack density, and water equivalence	H	M	
	Period of snow on the ground	H	H	
Extreme weather events	*Thunderstorms and lightning (number of storms, density of lightning strikes per period)*	M	H	- Extreme weather events such as wind, thunderstorms, and lightning have significant impacts on forests and are affected by climate change. - EC and other agencies routinely measure wind speed and direction, typically reported hourly (including maximum gusts). Some climate stations report on thunderstorms and hence the potential for lightning, but greater spatial coverage is provided by lightning detection networks. - Extreme heat, early and late frosts are discussed under the temperature dimension above; drought is discussed as an integrative measure below. - **Jurisdictions**: Generally as indicated above for temperature. Some provincial fire management agencies operate lightning detection networks during the fire season.
	Wind, including mean wind speeds and maximum gusts above a given threshold and the occurrence of specific storm types such as hail storms, tornados, derechos, and hurricanes	M	M	
Integrative indicators	**FWI**	H	H	- Changing FWI reflects changes in temperature, wind, relative humidity, and precipitation patterns. The FWI System is an empirical weather-based index. - The start and the end of the fire weather index calculations (this is an on-the-ground measure of snow arrival and disappearance and can also be a measure of the length of the fire season). See also Precipitation and Forest fires. - The applicability of alternative drought indices to various biophysical processes and regions requires critical review and evaluation. - The PDSI and related indices are commonly used in agriculture and may be applicable as a relative drought indicator for forests (negative values indicate more severe drought). See also Extreme weather. - The CMI provides a versatile absolute indicator of annual changes in moisture regimes and drought severity for forests in the western Canadian interior (Hogg 1997). See also Extreme weather. - The SMI (Hogg et al. 2013) provides an indicator of seasonal and long-term changes in moisture conditions in remote forested regions where climate data are typically limited to very basic weather observations (temperature and precipitation only). Estimates of modeled monthly soil moisture can also be readily obtained for any global location (1948 to present) from a web-based reporting system (Fan and van den Dool 2004). See also Soil temperature and moisture, and Extreme weather.
	The start and the end of the fire weather index calculations	H	H	
	The Drought Code of the FWI System. See also Extreme weather and Forest fires	H	H	
	The **PDSI** provides a relative indicator of drought	H	H	
	The CMI calculated as the difference between annual precipitation and potential evapotranspiration (water balance per year)	H	H	
	Soil moisture models including the soil moisture index (SMI). See also Extreme weather	H	M	

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[b] Sensitivity of indicator to climate change: High (H), Medium (M), Low (L).
[c] Feasibility of measuring in a regional or national tracking program: High (H), Medium (M), Low (L).

FOREST SYSTEM

LANDFORMS AND HYDROLOGY

What are landforms and hydrology and how are they organized?

The landforms and hydrology category considers three broad dimensions: freeze–thaw dynamics (including permafrost, glaciers, and lake and river ice), landslides, and water levels and quality (primarily temperature) (Table 2).

Why are landforms and hydrology relevant to climate change?

Climate shapes landforms and hydrological systems. In turn, features of the earth's surface and physical processes affect forest ecosystems. For example, freeze–thaw dynamics influence forest structure and function, and transportation infrastructure. Even though assessment of global data since 1970 by the Intergovernmental Panel on Climate Change (IPCC 2007) has shown that natural systems on all continents and most oceans are being affected by regional climate change, particularly temperature increases, here we deal only with landforms and physical systems most relevant to forests; those associated with the phase shift of water from solid to liquid are particularly important. Globally, most discussions of climate change effects on physical systems also concern sea level rise, sea ice, storm surges, and estuary vulnerability. Where forests border oceans and lakes, some of those may affect forests and may warrant further consideration.

How will climate change affect landforms and hydrology and how can these effects be measured?

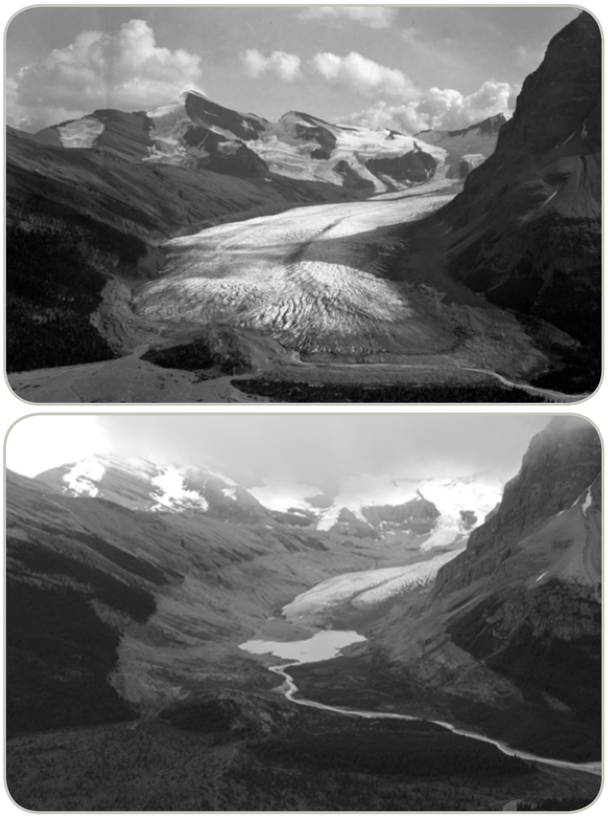
Freeze–thaw dynamics

The timing of the first and last snowfall, and the freeze-up and breakup of ice on rivers and lakes are easily visible signs of the transition between seasons, and affect daily life and activities directly impacting the forest sector (modes of travel or methods of logging, for instance). Soils that remain frozen year-round, often facilitated by the insulative properties of a thick organic soil layer, characterize much of the northern boreal and taiga regions. While forest productivity is often constrained by the restricted saturated rooting zone that results, the summer thawing of previously frozen soils can result in considerable surface instability, with disastrous consequences for roads, buildings, airstrips, pipelines, or utility poles installed thereon. As well as affecting road integrity, the freeze–thaw cycle is also important for several aspects of forestry. Growing season frosts constrain regeneration of certain tree species and can cause frost-heave of container-grown seedlings newly planted in fine-textured soils (de Chantal et al. 2009). Algorithms and indices of freeze–thaw events may be developed for various applications such as regional-scale mapping of weather

conditions leading to forest decline (Bourque et al. 2005) (see Edaphic Conditions and Processes).

Thawing permafrost can affect local hydrology which in turn can affect road stability and the ecology of an area, including tree growth. It is very difficult to predict the ultimate climate change effects on permafrost, peatlands, and mires. It is estimated that mires may become drier than now, especially during summertime. Drier conditions would lead to barrenness of some mires and overgrowth of sphagnum peat. Permafrost thaw can result in large amounts of water at the surface (e.g., Barrow, Alaska; ACIA 2004), but this moisture could be lost if the depth of the active layer increases as projected. Sites in northern Sweden have thawed to progressively greater depths as climate has warmed (ACIA 2004). If the permafrost melts, soils can actually dry and erode. Because permafrost can thaw differentially, creating irregular surface topography, permafrost thawing will cause some ponds to drain and others to be created. Black spruce (*Picea mariana*) is the dominant tree in permafrost areas. On wetter sites, decreased water levels may allow tree growth to increase, but on drier permafrost sites, black spruce growth often decreases with higher summer temperatures. On other sites, spruce trees are at risk of collapsing from permafrost thaw (ACIA 2004).

Glacier retreat is one of the most publicly known signs of climate change effects. Glacier melt affects forested streams in much of western Canada by moderating interannual variability in streamflow and helping maintain higher runoff volume in times of extreme warm and dry conditions. Glacier melt also supports ecosystem functions by maintaining cooler water temperatures. Glacier retreat is already causing changes in the flow patterns and temperature of some forest streams and rivers in British Columbia (Moore et al. 2009). The same trends are likely true for Alberta (e.g., Bolch et al. 2010) and are likely to have significant effects on freshwater and estuarine ecosystems and aquatic species.



Change in position of Robson Glacier, Mount Robson Provincial Park, British Columbia, between 1911 (*top*) and 2011 (*bottom*). ((*Top*) Whyte Museum of the Canadian Rockies (V263/NA 6345, Byron Harmon); (*bottom*) Roger Wheate, University of Northern British Columbia; source GlacierChange.org)

Duration of lake and river ice, or surface ice cover generally, is closely linked to air temperatures in the fall and spring periods, and affects forests mostly through impacts on northern transportation routes. Analyses of river and lake ice freeze-up and breakup trends across Canada from the mid-1960s to the mid-1990s show contrasting seasonal responses with little change in freeze-up (with some evidence of earlier river ice formation over eastern Canada) but widespread trends for significantly earlier spring breakup (Zhang et al. 2001; Duguay et al. 2006). These results are consistent with trends in fall and spring temperatures. A more recent analysis of trends in freeze-up and breakup at approximately 40 lake sites across Canada from 1970 to 2004 using in situ and satellite observations shows greater evidence of significantly later freeze-up at several lakes (Latifovic and Pouliot 2007). From 1950 to 2005, the spatial pattern of trends in the thaw date shows that sites with significantly earlier breakup tend to be located in western Canada, which agrees with the spatial pattern of climate stations showing significant spring warming (Zhang et al. 2011).

Landslides

Climate change may affect precipitation, snowmelt, and vegetation by altering the frequency or magnitude of mass movements and erosion events which can affect forest cover. Although underlying geology is independent of climate, climate changes may affect surficial geology (via changes to soils, hydrology, and vegetation) and vegetation and thus affect mass movements through permafrost thaw (see above) and changes in the frequency of soil saturation. There is evidence that landslides are linked to shifts in overall climate as well as to specific weather events (e.g., Geertsema et al. 2007).

Water levels and quality

Climate-driven changes to hydrological systems are likely to cause changes in the physical, chemical, and biological characteristics of water in forest streams and lakes. Such changes may affect freshwater and estuarine ecosystems and aquatic species found in forests, particularly resident fish such as some trout and salmon (*Oncorhynchus* spp.) species that spend years of their life cycle in forest streams. Predicted lower flows in summer and early fall may reduce the amount of water available to forest ecosystems. In contrast, increased storms and precipitation amounts predicted because of climate change may result in higher than usual water volume and velocity for winter months in some regions, potentially leading to increased river turbulence, scouring, sediment loads, and reduced in-stream channel stability and damage to aquatic habitats in forests. Low flows may be associated with warmer water temperatures and declining water quality, both of which would threaten the health of aquatic ecosystems (Brooks 2009). Warmer temperatures are expected to affect the fitness, survival, and reproductive success of certain fish and other aquatic species (e.g., Manomet Center for Conservation Sciences 2010). Although important for water quality, water chemistry may be affected by climate change but is also affected by many other factors and hence we did not consider it a potential indicator.

Table 2. Indicators for landforms and hydrology.

DIMENSION	INDICATOR[a]	SENSITIVITY[b]	FEASIBILITY[c]	KEY CONSIDERATIONS
Freeze–thaw dynamics Permafrost	**Depth of thaw/active layer**	H	M	- Permafrost is highly sensitive to climate changes but it is difficult to sample extensive areas; careful spatial sampling design would be required. - There is potential to sample ponds, glaciers, and even permafrost thaw remotely. - **Jurisdictions**: Most northern jurisdictions measure (or suggest measuring) permafrost dynamics, lake and river ice, and glacier behavior.
	Areal extent and distribution of thaw	H	M	
	Changes in greenhouse gas production, soil and vegetation properties (e.g., loss of treed palsas)	M	L	
	Area and locations of forests affected by permafrost thawing (thermokarst), including flooding, chlorotic foliage, "drunken forests", and mass movements	H	M	
	Number and area of ponds in permafrost areas	H	M	
Freeze–thaw dynamics Lake and river ice	**Date of first melt**	H	L	- Lake and river ice is quite sensitive to climate change and can be measured. Ice duration is related to northern transportation issues but does not directly affect trees. It affects fish and aquatic animals in forests. - EC once had a larger program tracking ice on lakes and rivers but now focuses only on shipping routes. Information on lakes is currently collected by volunteers.
	Ice-free date (when rivers and lakes are completely free of ice)	H	H	
	Date of first permanent ice	H	L	
	Date of complete ice cover	H	M	
Freeze–thaw dynamics Glaciers	*Glacier area*	H	H	- Glacier retreat is one of the most publicly recognizable effects of climate change. It affects water flow and temperature but only indirectly affects terrestrial forests. Canada once had a glacier monitoring network that used remote sensing to track changes. Some monitoring continues by academics. - Volume and mass are more difficult to determine than area.
	Glacier volume or mass	H	M	
Landslides	*Landslide extent by location*	M	L	- For any rare event, such as mass movements, detecting trends is difficult. As well, the number of confounding factors (i.e., effects of land use rather than climate) that would mask or mislead interpretation of climate change effects makes mass movements a difficult indicator to pursue. And data to support monitoring the indicator on anything but a case study basis are not currently available. - As with any disturbance frequency indicator, a large reference area is required over which monitoring effort is applied equitably. - **Jurisdictions**: Some very mountainous jurisdictions (e.g., Austria) monitor landslides.
	Landslide frequency	M	L	
	Number/area of sand blowouts and other barren areas	M	L	
Water levels and quality	**Water flow in streams (including high and low flows)**	H	M	- Water flow and temperature are important for forest-dwelling fish and are highly sensitive to climate change. - The Water Survey of Canada of EC measures water flow at many places, and quality and temperatures at fewer stations. Measurements are not often in undisturbed areas or representative of forested systems. Data on small forested streams are few. - National Forest Inventory (NFI) plots and remote sensing could track wetland changes. Estimates of water evapotranspiration and storage, and carbon (C) release and sequestration associated with wetland changes are of interest but more difficult to assess than changes in wetland size, type, or depth. - A very long record is required to adequately distinguish between trends created by the Pacific Decadal Oscillation as it switches from one phase to another (cool to warm) and trends occurring due to broader climate change. - **Jurisdictions**: Water flow is commonly measured; few jurisdictions measure water temperature and water quality but usually suggest that water quality measures would be useful information.
	Wetland and lake size (area, water inflow, depth), wetland vegetation around lakes; change in wetland type or peatland to forest or vice versa	H	M–L	
	Annual watershed evapotranspiration and water runoff	H	L	
	Water temperature (surface and subsurface)	H	L	

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[b] Sensitivity of indicator to climate change: High (H), Medium (M), Low (L).
[c] Feasibility of measuring in a regional or national tracking program: High (H), Medium (M), Low (L).

NATURAL DISTURBANCES

What are natural disturbances and how are they organized?

The natural disturbances category includes both physical disturbances such as disruptions from extreme weather and fire, and biotic disturbances such as outbreaks of insects and pathogens. Note that extreme weather events such as drought, windstorms, ice storms, winter thaw–freeze events, and unseasonal frosts are treated under Climate Drivers. This category focuses on ecosystem disruptions resulting from those extreme weather events and so includes further discussion of windthrow, hail damage, and dieback due to freeze–thaw events, and drought, which can be considered a natural disturbance when it is sufficiently severe to cause massive tree mortality and crown dieback that is readily visible (Michaelian et al. 2011). The more widespread and subtle effects of drought, including decreases in tree growth and regeneration along with increases in "background mortality" (van Mantgem et al. 2009), are considered in Forest Stand Dynamics. The natural disturbances category considers four dimensions: extreme weather, forest fires, forest insect outbreaks, and pathogens (Table 3).

Why are natural disturbances relevant to climate change?

Under a changing climate the frequency and severity of natural disturbances are expected to increase in most regions of Canada (Dale et al. 2001; Flannigan et al. 2005; Haughian et al. 2012), leading to profound changes in ecosystem function and widespread impacts on forest ecosystems, the forest sector, and on Canadian society at large. Beyond the ecological impacts of natural disturbances are the associated socioeconomic effects, such as disrupted timber supply and unemployment rates or those that threaten human safety, habitation, and property. Depending on their severity, wind, hail, and ice storms can cause tree mortality, canopy disruption, and associated changes in forest structure. Wildfires affect not only forest ecosystems and timber supply but also human health and safety, notably in forest communities at the wildland–urban interface. Forest insect pests, primarily the bark beetles (Curculionidae: Scolytinae), defoliators, and alien species, could inflict extensive mortality and change the nature of the forest over large areas. Climate change will likely affect a suite of disturbances that act together to influence forests (McKenzie et al. 2009). The compounded effects of several disturbances can lead to unknown and unanticipated situations (Dale et al. 2001). For example, drought may weaken tree vigor, leading to greater susceptibility to insect infestations and diseases. The latter disturbances may in turn promote forest fires by increasing fuel loads. Forest fires can produce smoke which affects human health. Moreover, natural disturbances influence how much C is stored in trees, and their decay has been recognized as a significant C source (see also Human Dimensions Related to Forests).

How will climate change affect natural disturbances and how can these effects be measured?

Extreme weather

Large-scale wind damage, including hurricanes, tornados, and derechos, can cause extensive blowdown of forests (Ashley and Mote 2005). Other factors lead to increases in windthrow, such as wet ground or heavy snow-loading on trees. As well as causing blowdown, winds in summer are often associated with lightning storms and affect fire growth and rate of spread. Many studies have examined windthrow risk and the effects of extreme wind events in forest stands but few have assessed how windthrow may be affected by climate change. However, Haughian et al. (2012) projected decreased occurrence of extreme wind speeds during the summer in southern British Columbia, coupled with more frequent extreme winds in other seasons and other regions. In Finland, Peltola et al. (1999) suggested that climate change will affect not only wind but also tree rooting conditions; for example, the lack of frozen soils may increase windthrow. Local winds are not predicted directly by current climate change models (see also Sailor et al. 2008). Hail storms occasionally cause severe damage to forests (Riley 1953) and their impacts can pose a significant concern for local forestry agencies (Gillis et al. 1990). The January 1998 ice storm caused extensive damage to hardwood forests across 2.4 million ha of southeastern Ontario and southern Quebec (Hopkin et al. 2003), illustrating the potential importance of this disturbance type in eastern Canada. Such extreme storm events originate from mesoscale climatic conditions and thus may be affected by climate change.

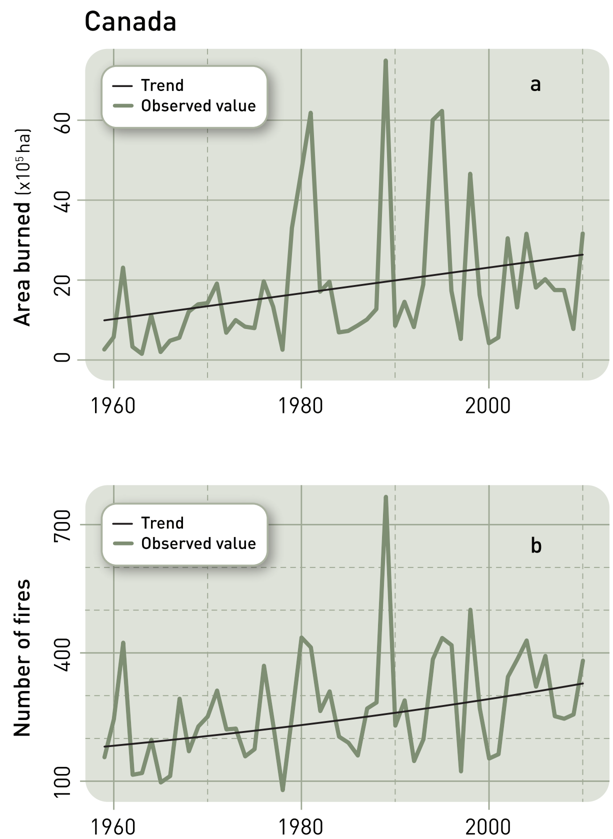
Climate change may already be leading to increases in winter thaw–freeze events that have been implicated as a cause of dieback and decline of hardwood species such as yellow birch (*Betula alleghaniensis*) (Bourque et al. 2005) and aspen (*Populus* spp.) (Hogg et al. 2002a). Other climatically sensitive events include red belt damage to conifers from winter desiccation in the foothills of western Alberta and elsewhere (Bella and Navratil 1987). In some cases, long-term decreases in early spring snow depths can lead to frost damage of roots and subsequent forest decline, as has been documented for yellow-cedar (*Chamaecyparis nootkatensis*) forests along the Pacific coast of Alaska and northern British Columbia (Hennon et al. 2005). Overall, the projected increase in unseasonable temperatures (either warm or cold) could be damaging to forest ecosystems. Spring frosts need not change in frequency or severity to cause increased injury to sensitive plant tissues if climatic warming leads to earlier bud burst (Gu et al. 2008).

Forest fires

Changes in fire rates are partially ascribable to climate (Gavin et al. 2007) and are influenced by interactions of harvest, fire suppression, fuel build-up and treatment, insects (e.g., Parker et al. 2006; Stephens et al. 2009; Naficy et al. 2010), and other natural disturbances. Several studies indicate that fire frequency is likely to increase considerably in various regions of Canada (Girardin and Mudelsee 2008; Bergeron et al. 2010; Wotton et al. 2010). The many boreal fire studies show a range of historical trends from decreasing to increasing rates of fire (e.g., Xiao and Zhuang 2007; Meyn et al. 2010); the variation is likely due to the location (often decreasing in eastern Canada, increasing in the west) and time scale (recent increases, longer-term decreases). Early springs and dry summers can increase the risk of large fires in forests. Patterns of fire intensity and severity may also change with the incidence of frequent and severe droughts and also be influenced by insect attacks (Hadley and Veblen 1993; Page and Jenkins 2007; Simard et al. 2011). Tree mortality because of fire may counterbalance, at the forest level, any productivity gain due to climatic warming.

Forest insect outbreaks

Almost all aspects of insect life history and population-level processes such as development rate, seasonal fluctuations, and voltinism (generations per year) are influenced by temperature (Tobin et al. 2008). Hence, climate is an important factor in defining the ranges of most insect species of temperate regions. Rapid genetic adaptation of insects to seasonal temperature changes has already been documented, and range expansion has occurred in many cases as species move into new habitats created by increasing temperatures (e.g., Bentz et al. 2010; Régnière et al. 2012a). As pest species alter their ranges, both native and alien species can become destructive in areas where they did not occur before because the ecosystem may not be well adapted to this disturbance type. Thus, timing of insect emergence and bud burst of their host plants may be an appropriate indicator of the response of both insects and plants to increasing ambient temperature because of climate change.



Trends in (a) area burned (hectares) and (b) number of large fires (>200 ha) across Canada between 1959 and 2010. (Yan Boulanger, Natural Resources Canada)

There are indications that climatic warming has played a major role in the recent, unprecedented eruption of bark beetle species across vast areas of western North America (Raffa et al. 2008; Bentz et al. 2010; Safranyik et al. 2010). Some defoliators (budworms (Tortricidae) and loopers (Geometridae)) can also affect large areas and may be affected by warm temperatures during larval development. The fitness of defoliating insects and the severity of damage they cause are contingent on synchrony with bud flush of their host plants. Some insects, such as bark beetles, respond quite directly to climate and may erupt into an outbreak when weather conditions are favorable provided hosts are present. Others (e.g., many budworms) depend more on hosts, and their populations are more cyclic regardless of weather conditions. Insect responses to climate change can be characterized by a high degree of complexity and uncertainty, as populations are influenced directly by shifts in temperature and indirectly through climatic effects on community associates and host trees. Those climate changes will not be uniformly distributed across years, and not all temperature-dependent processes will be equally affected. The resulting dynamics depend on both the complexity in the responses of physiological processes to climatic factors and the interactions among these species.

Pathogens

There is considerable uncertainty about how climate change may affect the future dynamics of forest pathogens, partly because of the complexities of host–pathogen interactions (Sturrock et al. 2011). The common feature in most forest pathogen responses to climate change seems to be a shift in the relationship between (or seasonal fluctuations of) temperature and precipitation or soil moisture. Although many fungi benefit from warmth and moisture, they are also affected by the health of their host trees (Londsale and Gibbs 1996) so that impacts of native and introduced forest pathogens on Canadian forests are expected to increase in tandem with projected increases in drought and other abiotic stressors. The effect of climate change is more predictable for groups of pathogens that have life cycles directly affected by climate, especially by changes in temperature and moisture. Rusts, for example, will benefit from episodes of high humidity. Drought may increase some foliar diseases while high humidity could benefit others (Kliejunas et al. 2009). In contrast, pathogens such as *Armillaria* spp. causing root disease of forest trees are indirectly affected by climate and more affected by stress levels of their host trees (Kliejunas et al. 2009; Lowther 2010; Sturrock et al. 2011). Most authors, however, suggest warming will increase incidence and aggression of root rots. Although empirical data are limited, a rise in atmospheric carbon dioxide (CO_2) and increased growth of tree roots may result in an increase in severity or frequency of root disease. More extensive root systems would increase the probability of invasion (O'Neill 1994) which could be offset by increased plant vigor and disease resistance (Runion et al. 1994).

Predicting climate change effects on the behavior of many pathogens is challenging and highly uncertain because of their direct tie to precipitation which has much greater uncertainty than temperature in predicted patterns (IPCC 2007). Even if predictions were less variable, most climate models produce outputs on seasonal or monthly time scales, while disease organisms are sensitive to precipitation patterns on shorter scales (Weltzin et al. 2003). Despite these complications, the general expectation is that the geographic distribution of some pathogens will broaden under climate change as conditions for them become favorable, leading to more frequent and extensive disease outbreaks. Tracking actual changes (rather than relying on models) will be important. It is difficult to predict the direction and location of the spread of specific diseases that depend so much on specific weather events that can happen under many different climate change scenarios. New diseases may occur or become more prevalent while others less so. Woods et al. (2005) have already published this kind of evidence relative to an increase in lodgepole pine (*Pinus contorta*) mortality in north-central British Columbia from a native disease, Dothistroma needle blight caused by the fungus *Dothistroma septosporum*. Changes in pathogen distribution, incidence, and impact may be used as climate change indicators. Tracking such changes should allow early intervention to minimize spread and impact, and accounting for likely changes in harvestable timber supply.

Table 3. Indicators for natural disturbances.

DIMENSION	INDICATOR[a]	SENSITIVITY[b]	FEASIBILITY[c]	KEY CONSIDERATIONS
Extreme weather	*Windthrow extent, type (landscape or stand), frequency, and timing*	M	M	- Wind, hail, and ice storms can have significant effects on forests and are sensitive to climate change. - EC and other agencies track wind at climate stations but measurements of wind and its impacts on forests are limited to research projects at a few sites. Many companies track wind damage so that timber can be salvaged but do not necessarily report it. Some provinces conduct aerial surveys that would detect large areas of windthrow. - Stand-level windthrow is influenced by many factors other than weather or climate. Landscape-level windthrow studies have more potential to link to climate trends, especially if done in areas not disturbed by humans. Even so, trends in relatively rare extreme events (such as windthrow) take long time periods to detect changes or ascribe causation. - **Jurisdictions**: Many jurisdictions of the world measure wind but few reported on wind damage systematically. The European Forest Institute has compiled a database of forest disturbances in Europe (Schelhaas et al. 2003).
	Extent and severity of damage to forests by hail and ice storms	M	M	
	Extent and severity of damage to forests by drought	H	M	
	Damage by unseasonal frost	H	M	
Forest fire	**Area burned/fire size**	M	H	- Fire is measurable, sensitive to climate change, and has significant impacts on forest resources and forest-dependent communities. - Most measurements of fire in Canada are done by provincial and territorial natural resource agencies. - It should be relatively easy to track trends using a data set of large fires dating from 1959. - Fire, as for any stochastic disturbance, will be difficult to relate to a climate change signal, rather than weather events or other influences (harvest, suppression, insects, fuel treatment, etc.). - The Canadian Wildland Fire Information System provides daily national maps of FWI codes based on spatial interpolation of weather data across Canada. Similar systems are operated by provincial fire management agencies. - **Jurisdictions**: Fire starts (frequency) and extent (area burned) are generally reported annually; some jurisdictions measure fire severity, which can also be assessed by remote sensing.
	Fire severity/intensity	H	L	
	Number of fires	H	M	
	Fire timing/season	H	H	
	FWI System components (see also Climate Drivers)	H	M	
	Fuel consumption, depth of burn, fire frequency	M	L	
	Emissions of CO_2, other greenhouse gases, and smoke from wildfires. See also Human health	M	L	
	Hotspot counts (as detected and reported daily by the Moderate Resolution Imaging Spectroradiometer) and length of period during which fire is present	M	H	

[a] Regular font indicators are from the workshops, italic indicators are from the scan, bold indicators are from both the workshops and the scan.
[b] Sensitivity of indicator to climate change: High (H), Medium (M), Low (L).
[c] Feasibility of measuring in a regional or national tracking program: High (H), Medium (M), Low (L).

(*Continued*)

Table 3. (*Concluded*)

DIMENSION	INDICATOR[a]	SENSITIVITY[b]	FEASIBILITY[c]	KEY CONSIDERATIONS
Forest insect outbreaks	**Changes in the distribution, frequency, and severity of outbreaks for major forest insect species having a long record of insect surveys, e.g., eastern spruce budworm (*Choristoneura fumiferana*), forest tent caterpillar (*Malacosoma disstria*), bark beetles.** See also Range shifts in key animal taxa	H	M	- Insects are highly sensitive to climate with the ability to impact large areas of forest with serious economic implications. - The CFS historically conducted annual insect and disease surveys nationally; since the late 1990s they have been conducted by the provinces (e.g., Westfall and Ebata 2010). - NFI photo plots have an insect-damaged layer; species not identified. - Interactions among different types of natural disturbances such as fire and insects (Fleming et al. 2002), and cumulative impacts of natural disturbance regimes, abiotic factors, and land-use changes should be considered. - **Jurisdictions**: Almost all jurisdictions measured or discussed insect damage and outbreaks (see Appendix 1), but measurement protocols and standards are highly variable. Internationally, there are notable examples of well-developed programs for monitoring forest health (e.g., the US Forest Inventory and Analysis National Program and the National Forest Health Monitoring Program; the European International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests). Research and monitoring in this area have been ongoing strengths of the CFS.
	Extent of insect attack by species and host (particularly for bark beetles and defoliators, but also for new alien species or other species)	H	M	
	Attack severity	M	L	
	Attack timing	M	M	
	Frequency of attack	M	M	
	Asynchrony (insect to host tree; timing of overwinter life stages, etc.)	M	L	
	Annual mapping of defoliation and mortality. See also Mortality	H	M	
	Assessment of insect impacts through plot-based assessments and tree-ring analysis. See also Growth	M	M	
	Voltinism of pest species. See also Insect phenology	M	L	
Pathogens	**Extent of infections by species and host**	H	M	- Diseases are sensitive to climate with the ability to impact moderately large areas of forest with serious economic implications. - The CFS historically undertook insect and disease surveys; in BC they are continued by the province (e.g., Westfall and Ebata 2010). Other provinces may have similar programs. - Historical distribution and outbreak data would allow assessment of distribution changes and disease outbreak frequency over time. - **Jurisdictions**: Many jurisdictions measure or discuss pathogen extents and damage.
	Infection severity	H	M	
	Infection timing	H	M	
	Frequency of infection	H	M	
	Significant changes in tree mortality and volume losses caused by native pathogens. See also Mortality	H	M	
	Changes in pathogen distribution (e.g., the fungus *Phellinus tremulae* on aspen) and incidence (rusts, Dothistroma needle blight, the fungus *Armillaria ostoyae*)	H	M	
	Degree of damage to the host (e.g., Host Damage Rating, Edwards 1991)	H	L	

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[b] Sensitivity of indicator to climate change: High (H), Medium (M), Low (L).
[c] Feasibility of measuring in a regional or national tracking program: High (H), Medium (M), Low (L).

SPECIES PHENOLOGY

What is species phenology and how is it organized?

The focus of this category is climate effects on the phenology (i.e., the timing of seasonal biological events) of plants (both trees and understory) and animals (primarily birds, but also other vertebrates and insects) (Table 4).

Why is species phenology relevant to climate change?

The timing of recurring seasonal biological events in the development of organisms (Cleland et al. 2007) is expected to change with changing climates, particularly with warming temperatures. These distinct events include phenomena such as bud burst, plant flowering, insect overwintering period and emergence, and the timing of bird migration and reproduction (Parmesan 2006; Morisette et al. 2009; Forrest et al. 2010). Phenological shifts can have major implications for frost susceptibility, reproductive ability, intra- and interspecific relationships, and species distributions (Morin et al. 2009; Chuine 2010). The northern limit of many temperate and boreal plants species' ranges is determined mainly by the inability to undergo full fruit maturation, whereas the southern limit appears to be caused by the inability to flower or unfold leaves owing to a lack of chilling temperatures that are necessary to break bud dormancy (Chuine 2010). While some species will face new abiotic or biotic stresses because of changing phenology, others may benefit from new opportunities to expand their range or increase their dominance. Species that depend on phenological synchrony for specific aspects of their life cycle or that rely on asynchrony, for example, to escape herbivory (Parmesan 2007; Singer and Parmesan 2010) may be affected by phenological changes resulting from climate change.

How will climate change affect species phenology and how can these effects be measured?

There is growing evidence that the timing of seasonal activities has already changed because of a warming climate (Parmesan and Yohe 2003). Changing temperatures are the main phenological driver. A meta-analysis of plant phenology in Europe revealed that fruit ripening of both wild and cultivated species was advanced for 75% of all recorded species from 1971 to 2000 and that it was directly attributed to an increase in temperature (Menzel et al. 2006). Temperature changes affect the dates of cues that initiate phenological events, for example, for seasonal migration in bird species, or they may directly alter rates of biochemical processes, which in turn will impact organism growth, reproduction, and dispersal (Réale et al. 2003; Cleland et al. 2007; Jepsen et al. 2011).

However, although many phenological responses are triggered principally by temperature, others are more responsive to day length (Menzel et al. 2006) and still others are also affected by precipitation.

Tree phenology

One of the first signs of climate change effects on forest ecosystems will be phenological changes in trees (Cleland et al. 2007). The phenology of reproduction and development stages (e.g., from flowering and pollen shedding to seed production and maturation, or from bud flush to leaf senescence) is influenced by climatic conditions of the current and previous years. Most northern tree species flush in the spring in response to degree-days above species-specific thresholds in air temperature, so spring flush dates are days to weeks earlier with warmer temperatures. Generally, climate records from the last 100 years or more show that growing seasons have lengthened significantly throughout Canada. Bud burst in sugar maple (*Acer saccharum*) and the flowering of aspen are occurring earlier in the year (Johnston et al. 2009). In temperate forests with significantly longer growing seasons, earlier leaf unfolding (timing of bud burst) and a delay in leaf senescence (timing of bud set) have been observed (Peñuelas et al. 2009). For many species, the occurrence of cold nights after the onset of the phenological spring is very significant. Cold injury may occur if growth is initiated too early in spring or continues too late in summer or early fall (Aitken et al. 2008). Frequent episodes of winter thaw and late spring frost have led to widespread tree crown dieback in yellow birch throughout eastern Canada (Bourque et al. 2005). The predicted patterns of climate change for northern tree species will likely have beneficial effects on reproduction in some parts of species' ranges, at least initially, but as temperatures increase, the beneficial effects of warming (and elevated CO_2) may diminish (Johnston et al. 2009). While advancing trends in seasonal events will continue as climate warming increases in the years and decades to come, it is uncertain how different species will respond when temperature thresholds

Two stages of white spruce (*Picea glauca*) apical bud break: (*left*) stage 4, translucent bud; (*right*) stage 5, split bud. (Dhont et al. 2010)

are reached and whether linear relationships between temperature and growing season will be realized. Reproduction and development phenophases (e.g., bud burst, flowering, seed maturation, leaf out, etc.) can be used as predictors of the potential for changes in tree distribution as the climate changes (Chuine and Beaubien 2001). Monitoring crucial phenophases in representative tree species would help predict the potential climate change effects on forest ecosystems.

Understory phenology (vascular plants and fungi)

Typical plant phenology indicators are first bloom date and first leaf date. The first leaf date is particularly important ecologically as it often displays the strongest response to temperature change, and is crucial for accurate assessment of processes related to the start and duration of the growing season (Schwartz et al. 2006). In the same way as for trees, a general warming trend will lengthen the growing season and result in early flowering for many plant species. Changes in temperature, winter chill, snowmelt, and growing season affect growth, bud burst, leaf senescence, and hardening in fall. Further winter warming could lead to the untimely start of plant growth in late winters or early springs, with increased danger of frost damage. The European Environment Agency (EEA 2008) noted that the timing of seasonal events in plants is changing across Europe, due mainly to changes in climate conditions; 78% of leaf unfolding and flowering records show advancing trends and only 3% show a significant delay. Date of snowmelt at high altitudes, which initiates the growing season, has had important repercussions for some common perennial herbaceous wildflower species (Inouye 2008).

Several understory species such as spring ephemerals, small-fruit species, and edible mushrooms are sensitive to climate conditions and thus can be appropriate indicators of phenological changes induced by climate changes (Lapointe 2001; Flinn and Vellend 2005; Aubin et al. 2007). Due to their high synchrony with soil thaw and tree leaf emergence, spring ephemerals might be particularly sensitive to climate change, with a significantly earlier blooming of two to three days per 1°C increase in mean spring temperature observed for this group of species in Quebec (Houle 2007). A program called PlantWatch (Beaubien 1997; Beaubien and Hamann 2011) has found that flowering dates of key perennial plants in Alberta are closely related to the average temperature two months before bloom, and a 26-day shift to earlier onset of spring has already occurred there over the past century (Beaubien and Freeland 2000). The spring flowering index derived from PlantWatch data was correlated with Pacific sea-surface temperatures, including El Niño events (Sauchyn and Kulshreshtha 2008).

Fungus growth and the development of fungal fruiting bodies are very sensitive to temperature and moisture (i.e., increased temperature results in increased growth; decreased moisture results in decreased growth). Long-term records of the period of fungal sporocarp (fruiting bodies such as mushrooms) production and the patterns of fruiting body production (e.g., once or twice a year) might indicate climate changes, especially temperature. Changes in the fungal species phenology could have economic consequences for the use and trade of these products. The timing and yields of wild foods such as mushrooms and berries are obviously of socioeconomic importance (see Human Dimensions Related to Forests).

Animal phenology (birds and other vertebrates)

Animal phenology is strongly influenced by variations in temperature, and thus climate change may affect their behavior, distribution, and ultimately their productivity and mortality rates. In many areas of the world, spring events in the animal world have been happening earlier over the last 30 years (Parmesan and Yohe 2003; Menzel et al. 2006; EEA 2010). Birds have advanced their migration timing, frogs call earlier, and hibernation patterns have changed. In some cases the observed changes do not match changes in prey species, which has led to an asynchrony between the demand for food and its availability (Visser et al. 2004; Visser and Both 2005). Mammals may emerge or migrate before or after their plant food supply has bloomed.

The timing of avian spring migration is the phenological trait with the largest body of data for vertebrate animals (Visser et al. 2004; Jonzen 2007). Yet, despite strong evidence for an advancement of spring passage and arrival, there is still very limited understanding of the mechanisms underlying the phenotypic changes observed. It is well known that birds respond to day length and to local climatic (e.g., air temperature, precipitation, wind, etc.) and biotic variables (plant and insect phenology) (Visser et al. 2010). These variables are conditional cues to the initiation of spring and fall migration and breeding activities. Atypical annual fluctuations of these variables can directly affect birds' fitness. However, many changes in avian abundance and distribution are not due to climate change (Kessel and Gibson 1994). These include population declines among some species of long-distance migrants that may be due to habitat changes (including anthropogenic ones such as deforestation) on distant wintering grounds. The nonmigratory behavior of amphibians is likely to make them more closely correlated to local climate phenomena.

Insect phenology

Although other insect groups (e.g., ground beetles (Carabidae)) are important components of forest biodiversity and ecosystem function, the focus here is insects that are forest pests. Temperature directly affects development, survival, range, and abundance of insect herbivores. In northern latitudes, temperature is the key variable that determines winter survival. Higher temperatures increase the available thermal budget for growth, survival, and reproduction (Bale et al. 2002). Therefore, the number of generations (i.e., voltinism) an insect species can complete in a year is directly related to temperature. For instance, species such as a common wood-boring beetle, the whitespotted sawyer (*Monochamus scutellatus*), have different phenologies based on their location (i.e., one to two years in the south and two to three years in the north). For some insect pests, if voltinism increases because of climate change, the intensity of outbreaks will increase. Increases in temperature may enhance metabolic rates of insects, may shorten the time required for hatching, and accelerate larval development which could strongly influence the period of insect flight. Evaluating changes in timing of insect flight could help detect and indicate climate changes. This information is needed to evaluate host–pathogen synchronization which would help determine periods of insecticide spraying, for example. Not all climate change effects will increase insect pest damage. For example, insects are expected to pass through their juvenile stages at a faster rate, perhaps resulting in smaller body size and mismatches with host phenology (Parmesan 2006). Also, changes in development may mean that some insect pests could enter winter periods with insufficient energy reserves to survive extended cold periods.

Table 4. Indicators for species phenology.

DIMENSION	INDICATOR[a]	SENSITIVITY[b]	FEASIBILITY[c]	KEY CONSIDERATIONS
Tree phenology	**Bud burst** (especially in angiosperms)	H	M	- Phenological changes are highly sensitive to climate change and many can be measured. Knowledge of changes in climate drivers will be necessary to ascertain cause and effect. - The timing of these phenomena within a given population can be characterized in terms of the beginning, peak, and end of the process. - Some tree phenology measurements are easily recorded and can be done by volunteer networks; currently phenological changes are reported by volunteers such as PlantWatch (http://www.naturewatch.ca/english/plantwatch/) (see Miller-Rushing and Primack 2008 for use of volunteers) and the Ecological Monitoring and Assessment Network. However, a national phenological network supported by detailed and standardized protocols would be essential. Phenological measurements could be organized by or added to responsibilities of the CFS or other agencies. - Other sources of information include web-based surveys for provincial staff and citizen scientists, literature searches, provincial seed orchard records, maple syrup producers, and The Weather Network pollen forecasts and web cams at Fluxnet sites (also known as the Canadian Carbon Program http://fluxnet.ccrp.ec.gc.ca/) and national parks. - Uncovering phenological trends requires many years of measurement. There is already an established multidecadal tree phenology database. As well, sampling needs to be at a landscape level and should cover north to south variation in populations. - There are many indirect means of measuring phenological changes, e.g., digital cameras, remote sensing, and plot-based observations. - Established provenance trial experiments for numerous commercial species can be easily measured. Model species such as white spruce (*Picea glauca*) and balsam poplar (*Populus balsamifera*) could be studied more intensively because they are representative of gymnosperms and angiosperms, respectively, that are distributed across Canada, and are the subjects of many common garden and provenance trials. - Records from mycological societies and/or herbaria may contain phenological details on vascular plants and mushrooms. - **Jurisdictions**: Most jurisdictions suggest tracking plant phenology.
	Timing of fall color	H	H	
	Period of maple sap production. See also Human Dimensions Related to Forests	H	H	
	Timing of pollen shed	H	M	
	Timing of male bud formation Timing of female bud formation	H	M	
	Timing of leaf senescence	H	M	
	Timing of bud set (especially in conifers)	H	M	
	Timing of seed maturation	H	M	
	Timing of indeterminate shoot growth and growth cessation	H	L	
	Date of first leaf	H	H	
	Date of first flower; timing of peak flower abundance	H	M	
	Frost damage to trees and regeneration. See also Human Dimensions Related to Forests	H	M	
	Growing season start (and finish)	H	M	
Understory phenology	**Date of spring ephemeral leaf emergence**	H	L	
	Date of spring ephemeral flowering	H	M	
	Date of flowering peak	M	L	
	Date of spring ephemeral senescence	H	M	
	Date of blueberry picking (mature fruits). See also Human Dimensions Related to Forests	H	M	
	Period and patterns (number of periods per year) of fungal sporocarp production	M	L	
	Dates of harvesting and biomass of edible mushrooms, related to the period of fruitbody production. See also Human Dimensions Related to Forests	M	M	

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[b] Sensitivity of indicator to climate change: High (H), Medium (M), Low (L).
[c] Feasibility of measuring in a regional or national tracking program: High (H), Medium (M), Low (L).

(*Continued*)

Table 4. (*Concluded*)

DIMENSION	INDICATOR[a]	SENSITIVITY[b]	FEASIBILITY[c]	KEY CONSIDERATIONS
Animal phenology	**Timing of migratory bird first appearance and arrival on territory across the landscape (north to south and east to west)**	H	H	- Currently, phenological changes in animals are reported by volunteers (breeding bird counts, FrogWatch) and by some agencies (Ducks Unlimited) but could be organized by or added to the responsibilities of the Canadian Wildlife Service (CWS) or other agencies. - Large-scale and long-term bird population data are largely available from existing resources, programs, agencies, and jurisdictions, including the Breeding Bird Survey (BBS) program; Atlas of the Breeding Birds of Ontario; Canadian federal (e.g., CWS), provincial/territorial (e.g., Ontario Ministry of Natural Resources), and municipal environmental agencies; US federal and state environmental agencies; natural history museums; universities and colleges; environmental societies, clubs, and groups; bird banding/monitoring centers/ observatories; and online migration monitoring networks. - Data on bird migration are available from the last 40 years or more; future timing measurements should be yearly, monthly, weekly, and daily to capture significant changes. - Future measurements on bird migration should be made at the regional scale in the boreal forest (differentiating east from west, because they differ in bird composition and subpopulations). - **Jurisdictions**: Only a few jurisdictions track animal phenology and usually only for a few selected species, for example, bird arrival and nesting times. Usually species of public interest such as swallows are selected. For forestry, selections of species might be different.
	Timing of territorial/ courtship displays (singing)	H	M	
	Timing of nest building	H	M	
	Timing of egg laying	H	M	
	Timing of fledging	H	M	
	Timing of migratory bird departure from territory	H	M	
	Synchronicity of bird activities to abiotic and biotic factors (e.g., air temperature; snow cover; ice cover; ground temperature; frost-free days; budding; leaf out; flowering; development of fruits, cones, and seeds; insect hatch dates and adult insect emergence dates)	H	L	
	Mammal migration timing and pattern	H	L	
	Hibernation timing/length (emergence dates)	H	L	
	Timing of frog calling	H	M	
Insect phenology	**Pest insect life cycle timing, voltinism.** See also Forest insect outbreaks	M	L	- Insect phenology is sensitive to climate change. - The CFS historically has tracked insect outbreaks and could look at timing. Some provinces also track extent of insects and have data on insect phenology. - In Canada, measurements should be done at the scale of the bioclimatic domain. - Indicators require many years of observations. Frequency of measurements needs to be quite high to ensure good resolution. - **Jurisdictions**: Few jurisdictions track insect phenology, although some examine butterfly arrival. More often damaging insects are tracked for extent of damage.
	Period of flight of saproxylic insects	M	L	
	Period of flight of lepidopteran species	H	M	
	Timing of egg hatching, larval or adult emergence	H	L	
	Butterflies (arrival)	H	M	
	Bee emergence	H	L	

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[b] Sensitivity of indicator to climate change: High (H), Medium (M), Low (L).
[c] Feasibility of measuring in a regional or national tracking program: High (H), Medium (M), Low (L).

SPECIES DISTRIBUTION AND ABUNDANCE

What are species distribution and abundance and how are they organized?

This category focuses on changes in the biogeographical distribution and abundance of plants (primarily trees but also herbaceous plants and fungi) and animal species in response to climate change (Table 5). Past studies of species distributional response to climate change have focused more on animals than plant or fungi species (Parmesan 2006; Lavergne et al. 2010). Here, we focus mainly on plants, given their key role in the forest sector, but also discuss animal taxa.

Why are species distribution and abundance relevant to climate change?

Climate exerts primary control over the biogeographic distribution of plants and animals (Parmesan 2006; Sexton et al. 2009; Willis and MacDonald 2011), and fossil records bear out marked redistributions in response to past climate changes (e.g., Delcourt and Delcourt 1988; Williams et al. 2004; Malanson et al. 2007). Recent, rapid climate change, however, will likely push many species beyond their natural tolerances and migration capacities (Parmesan 2006). Consequently, species will have to quickly adapt, move to more suitable climate space, or face extirpation (Millar et al. 2007). However, future species distributions will be determined not only by climate but also by many indirect and interacting factors (Corlett 2011), including alteration of natural disturbance patterns and site resources, human land use and other interventions, species demographic rates and dispersal capacities, species genetic adaptive potential, and interspecies interactions (Thuiller et al. 2008; Meier et al. 2012; Zarnetske et al. 2012).

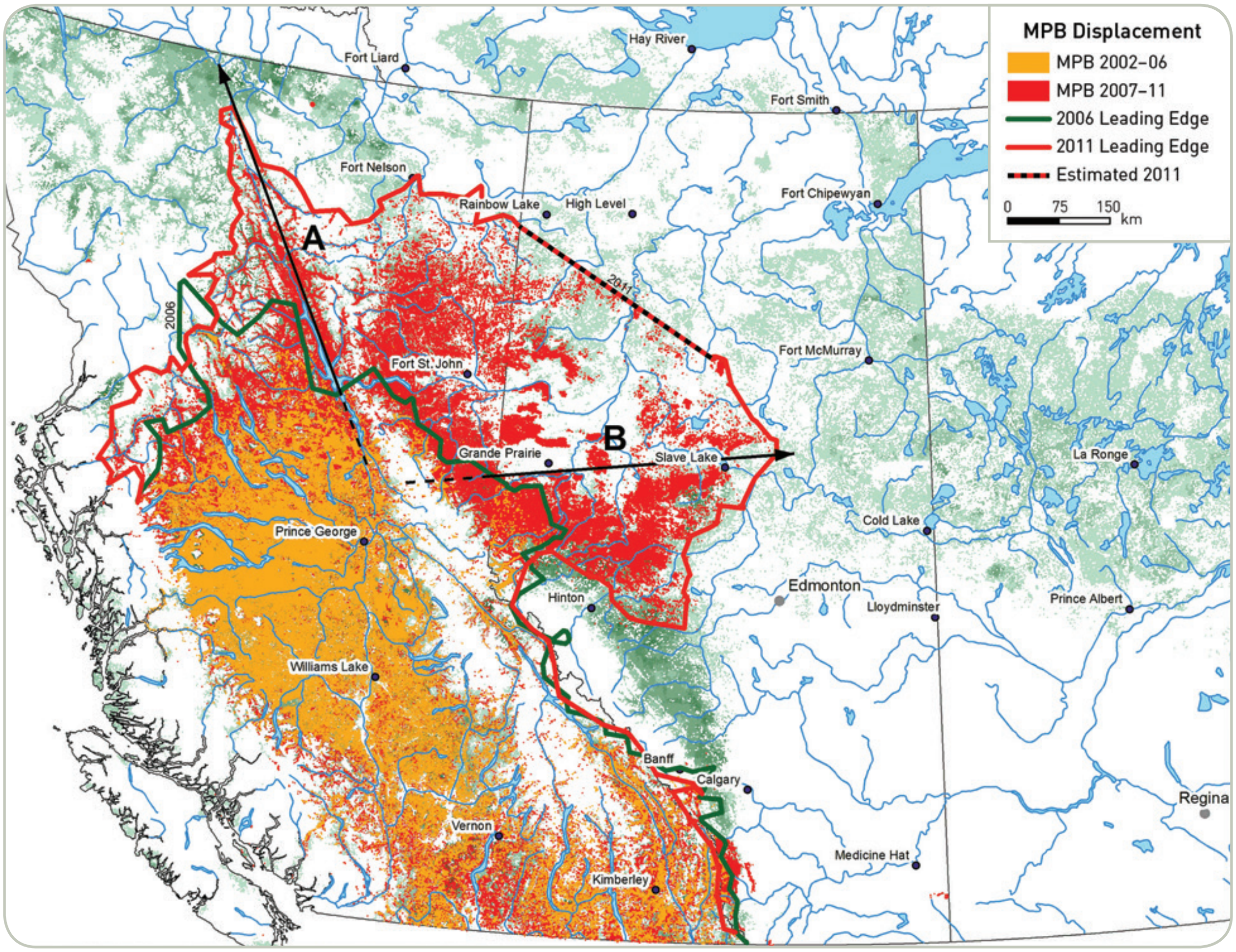
Changes in the distribution and abundance of plant and animal species across Canada will have major ramifications for society (Lemprière et al. 2008). For example, future range shifts of key commercial tree species will affect strategic forest management planning efforts and long-term wood supply (Steenberg et al. 2013); ecosystem function, including soil conditions (Seastedt et al. 2004); and even climate regulation (Bonan 2008; Shuman et al. 2011). Changes in animal distributions will alter key ecological services including pollination, seed dispersal, and pest control as well as influence local food gathering and recreational opportunities.

How will climate change affect species distribution and abundance and how can these effects be measured?

It is estimated that in the Northern Hemisphere, northern and upper elevational boundaries of plant and animals species have moved, on average, 6.1 km per decade northward or 6.1 m per decade upward over the past century (Parmesan and Yohe 2003). However, shifts in the distribution and abundance of plant and animal species are unlikely to occur uniformly, but rather change in a complex fashion, influenced by regional changes in climate variables, landscape heterogeneity, local disturbance regimes, and interspecies interactions (Harrison et al. 2010; Traill et al. 2010; Johnstone et al. 2011). Species are expected to be redistributed independently, leading to novel community assemblages and forest types for which we have no current analogue (Williams et al. 2004; Williams and Jackson 2007). Shifts in species will potentially change the character of whole communities and possibly desynchronize key species interactions, such as insect pollinators and flowering phenology (Tylianakis et al. 2008; Burrows et al. 2011; Zarnetske et al. 2012).

Range shifts in plants

Unlike most animal species, plants and fungi are primarily sessile organisms with limited capacity to move in response to climate change. Consequently, many plants will have to adjust to climate changes in situ, by acclimatization, genetic adaptation, or by shifting their distributional range via propagule dispersal. Generally, upward and poleward shifts of species, and entire vegetation communities, are expected under climatic warming, and considerable empirical evidence supports these broad predictions. Rousch (2009) observed that warming over the last 100 years has caused tree lines to shift upslope in the central Canadian Rockies. Tree lines have shifted northward in eastern Canada (Lescop-Sinclair and Payette 1995; McManus et al. 2012). Similar results have been observed globally (e.g., Soja et al. 2007). Cold temperatures are generally thought to limit the northward spread of many plant species, e.g., black spruce and balsam fir (*Abies balsamea*) (Meunier 2007). Faster warming at higher latitudes is expected to accelerate northern expansion. However, temperature is not the only control over tree species distribution (Malanson et al. 2007). Other factors including soil properties and species interactions are considered critical determinants of a species'



Mountain pine beetle (*Dendroctonus ponderosae*) displacement in western Canada from 2002 to 2011. (Nealis and Cooke 2014)

realized niche. For example, although northward treeline advancement has been observed across Canada's north, in parts of Alaska, this advancement has been relatively slow, partly due to dry soil conditions. Dry soils also prevent conifers from regenerating naturally following fire and other disturbances. This raises concerns that future climatic drying could lead to losses of forest cover along the southern edge of the boreal forest in western Canada (Hogg and Schwarz 1997). Recent studies suggest that tree mortality has already increased in response to climatic warming and recent droughts, especially in the Canadian Prairie provinces (Michaelian et al. 2011; Peng et al. 2011).

The distributions of most plant species in Canada are quite broad. Therefore, landscape-level monitoring of species absence and presence or abundance data will be necessary to detect potential shifts in species' ranges. As well, response to climate change is likely to be species-specific and will require species-level monitoring. Detectable changes in the distribution of some shorter-lived, widely-dispersed species may occur annually, while changes in longer-lived tree species may require decades before noticeable range shifts can be detected. Examining distributions of plants at high elevations, and at the northern and southern edges of their ranges, is key to revealing shifts in distributions. For many tree species, robust range maps, historical data, and georeferenced observations of tree species occurrence are available (e.g., McKenney et al. 2007b). Data concerning forest understory plant and fungi species are less plentiful. Increasingly, a wide variety of models are being developed to project future species distributions in response to climate change scenarios, from simple statistical models to more sophisticated mechanistic models (Elith and Leathwick 2009; Zimmermann 2010). The most basic and widely applied modeling method is the habitat suitability or climate envelope approach (Elith and Leathwick 2009; Lavergne et al. 2010; Araújo and Peterson 2012), which predicts future species distributions based on forecasted changes in suitable habitat conditions. Hamann and Wang (2006) used this approach to determine how present-day tree distributions might change in area, elevation, and spatial distribution in British Columbia. Species with their present northern range limit in British Columbia were predicted to gain potential habitat at a rate of at least 100 km per decade (e.g., Douglas-fir (*Pseudotsuga menziesii*), grand fir (*A. grandis*), and western redcedar (*Thuja plicata*)). However, some commercial conifer species (e.g., lodgepole pine) were expected to lose significant areas of suitable habitat, while most common hardwoods were unaffected (e.g., balsam poplar and mountain alder (*Alnus incana*)). Using a similar approach, Bourque and Hassan (2008) and Bourque et al. (2010) found that in Canada's Maritime provinces, several common boreal tree species (e.g., balsam fir and white birch (*B. papyrifera*)) will lose suitable habitat at their southern extent. Conversely, some temperate hardwood species, such as red oak (*Quercus rubra*) and sugar maple, will expand their northern range. This was also predicted by Steenberg et al. (2011) using a mechanistic landscape model, LANDIS-II.

Nonetheless, a major uncertainty inherent in many species distribution models, particularly those reliant on the climate envelope approach, is the extent to which species populations will actually track changes in habitat suitability (Lavergne et al. 2010). In fact, several modeling experiments testing more realistic species distribution approximations have found that many models underrepresent species dispersal constraints and grossly overestimate potential species migration rates (Engler and Guisan 2009; Meier et al. 2012). Natural migration rates, however, are not necessarily limiting. Increasingly, assisted migration (i.e., actively moving particular genotypes or species to climatically favorable locations beyond their current distribution) is being considered an adaptive forest management option to climate change (Ste-Marie et al. 2011). However, there remains much ethical and scientific debate over the usefulness and feasibility of such a strategy (Lavergne et al. 2010; Aubin et al. 2011; Zarnetske et al. 2012).

Range shifts in key animal taxa

Regional changes in temperature and precipitation will initiate range shifts in some populations of animals, particularly specialized species adapted to specific environmental conditions (Traill et al. 2010). A recent meta-analysis of species' range boundaries showed an overall significant shift northward for hundreds of species (Parmesan and Yohe 2003). In Canada, it is generally accepted that the range of most forest animal species will expand northward. However, as previously discussed for plant species, shifts in the distributions of animal species are unlikely to occur uniformly across the country, but rather change in a complex fashion (Tylianakis et al. 2008; Traill et al. 2010). Moreover, unlike plant species, animals are primarily mobile organisms that can run, swim, jump, or fly. This presents unique challenges for detecting shifts in animal species distributions. When considering specific taxa, birds are expected to migrate farther north (Berteaux et al. 2006), and some that usually migrate south may become resident. Physiological studies indicate that northern boundaries of North American songbirds are strongly limited by winter nighttime temperature (Root 1988; Burger 1998). In recent years, migratory bird species have been observed farther north than ever before, birds for which the Inuit have no historic names in their native languages.

Like birds, many mammal species are expected to move north. Alternatively, some mammals, such as polar bears (*Ursus maritimus*), are now reported to wander much farther south in search of food due to arctic sea ice loss, creating safety concerns in more southern communities (Stirling and Derocher 2012). Already, it is predicted that in the Western Hemisphere, 87% of mammalian species will experience reductions in range size due to loss of suitable climate space and dispersal limitations caused by human-induced habitat fragmentation (Schloss et al. 2012). Mammals are important study organisms for monitoring the ecological effects of climate change largely because they occupy most ecosystems across Canada and also because of their economic value, and because there are long-term data sets available describing fluctuations in numbers for many populations (Berteaux et al. 2006; Berteaux and Stenseth 2006). Climate change effects will also be felt by other vertebrates such as amphibians, reptiles, and fish (Pounds 2001; Parmesan and Yohe 2003). Desiccation of amphibians due to low snow cover in winter and subsequent drying of wetlands in summer may alter whole species distributions (Rodenhouse et al. 2009). Reptiles may benefit from warmer summers and actually expand their ranges (Kimmel 2009). Cold-water fish species (e.g., arctic char, *Salvelinus alpinus*) may shift their distributions in response to warming of cold-water tributaries (Catto 2010).

Several forest insect pest species have distributions known to be limited by temperature and, to a smaller extent, by host species' range (e.g., mountain pine beetle). With recent warming, many species are expanding their range northward, negatively affecting previously inaccessible timber resources and infesting new host organisms (Coops and Waring 2011; Régnière et al. 2012a). Similarly, some insects are carrying diseases with them as they move northward (e.g., human Lyme disease via deer ticks). Northward shifts of Lepidoptera (butterflies and moths) and Odonata (dragonflies and damselflies) have been well documented globally (Parmesan 2006).

Table 5. Indicators for species distribution and abundance.

DIMENSION	INDICATOR[a]	SENSITIVITY[b]	FEASIBILITY[c]	KEY CONSIDERATIONS
Range shifts in plants	Range maps of tree species	M	H	- Development of range maps should focus on those species most sensitive to climate change. - For many tree species, there are robust range maps currently available that can provide baseline measurements to compare historical and future trends. - Historical data, including archived aerial photography, satellite imagery, and permanent sample plots (PSPs), can be used to detect past trends in species distributions. - Detecting species' range shifts will require periodic measurements over potentially long time frames (10s to 100s of years). - Continent-wide, georeferenced observations of tree species occurrence are currently available (see http://planthardiness.gc.ca/; McKenney et al. 2007a). - Tree lines are visually distinctive, measurable, and sensitive to climate change; therefore they are potentially powerful indicators of climate change effects but will require long time frames to track changes. - The use of repeatedly taken satellite imagery and aerial photography will be key for tracking treeline shifts. - PSPs established along ecotonal boundaries could track shifts in community composition, including Canada's NFI ground plot program. - Forestry companies and governments have been collecting forest stand inventory data for over 50 years in many jurisdictions. - Tracking herbaceous plants and fungi species is typically not done by federal or provincial programs, but rather undertaken by specific academic research projects (e.g., Acadia University, http://botanicalgardens.acadiau.ca) or NGOs (e.g., conservation data centers, http://www.accdc.com/home.html), and naturalist and garden clubs (particularly for new and unfamiliar species). Integrating citizen science networks with formal government science programs could provide a robust monitoring system for detecting changes across Canada's forest landscape.
	Range maps of herbaceous plant and fungi species (including nonindigenous invasives)	M	L	
	Southern tree line to grassland boundaries	H	H	
	Northern tree line to tundra boundaries	H	H	
	Elevational treeline boundaries (lower to grassland, upper to alpine)	H	M	
	Relative abundance of plant community types over time (e.g., stand types)	L	H	
	New types of plant communities over time (i.e., novel community assemblages)	M	L	

[a] Regular font indicators are from the workshops, italic indicators are from the scan, bold indicators are from both the workshops and the scan.
[b] Sensitivity of indicator to climate change: High (H), Medium (M), Low (L).
[c] Feasibility of measuring in a regional or national tracking program: High (H), Medium (M), Low (L).

(*Continued*)

Table 5. (*Concluded*)

DIMENSION	INDICATOR[a]	SENSITIVITY[b]	FEASIBILITY[c]	KEY CONSIDERATIONS
Range shifts in key animal taxa	Range maps of key mammal species	M	M	- Animals vary greatly in their sensitivity, measurability, and relevance to climate change. Development of range maps should focus on taxa and species most sensitive to climate change. Large mammals may be less sensitive to short-term fluctuations in climate, but some insect populations may respond quite rapidly and demonstrate detectable shifts in range annually (Parmesan 2006). - Efforts to measure changes in animal ranges will require broad, landscape-level assessments, as many species have wide distributions across Canada. In particular, many migratory bird and insect species encompass large continent-wide distributions. These species are difficult to detect since they may be present in some areas for part of the year or only at endemic levels. Development of animal range maps must consider annual migratory patterns. - Given the mobility of most animals, their relatively short generation times, and their more immediate response to environmental change relative to plants, periodic reevaluation of range limits should occur every 5–10 years, depending on the animal taxa under consideration. - For some animal taxa, more unique monitoring techniques may be required to measure shifts in species' ranges. For example, small ephemeral or quasi-ephemeral wetlands, often cited as sensitive to climate change, provide essential habitat for a diverse array of animal species, including populations of amphibians that can be difficult to survey given their small size and seasonal presence. - Measurement of key animal species' ranges should focus on changes in northern (i.e., leading edge) and southern (i.e., trailing edge) boundary limits. - It may be easier to monitor mammal distributions on plains than in forests. - Various sources of absence and presence data for bird species already exist, including numerous, widespread networks of birders (e.g., BBS program), some supported by governments and NGOs. Many of these records coincide with annual weather indices (e.g., the Canadian National Fire Database), which may be useful in discriminating extraneous environmental factors and linking range shifts with climate change. - Annual aerial surveys of many forest insect pests have been conducted across Canada over the past 50 years, supported by provincial and federal governments. However, aerial surveys are of limited use since they capture primarily incidences of outbreaks and not endemic insect levels. - Aerial surveys may be supplemented with existing ground survey data and citizen science input to develop robust data sets of species' range changes over 1–5-year time intervals (e.g., the Biological Survey of Canada, biologicalsurvey.wordpress.com). - Citizen science networks represent a diverse and valuable means of monitoring animal species distributions (e.g., NatureWatch, http://www.naturewatch.ca/english/).
	Range maps of key bird species	M	H	
	Range maps of key reptile and amphibian species	M	M	
	Range maps of key fish species (cold-water and warm-water species)	L	L	
	Range maps of key insect species (for tracking insects that damage forests, see also Natural Disturbances)	H	H	
	Relative abundance of animal community types over time	L	L	
	New types of animal communities over time (i.e., novel community assemblages)	M	L	

[a] Regular font indicators are from the workshops, italic indicators are from the scan, bold indicators are from both the workshops and the scan.
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FOREST STAND DYNAMICS

What are forest stand dynamics and how are they organized?

This category focuses on climate-related effects on stand-level regeneration, growth, and mortality in Canada's forests. Other aspects of stand dynamics such as insect and disease disturbances are captured in other indicators. Three dimensions are considered in this category: regeneration; growth, and mortality.

Why are forest stand dynamics relevant to climate change?

Stand dynamics are influenced by many factors, including physical site conditions and processes, disturbance regimes, as well as biotic interactions such as forest pests and competition among trees for light, water, and nutrients. All of those factors are affected by climate change. Over time, stand dynamics change forest structure and function, including tree species composition, diversity, and biomass accumulation (Drake et al. 2011; Taylor and Chen 2011) which influence water, C and nutrient cycling, the availability of wildlife habitat, and the provision of goods and services for society. An understanding of stand dynamics in light of climate change is vitally important to maintain the ecological and social values of our forests and to determine the quality and quantity of wood products that can be sustainably harvested.

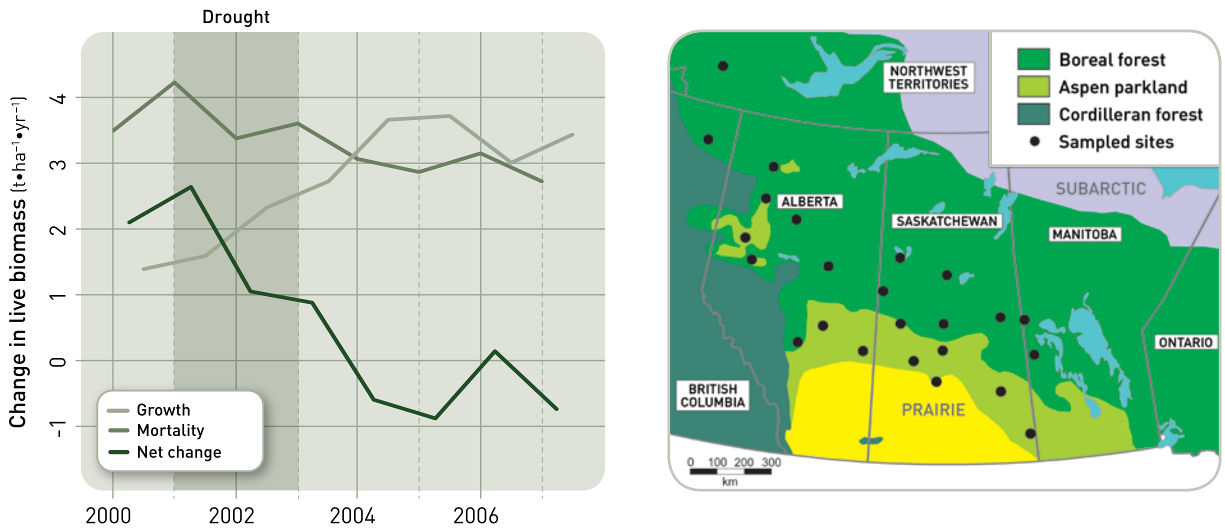
How will climate change affect forest stand dynamics and how can these effects be measured?

There is growing evidence that climate change is already having profound, large-scale effects on stand dynamics in southern portions of the Canadian boreal forest (Peng et al. 2011; Ma et al. 2012), in forests across the western United States (van Mantgem et al. 2009), and globally (Allen et al. 2010). To build a complete picture of climate-related effects on forest stand dynamics, there is a need to integrate information on changes in tree mortality with information on tree growth and regeneration across a wide range of spatial and temporal scales. Simulation models are often useful to integrate that information. In the past, the effects of climatic variation were rarely included in models used in forecasting forest growth and yield (wood fiber supply) and forest carbon cycling. But more recent models attempt to integrate climatic effects. One of the major challenges is that forest stand growth and productivity are highly influenced by multiple interacting ecosystem factors as stands age, including changes in the natural physiology of aging trees and successional changes in species composition and diversity (Binkley 2004; Drake et al. 2011; Paquette and Messier 2011). Discriminating these natural factors from climate change influences is critical in planning adaptive forest management practices and policies under a changing climate.

Regeneration

According to resilience theory, forests are most vulnerable to climate change effects immediately following stand-replacing disturbance during the regeneration stage of stand development (Johnstone et al. 2010). Seedbeds, seed production, and the establishment of seedlings or suckers are all influenced by climatic controls (e.g., temperature and moisture availability) and can therefore be affected by climate changes (Jasinski and Payette 2005; Moss and Hermanutz 2009). Mortality of seedlings and saplings is a likely consequence of severe drought, but quantitative estimates of how much seedling mortality might increase with climate change are lacking. In forest regions that experience drought, there is likely to be regeneration failure in dry years and a gradual reduction in tree cover and expansion of grassland or shrubland, especially on xeric sites and in climatically dry regions such as the Prairie provinces (Hogg and Schwarz 1997) and Yukon (Johnstone et al. 2010). Some herbaceous and shrub species that compete vigorously for light, moisture, and nutrients with tree regeneration (e.g., De Grandpré et al. 2000) may migrate northward as temperature increases and affect tree regeneration in new areas. Competition may also contribute to the transformation of closed forests to open woodlands (Jasinski and Payette 2005).

Managed forested areas are often regenerated by planting, thus seed and seedlings can be moved to areas potentially best suited for them, and regeneration is not necessarily limited by the natural limits on a species' ability to disperse and migrate. As discussed in Species Distribution and Abundance, assisted migration is a potentially useful but complicated endeavor with pros and cons to widespread implementation. Knowledge of frost, heat, and moisture stress events is important to select sites where assisted migration is likely to be most successful, and monitoring results is crucial to allow learning.



Annual net changes in trembling aspen (*Populus tremuloides*) biomass (growth gains minus mortality losses) during and following severe drought in the western Canadian interior. (Adapted from Hogg et al. 2008)

Growth

Climate change is affecting rates of photosynthesis and respiration of trees in Canada's forests, which ultimately affects C sequestration, biomass accumulation, and the supply of wood fiber for the forest sector. Positive effects of CO_2 on photosynthesis and water use are complicated by interactions with temperature, precipitation, and nutrients. They often differ when assessed for individual trees or forest stands, and vary as trees age (Körner 1993). However, despite the complications, some studies have documented increases in forest productivity in response to lengthening growing seasons, CO_2 fertilization, increases in nitrogen (N) deposition, and other factors (Boisvenue and Running 2006; Kirilenko and Sedjo 2007). On the other hand, forest productivity may be negatively affected in regions where climate change leads to more severe droughts and associated increases in damage by insects and diseases (e.g., Hogg et al. 2008). Also, growth responses are highly variable among species and site types (Girardin et al. 2012; Hember et al. 2012). For example, higher CO_2 concentrations have been found to increase the growth of various types of poplar (*Populus* spp.), but have little or no effect on the growth of Douglas-fir, aspen, and sugar maple (Johnstone et al. 2010). Species-specific effects may alter future stand composition and diversity by altering the competitive interactions between species or by affecting the relationships of some tree species with other organisms (e.g., mutualistic mycorrhizal interactions; Clark and St. Clair 2011; Thorpe et al. 2011). Growth responses to climate change also vary with site characteristics. Chen et al. (2002) showed that net primary productivity (NPP) on more productive sites culminates at a higher value and at an earlier age and also declines more rapidly thereafter. They also suggested that uncertainty in NPP estimates with climate change can be substantially reduced with a better quantification of fine-root turnover and litterfall. The variety of phenological responses to temperature and CO_2 shows how complicated it is to model growth and NPP with climate change, and underlines the importance of empirical tracking of actual responses.

Mortality

Often, the effects of CO_2 and temperature on growth are considered in isolation from the effects of reduced precipitation or drought. Drought can negate the positive effects of CO_2 and temperature by stressing trees, making them more susceptible to insects and pathogens. Mortality due to abiotic stresses (principally drought and fire) and biotic (insect and pathogen) interactions is also a function of climate, but may be highly confounded with other factors. The multiplicity and complexity of such interactions seriously question our ability to predict conditions through modeling only, and further suggest the need for an integrated modeling and monitoring approach spanning spatial scales from stand and management unit through the ecoregional level to nationally. Neither modeling nor monitoring activities considered alone would be adequate to address key issues relating to climate change, which are biophysically complex and long term.

Widespread increases in forest dieback and mortality, often readily visible from the air (e.g., Michaelian et al. 2011), have been documented following recent droughts and other climatic events (Allen et al. 2010). When episodic and patch-generating, such mortality events can be interpreted as part of the disturbance regime (see Natural Disturbances). Frequently, however, climate change effects are subtle and are reflected in gradual, longer-term increases in "background" tree mortality rates across large areas (e.g., Hogg et al. 2008; van Mantgem et al. 2009; Peng et al. 2011). One of the major challenges is that tree mortality often has multiple causes and is highly episodic and patchy, which poses challenges for tracking and determining causation (Morelli and Carr 2011). Seedlings are usually more sensitive to drought and high temperatures than older trees; therefore, as noted previously, regeneration success is an important early warning of climate-related stress. Once established, mature trees can persist in climates that are unsuitable for the establishment of new seedlings, creating the potential for a deceptive perception of the lack of climate change effects on forests over the short term.

Table 6. Indicators for stand dynamics.

DIMENSION	INDICATOR[a]	SENSITIVITY[b]	FEASIBILITY[c]	KEY CONSIDERATIONS
Regeneration	**Success and failure of natural forest regeneration postharvest and post disturbance**	M	M	- Regeneration is sensitive to climate change and highly relevant to future forest productivity. - Regeneration success or failure is relatively simple to assess. Those measures should be supplemented with observations that track the progress of plantations through the establishment phase. The planted crop tree may not be the best performer after 10 or 20 years. - Data on regeneration success and failure should be collected by management unit, and stratified by elevation, aspect, ecological unit, and species. Provincial governments and individual companies hold data. This could be done by light detection and ranging (LiDAR, a remote sensing technique) or derivative Semi-Global Matching (SGM) techniques. - Causes of regeneration failures should be noted where possible. - Information from assisted migration trials could be gathered (assuming provinces are monitoring their success). - Recording changes to the planting window is simple but requires cooperation of companies to record and report planting timing and reasons for scheduling changes. - Sample plots would need to be established to assess success of boreal vegetative regeneration if that is a key interest, because that indicator is not likely already assessed by any agency/group. - **Jurisdictions**: Although several jurisdictions suggest that regeneration may become a problem, to our knowledge, not all jurisdictions track regeneration success and there is no standardized protocol for data collection.
	Success and failures of assisted migration blocks (establishment rates)	M	M	
	Tree cone and seed crop production	M	M	
	Postdisturbance regeneration	M	M	
	Densities and distributions of competitive shrubs and herbs that limit tree regeneration and growth. See also Range shifts in key animal taxa	M	L	
	Change in frequency and abundance of sexual regeneration in boreal and subarctic trees	H	L	
	Planting timing	M	M	

[a] Regular font indicators are from the workshops, italic indicators are from the scan, bold indicators are from both the workshops and the scan.
[b] Sensitivity of indicator to climate change: High (H), Medium (M), Low (L).
[c] Feasibility of measuring in a regional or national tracking program: High (H), Medium (M), Low (L).

(*Continued*)

Table 6. (*Concluded*)

DIMENSION	INDICATOR[a]	SENSITIVITY[b]	FEASIBILITY[c]	KEY CONSIDERATIONS
Growth	*Tree growth (height, diameter at breast height, volume)*	M	H	- Growth, productivity, and mortality are sensitive to climate change and are of primary interest to the forest industry and Canada's economy. Growth also affects CO_2 sequestration, making it an important variable for national reporting in support of international climate change agreements. - Addressing this will require an integrated, multiscale approach that includes tracking changes from individual trees, ground plot measurements, forest inventories, and remote sensing (e.g., LiDAR or other SGM remote sensing). - Growth data are best collected using PSPs. Canada's NFI plots have similar potential as the US Forest Inventory and Analysis database and can track mortality, regeneration, growth, and volume. - Changes in GPP of forests can be based on satellite observations of greenness and modeling of light use efficiency, coupled with tower-based measurements. - Climate-related changes in tree productivity at the stand level can be measured from networks of ground plots and tree-ring studies coupled with allometric biomass equations. - Changes in the frequency of distinctive tree-ring characteristics may enable assessment of long-term changes in extreme climatic events (Girardin et al. 2009; Hoffer and Tardif 2009; Tardif et al. 2011), and/or insect defoliation (Hogg et al. 2002b). - Changes in tree crown architecture in response to climatic events such as drought are a potentially important factor leading to longer-term effects of climate on forest growth due to changes in the light-gathering capacity of tree canopies (Girard et al. 2011a; Girard et al. 2011b). - Changes in the nutrient levels of tree foliage may be influenced by climate, and lead to changes in tree photosynthesis rates (especially N). - Like trees, understory vegetation is sensitive to climate change. - Changes in understory growth will be difficult to link to climate due to confounding/complicating effects of changing overstory conditions. It will be difficult to distinguish change in understory due to climate from change due to normal successional trends or from changes due to grazing, etc. - Changes in grasslands would be easier to relate to climate than changes in understory herbs and shrubs, but still will be confounded by land use and grazing. - **Jurisdictions**: Almost all jurisdictions reported some measure of forest productivity. Often that measure, however, was just area of forest and amount of afforestation. Statistics on tree growth, productivity, or mortality were reported less commonly. Few reported on growth of understory shrubs and herbs. Exceptions were where ecotones from trees to shrubland and/or grasslands have been examined and progression of shrubs, trees, or grasses recorded.
	NPP of forests	M	M	
	Gross primary production (GPP) of forests	M	M	
	Aboveground tree productivity at the stand level	M	H	
	Total and commercial wood volumes produced in plantations and provenance trials	M	H	
	Distinctive tree-ring characteristics	M	M	
	Tree crown architecture	M	L	
	Nutrient levels of tree foliage. See also Edaphic Conditions and Processes	M	L	
	Understory cover over time (selected species of shrubs and herbs)	M	L	
	Densities and distributions of competitive shrubs and herbs that limit tree regeneration and growth. See also Range shifts in plants	M	L	
Mortality	**Tree mortality (percentage of stems dying per year)**	M	M	- Tree mortality is routinely measured in PSPs and other long-term monitoring studies. - Determining the role of climate change in mortality may be difficult. - Climate-driven stand-level changes in mortality and biomass can be assessed through plot-based tree measurements and allometric biomass equations, coupled with analyses of climate drivers and history of disturbance. - Aerial surveys and remote sensing can be used to map the extent of dieback and mortality episodes when severity exceeds the detection threshold (typically about 20% dead). - Records from provincial governments and industry can also provide information on seedling and sapling mortality.
	Tree dieback (percentage of crown with dead branches on living trees)	M	M	
	Mortality losses of tree biomass within stands	M	M	
	Seedling and sapling mortality in regenerating and managed stands. See also Natural Disturbances	M	M	

[a] Regular font indicators are from the workshops, italic indicators are from the scan, bold indicators are from both the workshops and the scan.
[b] Sensitivity of indicator to climate change: High (H), Medium (M), Low (L).
[c] Feasibility of measuring in a regional or national tracking program: High (H), Medium (M), Low (L).

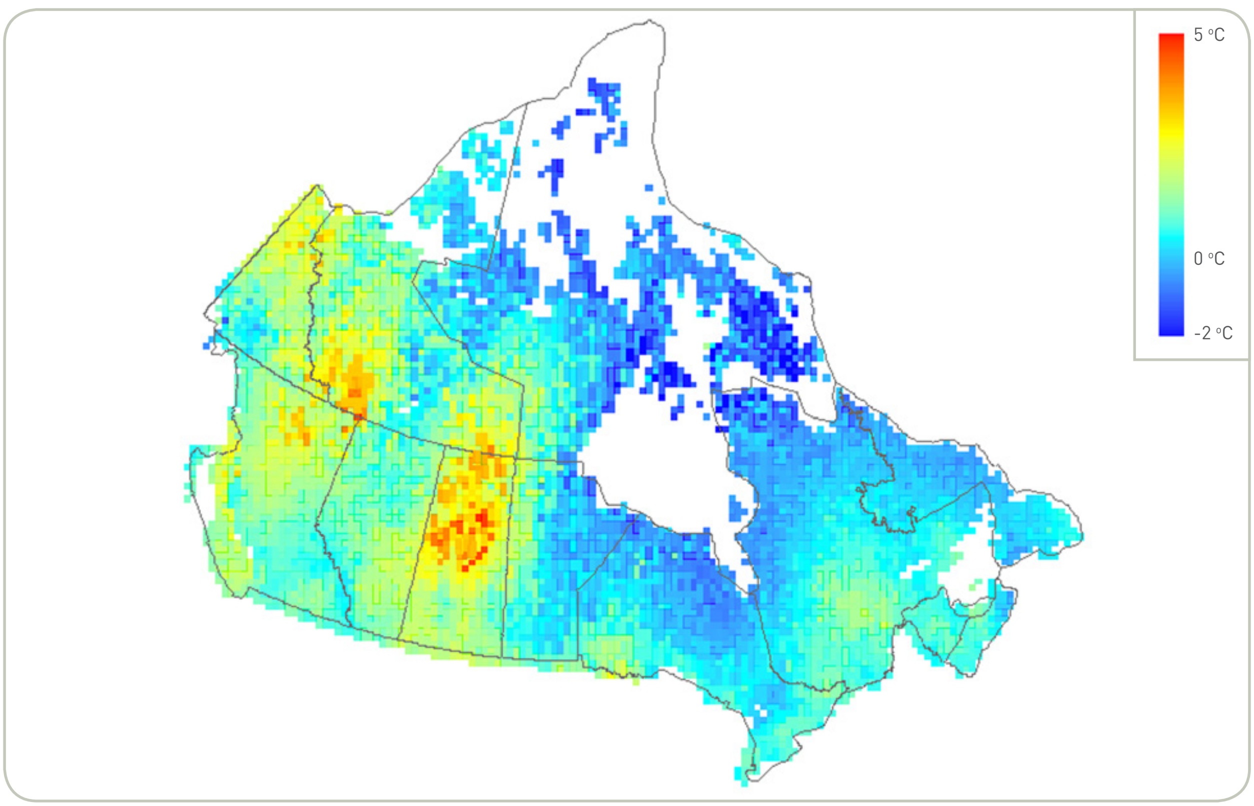
EDAPHIC CONDITIONS AND PROCESSES

What are edaphic conditions and processes and how are they organized?

Edaphic conditions and processes refer to the soil biotic and abiotic structure and function. Soil is a complex assemblage of geological materials, dead organic matter, living roots, animals and microbes, soil water, and soil atmosphere. It is influenced by the nature of parent material, its topographic position, the climate, the vegetation it supports, the other biota, and the conditions of development (Kimmins 2003). Three dimensions are considered under this category: soil temperature and moisture, soil biological components, and dead organic matter production and decomposition (Table 7).

Why are edaphic conditions and processes relevant to climate change?

Climate change will likely influence the biological, physical, and chemical processes that occur in soils (Paul 2007). Yet, soils provide the physical and chemical conditions necessary for plant life and consequently for most forms of animal and microbial life (Trumbore 2000). Soils are a major determinant of the productive potential of forests. Soil properties control the fate of water in the hydrologic system (Brady and Weil 1999); forest evapotranspiration plays an important role in controlling water and energy balance in ecosystems (Govind et al. 2011). Changes in soil C content with global warming can have a significant effect on the global C budget (Trumbore et al. 1996). Indeed, soils contain a stock of C about twice as large as that in the atmosphere and about three times that in vegetation (IPCC 2001) and even a small change in CO_2 efflux (or soil respiration) could exceed the annual input of CO_2 to the atmosphere via land-use changes or fossil fuel combustion (Rustad et al. 2000). Hence, in addition to responding to climate change, soils could also play an important role in C sequestration and climate mitigation (e.g., Lal 2004).



Changes in the annual mean simulated soil temperature at 20-cm depth during the 20th century. (Adapted from Zhang et al. 2005)

How will climate change affect edaphic conditions and processes and how can these effects be measured?

Changes in temperature and precipitation will affect the activity of roots and soil biota, decomposition rates, and nutrient and water uptake. Despite the relatively robust literature on the response of individual edaphic conditions and processes to climate change, it is not clear which processes will be most affected by warming and by changes in precipitation patterns. For example, increasing temperature will result in greater soil respiration (e.g., Peterjohn et al. 1993; McHale et al. 1998), which is the largest source of CO_2 from terrestrial ecosystems. At the same time, an increase in soil respiration is likely related to an increase in soil microbial activity and in nutrient mineralization. An increase in nutrient availability by this nutrient mineralization may enhance plant growth, which may increase C sequestration (Melillo et al. 1993). Soil C changes driven by future climate change may thus range from small losses to moderate gains and will likely show regional variation (Arnell et al. 2013; Gottschalk et al. 2012).

Soil temperature and moisture

Projected increases in temperature will influence soil temperature, which is partly affected by meteorological conditions (Zhang et al. 2005). As for precipitation regimes, the expected increase in severe drought and flood events will likely affect soil moisture regimes regionally. Moreover, soil temperature affects soil drying by evaporation. Both soil temperature and soil moisture have an important influence on a wide range of soil and plant processes, such as soil respiration, decomposition rates, and other microbially mediated transformations (Bonan and Van Cleve 1991; MacDonald et al. 1995).

Soil biological components

Current projections of increased soil temperature will likely affect root growth both directly through its effect on physiological activity, or indirectly through its effect on soil microbial interactions, and the likely increase in soil nutrient mineralization (Rustad et al. 2001) and plant nutrient availability (Trumbore 2000). Indeed, soil temperature and moisture strongly influence microbial communities (Davidson et al. 2006). Rustad et al. (2001) found that a mean experimental increase in soil temperature of 2.4°C across 32 studies enhanced soil respiration by a mean of 20%, whereas net N mineralization rates increased by an average of 46%. Increased root growth may enhance nutrient cycling, and increase root and microbe respiration rates (Schlessinger and Andrews 2000). Higher temperatures can increase N availability through enhanced turnover of soil N, which can result in an increase in C sequestration (Melillo et al. 1993). According to Sullivan et al. (2008), areas experiencing significant increases in NPP can be important C sinks, despite increases in soil respiration. Temperature, precipitation, and CO_2 enrichment can also affect soil biota directly. Warming and increased precipitation, for example, can directly stimulate soil microbial activity (Fierer and Schimel 2002). Blankinship et al. (2011) showed that colder and drier conditions reduced soil biota abundance. Although it is widely recognized that available moisture exerts a significant influence on soil microbial activity (Paul and Clark 1996), there have been fewer studies assessing the direct effect of changing rainfall patterns on soil processes (e.g., Emmett et al. 2004). Since soil temperature affects soil drying by evaporation, most studies address soil moisture as an explanation for the lack of response of soil processes to increasing temperature (e.g., Peterjohn et al. 1994; Robinson et al. 1995). Smith et al. (2005) suggest that despite large temperature increases, dry conditions may slow soil organic matter decomposition rates. Moreover, prolonged periods of waterlogging, especially in warm conditions, can lead to anaerobic conditions with impacts on soil chemistry and soil biological activity (e.g., Kozlowski 1986).

Dead organic matter production and decomposition

Decomposition in soils is strongly influenced by soil microbial communities (Göttlicher et al. 2006; Monson et al. 2006). Yet, as stated previously, the temperature of forest soils is a major determinant of microbial processes. McHale et al. (1998) found an increase in litter decomposition with soil temperature increases (temperatures ranging from 2.5 to 7.5°C at 5-cm depth). Moreover, increased root growth as a consequence of increased mineralization rates generates more C belowground, which can help accelerate decomposition (Schlessinger and Andrews 2000). Higher decomposition means higher C turnover in soils, which would decrease C stored as organic matter. However, the decomposition rate may be slowed due to dry conditions. In some European regions, for example, where the future climate is projected to dry, the decomposition rate is expected to be slower, despite increases in soil temperature (Smith et al. 2005).

Table 7. Indicators for the edaphic conditions and processes.

DIMENSION	INDICATOR[a]	SENSITIVITY[b]	FEASIBILITY[c]	KEY CONSIDERATIONS
Soil temperature and moisture	Soil temperature	H	M	- Soils will be affected by climate change, but teasing out those effects will be difficult. - It is difficult to examine causes for changes in soils. Moreover, soil spatial variability can be significant. Therefore, various forest types located in different climatic regions and soil conditions should be sampled and appropriate statistical replicates must be planned. - Use plot-level studies stratified by areas of interest and then extend to landscape and regional scales. - Soil temperature could be measured at various depths along toposequences. Data could be compared to Fluxnet and ECOLEAP (the Extended Collaboration to Link Ecophysiology and Forest Productivity) sites. - Soil moisture within the tree rooting zone (commonly 1–2-m soil depth) is a key indicator of drought effects on forests but multiyear data sets are currently limited to a few sites (e.g., Fluxnet Canada tower sites; Bernier et al. 2006; Zha et al. 2010). See also soil moisture index models (Table 1). - Litter production measurements could be done through the National Network of Latitudinal Transects, the Climate Information for Public Health Action program, and other research programs. The Canadian Intersite Decomposition Experiment could provide standardized materials and methods. - Although currently not readily available, remote sensing (e.g., synthetic aperture radar) is a promising approach to provide a more practical means of monitoring key edaphic attributes. - **Jurisdictions**: Few (see Appendix 1) reported any soil indicators aside from erosion concerns. A few track some biochemical cycling, and sometimes soil condition is noted as a concern. In Europe, the European Environment Agency recognized soil as a monitoring gap and suggested soil erosion, soil water-holding capacity, and soil organic C as new indicators. China examines soils for its role in CO_2 cycles. Some jurisdictions report C storage as a concern. None actually tracked changes in nutrient levels, temperature, or water-holding capacity. None used or discussed mycorrhizae as soil condition indicators. No reports from jurisdictions indicated how countries track soil conditions.
	Soil redox potential	M	L	
	Soil moisture	H	M	
	Stored soil C	M	L	
Soil biological components	**Soil respiration**	H	L	
	Biota biomass	M	L	
	Abundance of soil biota	M	L	
	Ratios of different types of soil biota (e.g., fungi to bacteria), microbial nutrients (e.g., microbial C to microbial N), microbial nutrients to total nutrients (e.g., microbial C to total C), etc.	M	L	
	Rate of soil microbial activity	M	L	
	Diversity of soil microbial populations	L	L	
	Soil nutrients	M	M	
	N mineralization rates	M	L	
Dead organic matter production and decomposition	**Annual litter decomposition rate**	M	M	
	Annual litter production rate	L	M	

[a] Regular font indicators are from the workshops, italic indicators are from the scan, bold indicators are from both the workshops and the scan.
[b] Sensitivity of indicator to climate change: High (H), Medium (M), Low (L).
[c] Feasibility of measuring in a regional or national tracking program: High (H), Medium (M), Low (L).

HUMAN SYSTEM

HUMAN DIMENSIONS RELATED TO FORESTS

What are human dimensions related to forests and how are they organized?

Human dimensions pertain to how social systems relate to and affect their forested environment. Social systems encompass components such as individuals, families, businesses, communities, groups, organizations, institutions, and societies. As for their relationships with the forests, it is envisioned both from a user and nonuser perspective, acknowledging the multiple drivers such as economic, sociological, spiritual, ethical, psychological, political, and cultural spheres that shape the complex relationships existing between social systems and forested environments. These forested environments, which fall under different types of ownership and forest management regimes, are found across the landscapes in cities, at the urban/rural interface, and in rural and remote areas. The human system is divided into eight dimensions related to the climate change effects on the system and the capacity to adapt to climate change: natural capital, forest uses, infrastructure, the economy, social capital, demography, human health, and institutions and governance. Some elements of the human dimensions refer to the climate change impacts, whereas others refer to key assets related to society's adaptive capacity. For example, changes induced by climate change might alter the economy of certain regions, thus triggering society's need to adapt to climate change. As work on potential effects of climate change on the human system has progressed recently, below we stressed the importance of looking at dimensions affecting the ability of human systems to adapt to changes as well as factors affecting the willingness to act. In the indicator table (Table 8), we have also shown which potential indicators related to impacts and/or adaptive capacity. For the indicators related to the human dimensions, we did not assess the sensitivity and feasibility.

Why are human dimensions relevant to climate change?

Some of the most salient effects linked to climate change in forested environments are related to changes in patterns of natural disturbances that will likely affect or transform forest characteristics that are crucial for various forest uses. Climate change effects such as increased flooding, forest fires, insect outbreaks, and changes in seasonal weather might challenge the existence and maintenance of infrastructure in forested environments or stress the need for additional ones. Climate changes (such as those affecting forest disturbances; Flint et al. 2009) could affect the social, political, and economic systems of people who live, work, or recreate in the forested environment. Given the multidimensional nature of forest dependence (Beckley 1998), climate change may affect the way the society (i.e., individual, household, community, region,

province) relies on the forest (timber, forestry services, tourism and recreation, nontimber forest products, ecological services, etc.). Because of their location and heavier reliance on the forest, forest-based communities are considered to be among the most susceptible to climate changes (Mendis et al. 2003). Social systems will likely respond to climate change in a less deterministic manner than ecological systems because, aside from structural variables, social systems' responses to crises also rely on individual and collective ability to act based on will (Davidson 2010). Social systems have an inherent capacity to adapt to real or perceived changes and threats. For example, new emergency plans may be implemented to deal with extreme weather events. Forests can be used to address the issue of climate change through the creation of institutional mechanisms such as C markets or the United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD+). This capacity results from the collective ability to take advantage of opportunities or to meet needs, and has been articulated through concepts such as community capacity, community well-being, and resilience (Nadeau et al. 1999; Adger et al. 2004; Donoghue and Sturtevant 2007).

The subsequent social actions will be shaped by the society's perception of risk related to climate change. Risk perception (to property, to markets, to human health, to well-being, etc.) from various actors is thus an important factor to understand as it influences the decision-making process on those risks as well as the ensuing social actions (Davidson et al. 2003). These actions might be triggered faster among actors who are predicted to be directly affected by climate change such as those relying on seasonal activities like silviculture, tourism, firefighting, or maple syrup production. McFarlane et al. (2012) examined the community's risk perception of large-scale insect disturbance and found that while managers and residents had some common interests, residents expressed a broader spectrum of concerns. Stedman (2004) observed differences in perceptions among key forest policy actors, with environmentalists and university scientists associating greater risk to climate change than either industry or government representatives. Documenting the perception of salient risks posed by climate change to forested ecosystems and the social systems that depend on them is seen as a crucial step to inform the development of climate change policies (Hunt and Kolman 2012). Also, documenting these perceptions could help understand the context and trade-offs that nurture the development of adaptation or mitigation strategies, and provide a sense of why they occur in some places and not in others even though these might be subject to similar climate change effects and forecasts.

Current strengths and weaknesses in different components of the human system are likely to facilitate or hinder the design as well as the implementation of adaptive actions related to climate change (e.g., Freudenburg 1992; Teitelbaum et al. 2003). Equity issues are very much at the forefront of the society's adaptive capacity. The distribution of benefits and consequences of adaptation will vary among segments of society because of various factors such as geographic location or unique cultural, economic, or ecological characteristics (Burdge 2008; Lynn et al. 2011). Because of their location and use of the forests, remote and resource-based communities are vulnerable to drought, ice-jam flooding, forest fires, the absence of late spring frost, and warmer winter temperatures, which might result in repeated evacuations, disruption of vital transportation links, and stress on forestry-based economies. Hence, climate change effects on social systems and the ability of these systems to respond to real or perceived risks will vary according to spatial and social scales and will occur at different rates.

How will climate change affect human dimensions related to forests and how can these effects be measured?

Climate change will likely affect forest values related to the human dimensions, including health, property, markets, infrastructure, community well-being (Davidson et al. 2003), and the economic, life support, sociocultural, ethical, spiritual, and aesthetic aspects (Moyer et al. 2008). However, uncertainties around climate change effects on forests are likely to give rise to a wide range of perceptions among social actors about which values are at risk and to what level. As perceptions and attitudes toward risks nurture the will to respond to climate change, it is important to assess risks associated with climate change (Burdge 2008). Other key components and relationships within social systems such as the ones associated with community capacity (Beckley et al. 2008), forest communities' resilience (Lynn et al. 2011), and forest communities' well-being (Kusel 2001) will also play a significant role in a climate change context. A few authors have already started exploring the usefulness of these key components and relationships at the community level (Mendis et al. 2003; MacKendrick and Parkins 2005; Williamson et al. 2012), while others have instead taken an institutional approach and have looked into the capacity of policy sectors to respond to climate change issues (Craft and Howlett 2012; Doelle et al. 2012). Moreover, because of the complex nature of adaptive capacity and its sensitivity to contextual factors, the choice of indicators should depend on the issue of the "capacity to do what" as well as the unit of analysis (Adger et al. 2004; Beckley et al. 2008).

The ability of a social system to respond to change is a determinant of its vulnerability. This vulnerability will vary over time as the adaptive capacity is shaped by its response to changes in environmental, political, social, and economic spheres (Adger et al. 2004). Documenting the current state of key characteristics of social systems linked to adaptive capacity would provide reference levels that could then be monitored to develop a better understanding of how they enabled or constrained the overall system's ability to adapt to climate change. Moreover, the static description could be used to reflect on the sensitivity of these constituents to climate change and serve as building blocks to grasp the processes through which social systems react to different climate change effects. Economic and sociological characteristics that may render certain groups at risk or influence how they are able to respond to climate change are factors that are important to consider regarding equity (Davidson et al. 2003; MacKendrick and Parkins 2005; Lynn et al. 2011). For example, Flint et al. (2009) highlight the importance of documenting background data (demographic and socioeconomic conditions, level of tourism and amenity orientation, financial dependence on forestry, existing community action-oriented institutions, and patterns of resource utilization) to help better understand the threat posed by forest insect disturbances to different communities. Information related to inequity can be used to inform modeling and assessments of human dimensions of climate change (Lynn et al. 2011).

Natural capital

Natural capital relates to the "stocks" of various natural elements and resources that sustain a human's life and needs. Climate change effects might alter the quality, availability, and sometimes the location of various resources.

Forest uses

The forest ecosystem response to climate change and the change in climate drivers will not be spatially uniform throughout the country, suggesting that effects on forest uses are likely to differ among regions. The practice of various forest-related activities, their availability, and the location where they take place could be affected by changes in the quantity and quality of forest resources (flora, fauna) but also by changes in the weather itself (temperature, water flows, snow cover).

Morels (*Morchella* spp.), a nontimber forest product, after a recent burn. (Franck Tuot)

The predicted warmer and shorter winters in Canada translate into a likely reduced ability to access the forest. For example, an increase in unfrozen ground due to warmer temperatures likely results in decreased forest operations that depend on winter roads. Shorter winters may affect the start of the fire season and shorten the season for winter nature-based recreational activities (Hunt and Kolman 2012).

Infrastructure

The forest landscape is marked by infrastructure used for personal and commercial transportation as well as by infrastructure that is the backbone of industry and communities. Climate change effects such as increased flooding, forest fires, insect outbreaks, and changes in seasonal weather might challenge the existence and maintenance of infrastructure in forested environments or stress the need for additional ones. As they are costly to build and maintain, any actions to prevent infrastructure failure will impact the financial situation of various actors (families, businesses, industries, governments). This might translate into increases in taxation rates as well as increases in insurance claims.

The economy

Climate change is likely to affect the economic fabric of our society, and the current state of the economy is also likely to affect the adaptive capacity of social actors. Traditional indicators such as economic diversity, level of forest dependency (by households and/or communities), demand for forest products and their production levels, as well as employment and unemployment patterns, will remain important to monitor. Others, such as the work patterns related to seasonal activities (silviculture, firefighting, and maple syrup production), which are likely to be directly affected by forecasted changes in weather, will capture some attention. Indicators monitoring economic hardship and wealth such as incidence of low-income families would also contribute to a more complete picture of the direct and indirect effects that climate change might have in forested regions. Less traditional information such as economic assets at risk, and the cost of insurance coverage and forest protection might also be relevant in light of climate change.

Social capital

The concept of social capital refers to social norms and networks and the trust that comes into play in facilitating collective actions. The networks can consist of individuals and their personal connections (family, friends, neighbors), or they can consist of individuals or organizations that come together because they have similar concerns. While responses to hardships such as mill closures or natural disturbances rely on social networks, those hardships might also contribute to the development or strengthening of relationships, and trust or confidence between social actors (Varghese et al. 2006; Flint et al. 2009).

Demography

Demographic characteristics are central to social systems. Some changes induced by climate change might alter the demography of certain regions as people adapt their settlement and migration patterns. In turn, demographic traits (e.g., gender ratio, age distribution, and educational attainment) are also directly related to preparedness for adaptation.

Human health

Climate change is likely to have direct, as well as indirect, effects on human health. Some of those health effects will be related to the forested environment. The major concerns regarding human health in relation to forests are articulated around air quality, drinking water, incidence of vector-born diseases (e.g., West Nile virus, Lyme disease), health effects of extreme weather events, and change in individual physical and mental health conditions (e.g., asthma, stress levels).

Institutions and governance

Institutions encompass both informal and formal structures and mechanisms put in place to guide individual behaviors so they meet social norms and expectations. Climate change will affect these but also require alteration and adjustment to our current institutions and governance structures as well as to our forest management paradigms (Glück et al. 2009; Davidson 2010). Bruce (2003) suggested the design of larger openings for bridges or culverts on stream crossings to ensure that more frequent and higher flows of water can pass safely. However, for this change to occur, an institution would need to be mindful of changes and have mechanisms in place to enable the review of policy, regulations, and practices in light of climate change. In the Canadian context, the novelty of climate change issues, the scientific uncertainty, the need for behavioral adjustment, and the unequal burdens placed by climate change in different regions are identified as factors creating important governance challenges (Rayner 2012). These challenges reach across levels of government (local, regional, provincial, federal) and also to NGOs and industries involved in forest policy and management.

Table 8. Elements and potential indicators for assessing impacts and adaptive capacity for the human dimensions.

DIMENSION	ELEMENT[a]	POTENTIAL INDICATORS	CONSIDERATIONS
Natural capital	Air quality (im)	Number of days with warning to limit activity because of smoke from forest fires Hospital admittances due to smoke from forest fires	- Climate change effects on the biophysical system create social disruption.
	Snow cover and ice availability (winter recreation, harvesting, transportation) (im)		
	Fauna: species, quality and quantity, location (im)		
	Flora: species, quality and quantity, location (im)		
	Landscapes aesthetic (im, ac)		
	Social disruption related to climate (fire, flood, heat, freezing rain, relocation, etc.) (im)		
	Extreme weather events (im)	Number of days of evacuation by communities because of extreme weather events Number of days emergency shelters are used because of extreme weather events Cost of infrastructure failures due to weather events	
	Ecosystem services: provision, disruption (im)		

(*Continued*)

[a] Although a clear separation between impacts and adaptive capacity was not always possible, elements were characterized as related to assessing impacts (im) of climate change on human dimensions and/or adaptive capacity (ac) based on expert opinion. Hence, indicators of risk perception and equity (i.e., two elements that influence adaptive capacity) may apply to several dimensions. They represent cross-cutting dimensions and may be assessed through the following elements:

- Risk perception and awareness: risk to ecological systems and functions, to property and infrastructure, to human health, to well-being, and to forest uses, and awareness of climate change (understanding, communication, attitude, climate literacy).
- Equity: socioeconomic status of susceptible population (forest-based communities), average and median household income, level of employment per age group (per gender), access to basic services, and procedural and distributive dimension.

These key dimensions, elements, and potential indicators are derived from the work of many scholars and committees that have addressed the adaptive capacity issue (Beckley et al. 2002; Mendis et al. 2003; Adger et al. 2004; MacKendrick and Parkins 2005; Beckley et al. 2008; Centre for Indigenous Environmental Resources 2009; Glück et al. 2009; Innes et al. 2009; Kenney et al. 2011; Michalos et al. 2011).

Table 8. *(Continued)*

DIMENSION	ELEMENT[a]	POTENTIAL INDICATORS	CONSIDERATIONS
Forest uses	Timber extraction (im)	Use of harvesting methods (area, percentage of total volume) Number of days for winter harvesting Percentage of winter roads compared with regular forest roads Change in road-building standards	- Beckley (1998) presented a typology of human uses of the forest that provided a starting point to understand how those uses might be affected by climate change. - Depending on the scale at which forest uses need to be documented, different business organizations, recreational groups, and associations could provide information on these uses. - It might also be relevant to document who is using the resources to get a sense of potential displacement of activities (e.g., residents compared with nonresidents). - The studies and surveys led by EC on understanding the value of nature to Canadians and their nature-related activities might also provide useful information as they are completed (biodivcanada 2012). - Other sources, such as Statistic Canada's report on human activity and the environment (Statistics Canada 2012), or the Aboriginal Peoples Survey database, used by Bogdanski (2008) to document the state of the forest sector in the boreal region, could also be useful if updated.
	Forest timber products (im)	Quantity of products by group of species Quality of timber harvested	
	Silviculture (im)	Tree species planted and number Number of days available for silviculture activities	
	Nontimber forest products (im)	Product quantity: mushrooms, berries, maple products, botanical products, Christmas trees, and greenery Product quality Geographical area where they can be produced Number of days for seasonal production	
	Forest subsistence (im)	Availability of resources (food, fuel, timber, fish, animal, medicinal plants) for gathering activities Change in availability patterns (time, location)	
	Nature-based tourism and recreation: wildlife and flora viewing, hiking/snowmobiling, resort/cottages, ecotourism, hunting/fishing (im, ac)	Wildlife viewings Fall landscape Number of days for winter activities and tourism season Recreational trails at risk (hiking, driving all-terrain vehicles, snowmobiling, skiing, snowshoeing) Hunting and fishing: length of season, location, success rate	
	Ecological services (im, ac)	Air quality Water quality and quantity C sequestration, soil Existence/bequest (e.g., biodiversity, conservation) Historical and spiritual values	

(Continued)

[a] Although a clear separation between impacts and adaptive capacity was not always possible, elements were characterized as related to assessing impacts (im) of climate change on human dimensions and/or adaptive capacity (ac) based on expert opinion. Hence, indicators of risk perception and equity (i.e., two elements that influence adaptive capacity) may apply to several dimensions. They represent cross-cutting dimensions and may be assessed through the following elements:

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Table 8. (*Continued*)

DIMENSION	ELEMENT[a]	POTENTIAL INDICATORS	CONSIDERATIONS
Infrastructure	Transportation: roads, railways, airports, recreational trails (extent of network, physical characteristics, location) (im)	Extent of networks Location Number of days the networks are useable (e.g., winter roads, ice bridges, closure related to risk of/or fire, etc.) Cost of forest roads/trails construction and maintenance	- Reliability of existing infrastructure under changing conditions. - Needs for new or enhanced infrastructure.
	Industrial/Commercial: buildings related to forest industry and services, nature-based tourism (im)		
	Service: hospitals, schools, community center, sewers, water supply, etc. (im; ac)		
	Financial: tax revenue, property losses, insurance claims, tax revenue, rate of taxation (im, ac)		

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(*Continued*)

Table 8. (*Continued*)

DIMENSION	ELEMENT[a]	POTENTIAL INDICATORS	CONSIDERATIONS
The economy	Economic diversity (ac)		- Economic activities and indicators reflect a wide range of social and market influences functioning at multiple scales.
	Level of forest dependency (ac)		
	Demand for and production of forest products and nontimber forest products (type of products, market, etc.) (im, ac)		
	Economic sector/business profitability (im, ac)	Total revenue Total expenses Net revenue	
	Employment level by sector (ac)		
	Unemployment rate (im,ac)		
	Change in work pattern (when work can be done, productivity, overtime) (im, ac)		
	Incidence of low income (economic hardship and wealth) (im, ac)		
	Average/median household income (economic hardship and wealth) (ac)		
	Economic assets at risk: individual, community, business, industry (ac)		
	Insurance (access to, cost of coverage) (im, ac)	Average cost of home insurance in forested areas according to perceived increased risk of forest fires, floods, etc. Number and values of insurance claims in forested area due to extreme weather events and natural disturbances	
	Cost of emergency measures (im)	Cost of shelter and support to affected peoples Cost of emergency measures to control/fight extreme weather	
	Cost of forest protection (fire, insects) (im)	Cost of forest protection activities Cost associated with closure because of high risk of fire or fire activities	

(*Continued*)

[a] Although a clear separation between impacts and adaptive capacity was not always possible, elements were characterized as related to assessing impacts (im) of climate change on human dimensions and/or adaptive capacity (ac) based on expert opinion. Hence, indicators of risk perception and equity (i.e., two elements that influence adaptive capacity) may apply to several dimensions. They represent cross-cutting dimensions and may be assessed through the following elements:

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Table 8. (*Continued*)

DIMENSION	ELEMENT[a]	POTENTIAL INDICATORS	CONSIDERATIONS
Social capital	Sense of place/place attachment (as it relates to social agency) (ac)		- See McFarlane et al. (2012) for trust issues. - Social engagement, capacity, and indicators' results from a wide range of current and historic influences. - Links to climate will be difficult to demonstrate and must be made with caution.
	Cultural identity and traditional knowledge (im, ac)	Use of oral history Usefulness of traditional knowledge	
	Social Involvement (volunteerism, membership in organizations, participation in activities) (ac)		
	Leadership (sense of responsibility toward the group/community) (ac)		
	Trust (within group, toward others) (ac)		
	Relationships/networks (existence of formal and informal) (ac)		
	Social cohesion (strength of networks) (ac)		
	Crime rate (property, person) (ac)		
	Democratic engagement (ac)		
	Conflicts related to forest resources (availability, uses, management) (im,ac)		
Demography	Age, gender (ac)		- Data from Statistics Canada may be useful.
	Education level (ac)		
	Literacy rate (ac)		
	Population settlement and movement (density, location such as urban/rural interface) (ac)		
	Access to traditional knowledge (ac)		
Human health	Drinking water availability and quality (im)		
	Physical and mental health of individuals (im,ac)		
	Effects of heat waves, floods, droughts (im, ac)		
	Incidence of vector-born diseases (im, ac)		

(*Continued*)

[a] Although a clear separation between impacts and adaptive capacity was not always possible, elements were characterized as related to assessing impacts (im) of climate change on human dimensions and/or adaptive capacity (ac) based on expert opinion. Hence, indicators of risk perception and equity (i.e., two elements that influence adaptive capacity) may apply to several dimensions. They represent cross-cutting dimensions and may be assessed through the following elements:

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These key dimensions, elements, and potential indicators are derived from the work of many scholars and committees that have addressed the adaptive capacity issue (Beckley et al. 2002; Mendis et al. 2003; Adger et al. 2004; MacKendrick and Parkins 2005; Beckley et al. 2008; Centre for Indigenous Environmental Resources 2009; Glück et al. 2009; Innes et al. 2009; Kenney et al. 2011; Michalos et al. 2011).

Table 8. (*Concluded*)

DIMENSION	ELEMENT[a]	POTENTIAL INDICATORS	CONSIDERATIONS
Institutions and governance	External and internal constraints on adaptation (ac)		- Regarding institutions, we can look at how different institutional and governance structures are affected by climate change challenges (allocation of resources, increased collaboration or conflicts) as well as how they are faring in responding to these challenges. - Klenk (2012) identified four broad strategies that have repeatedly been put forward by various actors: resistance, resilience, response (facilitation), and mitigation. These have occurred at the strategic, tactical, or operational level of decision making. Those strategies reflect different institutional visions on how to approach climate change and are matched with different approaches in reviewing policy, regulations, and practices in light of climate change. - Monitoring the existence of cooperation/partnership agreements addressing climatic events, of emergency preparedness plans, and of early warning systems would also provide a sense of how climate change effects and their forecasts are influencing institutions and governance structures.
	Organizational coordination (policy planning levels, crisis response) (ac)	Number of fire/emergency services sharing agreements	
	Institutional capacity related to climate change issues(ac)	Number of positions created by governments that pertain to climate change-related research or adaptation	
	Mandate and resource endowments adapted to climate change (ac)		
	Mechanism to review policy, regulations, and practice in light of climate change (e.g., Annual Allowable Cut; forest practices such as plantation, hunting and fishing seasons, etc.) (ac)		
	Enforcement and compliance with policies and regulations (ac)		
	Cooperation and partnerships development (ac)		
	Distribution of power over decision making (ac)		
	Access to and use of climate-related knowledge (ac)		
	Role of civil society (ac)		
	Emergency preparedness plan (ac)		
	Early warning systems (ac)		
	Preparedness (ac)	Number of communities that have implemented the FireSmart program Percentage of participation in FireSmart program	
	Trust in institutions (ac)		

[a] Although a clear separation between impacts and adaptive capacity was not always possible, elements were characterized as related to assessing impacts (im) of climate change on human dimensions and/or adaptive capacity (ac) based on expert opinion. Hence, indicators of risk perception and equity (i.e., two elements that influence adaptive capacity) may apply to several dimensions. They represent cross-cutting dimensions and may be assessed through the following elements:

- Risk perception and awareness: risk to ecological systems and functions, to property and infrastructure, to human health, to well-being, and to forest uses, and awareness of climate change (understanding, communication, attitude, climate literacy).
- Equity: socioeconomic status of susceptible population (forest-based communities), average and median household income, level of employment per age group (per gender), access to basic services, and procedural and distributive dimension.

These key dimensions, elements, and potential indicators are derived from the work of many scholars and committees that have addressed the adaptive capacity issue (Beckley et al. 2002; Mendis et al. 2003; Adger et al. 2004; MacKendrick and Parkins 2005; Beckley et al. 2008; Centre for Indigenous Environmental Resources 2009; Glück et al. 2009; Innes et al. 2009; Kenney et al. 2011; Michalos et al. 2011).

The health and productivity of Canada's forests and forest sector are linked to climate, both directly and indirectly. Climate change is expected to affect many aspects of the environment, the economy, and society. In addition to implementing mitigation strategies, the forest sector will need to adapt, proactively when possible, to the outcomes of those changes. Adaptation requires placing actions into an adaptive framework to continually evaluate their effectiveness. The built-in feedback loop of tracking, assessing, and adjusting enables the evaluation of gaps between observed and desired conditions, and improvements of knowledge and tools in response to this evaluation. The adaptive iterative process of decision making will likely improve management of the forest and the forest sector in the face of not only climate change outcomes but also other types of fluctuations (market, changing values, global changes, etc.).

The identification of potential indicators of climate change effects carried out in this report shows that globally, processes related to the prioritization of indicators and the development of tracking programs are still at a very early stage. More development is needed to assess indicator feasibility, spatiotemporal scope, and relevance related to tracking system objectives. The assignment of indicators to different systems and the definition of selection criteria provide a basis for prioritizing candidate indicators for tracking. As the human system will likely respond to climate change in a less deterministic manner than the ecological systems, efforts to understand, define, and track its indicators will be key for assessing adaptation success.

Monitoring all indicators everywhere can be very costly, given the size and remoteness of Canada's forests. Traditional research and monitoring programs making use of remote sensing capacity and national forest inventories (i.e., NFI or provincial and territorial inventories), occasionally with slight adjustments, may be useful to track some of the suggested indicators. With assistance from diverse groups (Dickinson et al. 2012), such as scientists and teachers (e.g., Zoellick et al. 2012), citizen science programs may be one avenue to cost-effective information collection. Hierarchical deployment of indicators may also reduce costs. For instance, tracking specific forest indicators can be done at different spatial scales. At the national scale, indicators can be tracked using remote sensing to show where some of the climate change effects appear to be greater. At the regional scale, targeted monitoring may then be implemented to track these enhanced changes. Box 2 illustrates this with an example of the climate change effect on the range of the eastern spruce budworm. Observations reveal that the current range of insects, such as the spruce budworm, is expanding northward with potential impacts on ecosystem and forest productivity. As the outcomes of these impacts may depend on specific interactions among host and pest species, new indicators may have to be developed. As suggested by Beckley (2009), a multipronged approach can also be deployed with indicators identical across all spatial scales, another with indicators related to similar themes, and a third one with local indicators that reflect the unique character of a given place or forest management approach. Such an approach may help balance indicator representation across a range of environments, governance types, and institutional levels.

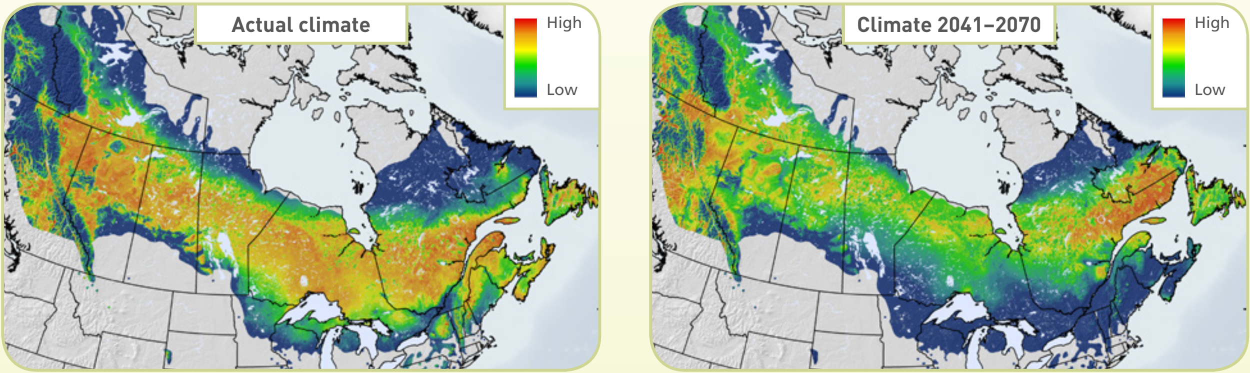
Implementing indicators requires developing standards that allow systematic data collection. Such standards should ensure cross comparability and data compiling in a central repository (i.e., data warehousing scheme) that allow for data mining and trend analysis by a variety of stakeholders. As an example, using standardized protocols and common sampling frameworks, the NFI assesses and monitors the extent, state, and sustainable development of Canada's forests. Such a process of standardization also requires ongoing communication and significant coordination of efforts among participating agencies. The National Ecological Observatory Network (NEON 2011) and the Alberta and Canada PlantWatch programs (Beaubien and Hamann 2011), for example, have developed valuable infrastructure for managing large, data-focused programs. In fact, the use of the Internet and geographic information systems allows the collection of large volumes of location-based ecological data that may be placed in centralized databases with data entry capacity (e.g., http://www.citsci.org/cwis438/websites/citsci/home.php?WebSiteID=7), data-sharing infrastructure, and web-based access portals (Dickinson et al. 2012). Moreover, by engaging different communities in data collection, visualization, and communication, existing programs provide good examples of success in raising awareness about climate change. Communicating technical information in an engaging and understandable way to a broad range of users is also needed, with attention given to particular target audiences (such as key decision makers) who are most likely to need and use this kind of information.

Collaboration and coordination among stakeholders are crucial for implementing all elements relevant to a tracking system (data collection, data standardization, data warehousing, data manipulation infrastructure, and communication). Partnerships among the different stakeholders will be essential to collectively augment and exploit the existing and new information and to ensure the viability of a broad climate change monitoring and reporting program. Several multistakeholder programs relevant to tracking climate change effects on Canada's forests are already in place, including long-term provenance tests, silvicultural trials, and forest inventory programs, and can be built on. There are, however, fewer examples of such monitoring programs related to the adaptive capacity and related elements of the human system, aside from information on the forest products industry and markets.

Globally, the information collected for a tracking system can contribute to adaptation if it increases the awareness and understanding of climate change effects, and results in enhanced preparedness for adaptation. Options can be confronted with different scenarios and subsequently be implemented to reduce the differences between desired and observed states. A final key requirement for successful adaptation will be adequate monitoring of the effectiveness of the implemented adaptive actions so that continuous improvement can be integrated into the climate change adaptation process.

Although a broad climate change monitoring and reporting program may seem to be costly in the short term, the cost of not adapting must also be considered. Climate change is both a short- and long-term reality, and its effects are likely to be cumulative and far-reaching. Adaptation should generate multiple benefits to Canada's forest sector by enabling responses to multiple sources of stress in addition to climate change. Within such an adaptive framework, Canada's forests and the associated forest sector will likely maintain their role as generators of services and well-being for Canadians. This report is the first step toward the implementation of a system to track indicators of climate change effects on Canada's forests and forest sector, an essential basis for supporting adaptation under continued climate change.

Box 2. Example of a hierarchical approach to monitoring: potential growth rate of spruce budworm (SBW) populations



Potential population growth rate index of SBW as a function of forest canopy cover (%). (Adapted from Régnière et al. 2012b)

Model predictions

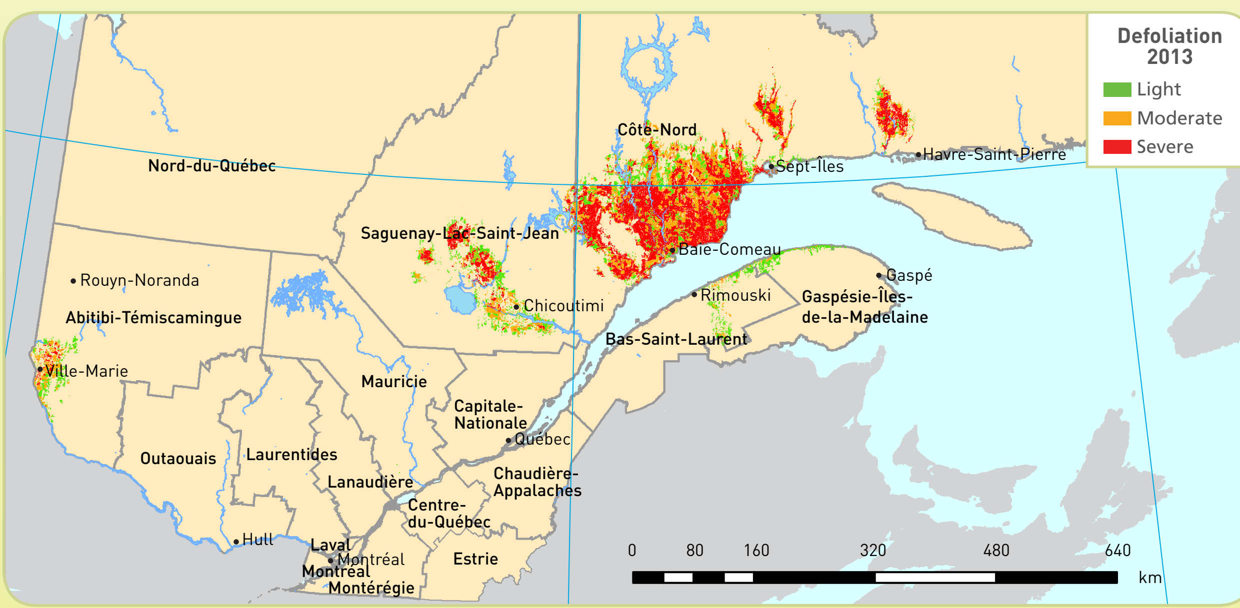
As the climate changes, the range of the eastern spruce budworm (*Choristoneura fumiferana*) is predicted to shift northward in forested ecosystems dominated by black spruce (*Picea mariana*) and previously only lightly affected by the insect. For Canada, models are predicting a 3° northern expansion of its range within the next 50 years (Régnière et al. 2012b).

Current observations

Observations confirmed predictions. Current outbreak foci have been located in northeastern Quebec since 2006 (see map below).

Predictions and need for tracking new indicators

With climate warming, some boreal forest zones may be at high risk of severe defoliation. An increase in temperature will allow the insect to complete its life cycle with lower mortality rates and it will no longer depend on migration from southern regions during outbreak phases to infest trees in northern latitudes. Furthermore, as temperatures continue to increase at northern latitudes, the phenology of the spruce budworm population will be synchronized with black spruce phenology, as it is the dominant tree species in the north. The dispersal potential of spruce budworm and the wide distribution of its host trees would allow it to expand its range and maintain populations in regions where climatic constraints previously limited its long-term persistence. Monitoring phenology and eventually ecosystem changes will inform us on future changes and help us to propose adaptation actions to reduce the impact of this disturbance on the black spruce forest ecosystem.



Spruce budworm defoliation zones in the developing outbreak in northeastern Quebec. (Data from Ministère des Ressources naturelles du Québec 2013, http://donnees.gouv.qc.ca)

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APPENDIX 1. INDICATORS OF CLIMATE CHANGE EFFECTS OBSERVED WORLDWIDE

Kremsater (2012) completed a literature review focused on identifying indicators used by other jurisdictions that would be potentially useful for the CFS. That report, and its associated appendices, provides detailed examples of indicators used by various countries interested in climate change effects on forests. Table A1 summarizes the types of indicators found for each jurisdiction. The letter "d" indicates that a jurisdiction discussed the indicator or described it as an impact in its government climate change strategies or monitoring systems. The letter "m" indicates that the jurisdiction actually measured (rather than simply discussed) the indicator. The table does not include research projects or case studies unless they are part of an organized monitoring program or adaptation strategy.

The review (Kremsater 2012) revealed some important generalities. At that time, no jurisdiction had a cohesive, comprehensive program to monitor climate change effects on forests. Eastaugh et al. (2009) noted that the European Environment Agency (EEA) excluded forestry from its 2004 report on climate change effects due to a lack of information. Treatment of climate change effects on forests ranges from tracking forest area and deforestation/afforestation rates to more in-depth indicators. Europe (especially the United Kingdom) and the United States have the most developed programs tracking climate change effects on ecosystems. Canada does considerable research but has fewer national data systems than most advanced US and European jurisdictions.

In the United States, the Forest Inventory and Analysis National Program and the National Forest Health Monitoring Program provide considerable information relevant to tracking climate change effects on forests. Many researchers and state-level programs have used this information, although none in a systematic national tracking effort. Several national agencies or organizations have documented expected climate change effects on forests, and these effects suggest corresponding indicators (e.g., Pew Research Center (established by The Pew Charitable Trusts), United States Environmental Protection Agency (EPA), United States Department of Agriculture (USDA) Forest Service, U.S. Geological Survey (USGS), and U.S. Department of the Interior). Some US government programs provide information of global utility. The National Aeronautics and Space Administration (NASA), for example, has many remote-sensing satellites that can relate pertinent information. Information is usually provided free and the agency is working on improving accessibility. The National Ecological Observatory Network (NEON) also provides a network of US sites to monitor continental changes in climate, ecosystems, and species (NEON 2011). When considering programs in specific states, California and the northeastern states have the most in-depth reports discussing climate change effects and solutions, and these include discussions of effects and actions in forested systems. The northwestern states are close behind. The Arctic Climate Impact Assessment group has done in-depth evaluations of climate change effects in Alaska and the Arctic worldwide. A new organization, the Arctic–Boreal Vulnerability Experiment, also focuses on monitoring climatic warming effects on land cover and land forms, permafrost thawing, forest disturbances, and carbon and water cycles in arctic and boreal ecosystems in the United States and Canada.

In Europe, the United Nations Economic Commission for Europe, and the European Union established the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests monitoring program that has tracked forest health since 1985, prompted by the desire to track the effects of pollution. Although these plots were not set up to track climate change effects, they provide measurements of large-scale variations of forest conditions over space and time in relation to natural and anthropogenic factors on about 6000 plots systematically spread across Europe. The program has level I, II, and III plots, each with different measures and intensities. As well, the EEA tracks forest conditions and conditions of the environment. Many of the assessments do not focus on climate change, and report on the state of the forest, but recent publications are addressing the climate change issue and noting likely impacts on forests.

The Partnership for European Environmental Research conducts some comprehensive pan-European research and assessments, and notes that monitoring climate change effects on forests is lacking. However, the European Forest Data Centre now acts as a focal point and host for policy-relevant forest data. It provides links to forest information, including data sets, and may facilitate the monitoring and analysis of climate effects on forests. Many European countries participate in the United Nations Framework Convention on Climate Change (UNFCCC) and complete national assessments of climate change effects, adaptation, and mitigation. The requirements for reporting on forests usually involve noting the amount of forest cover, afforestation efforts, carbon dioxide (CO_2) sequestration, and possible expected effects of fires, insects, disease, and drought. Some European countries are able to quantify these effects; others (including most developing countries within the UNFCCC) limit themselves to simply reporting forest cover, afforestation levels, and CO_2 sequestration. Even the small European countries (e.g., Estonia and Croatia) complete impressive national assessments for the UNFCCC.

Regarding individual European countries (including Russia), the United Kingdom and France have the most developed programs, with several other countries having strong forest monitoring programs. Many have strong monitoring of climate variables, but none focused on tracking changes in forests due to climate. The United Kingdom has many programs tracking changes in species; key among those is the MONARCH (Modelling Natural Resource Responses to Climate Change) project, which tracks changes in species distribution, abundance, and phenology. The United Kingdom has identified 34 climate change indicators. They are not very forest-specific, but include (as well as the usual abiotic climate drivers) bird phenology, frog calling, plant phenology (bud burst), growing season, water flow, health of beech trees, and more. France is developing a program for monitoring biodiversity in various ecosystems, including forests (ONERC 2010). Russia cooperates with Europe and other countries (including Canada) in the research of boreal systems. Germany, Finland, Sweden, and Norway also have strong forest monitoring but the focus is not climate change. While tracking climate change in forests is relatively unorganized, many jurisdictions have programs that track forest management activities and assess those against sustainable forest management indicators (e.g., Franc et al. 2001; FAO 2011).

Many country-wide assessments from Canada, the United States, and Europe use findings from specific research projects to provide evidence and examples of climate change effects, but rarely are those projects organized into a more comprehensive framework of provincial or national monitoring of climate change effects on forests. In contrast, many countries have very efficient systems in place to track changes in abiotic climate drivers (e.g., temperature, precipitation, snow, etc.) and changes in physical processes (e.g., glaciers, water flow). That situation is also true in Canada. Johnston et al. (2010) notes that climate data have been collected in southern Canada for more than a century and in other parts of Canada since the mid-20th century. These data, together with satellite data from the past few decades, provide a detailed picture of how the Canadian climate has changed over the past 50 years. For the country as a whole, we have historical and projected trends in temperature, precipitation, snowmelt, permafrost thawing, and many other abiotic indicators. For some of those indicators, historical trends and directions of predictions are fairly certain; for others, such as precipitation, historical trends are known but projections remain uncertain in both direction and magnitude. Despite the uncertainties, Canada nonetheless has accepted and well-measured indicators for many (but not all) the abiotic effects of climate change.

In Canada, our knowledge and understanding of how forests have responded or will respond to climate change, and our use of indicators to track changes in forests, lag behind our understanding of climate change effects on abiotic variables. The forested portions of Canada are expected to experience greater climate change effects than many areas of the world (Field et al. 2007), and many journal papers and technical reports outline those expected changes, but none of the provinces have organized monitoring of forest change due to climate. Several provinces have noted the need for monitoring climate change effects on forests, but none have initiated such monitoring rigorously. Quebec's Ouranos, a consortium on regional climatology and adaptation to climate change (Government of Quebec 2008), tracks many biological variables with climate change but does not focus on forests. Ontario has many research initiatives. British Columbia has identified indicators and initiated case studies on climate change effects but has not begun to track changes in forests. In British Columbia, a provincial body analyzes historical and projected climate drivers and abiotic changes, including glaciers, ice cover, and snowmelt, associated with climate change (Pacific Climate Impacts Consortium; see Rodenhuis et al. (2009)), but no similar efforts for tracking have been established for ecological systems. Alberta recommends the establishment of a monitoring body and already tracks many biological indicators systematically (i.e., Alberta Biodiversity Monitoring Institute), but not with a climate change focus.

Many jurisdictions, including areas of Canada, recognize that forests are changing with the climate, and desire information on those changes and recognize the importance of building from existing efforts (e.g., Beever and Woodward 2011). Initiating a tracking program such as the CFS envisions would support the many statements in strategic reports that note the need for monitoring (e.g., New Brunswick Climate Change Secretariat 2007; Atlantic Environment Ministers 2008; Alberta Environmental Monitoring Panel 2011), but do not make specific recommendations for monitoring. Although tracking climate change effects on forests by organized programs is nascent, research is abundant and provides a strong underpinning for international coordination and collaboration. Investing in tracking programs and enhanced coordination among governments, NGOs, and universities will help improve our capacity to track climate change effects on forest ecosystems, which is essential to develop proactive mitigation and adaptation strategies.

Table A1. Summary of the indicators listed in the review by jurisdiction: Canada, the United States, Europe, and other countries/global. d = variables discussed as desirable information; m = variables measured in some systematic framework

Canada	NTL	BC	AB	SK	MB	PR	ON	QC	ATL	NB	NS	NL	YT	NU
Climate drivers														
Growing season	d	m	d	d		d	d	d					d	
Temperature	m	m	m	m	m	m	m	m	m	m	m	m	m	
Precipitation	m	m	m	m	m	m	m	m	m	m	m	m	m	
Extreme weather	m	m	m	m	m	m	m	m	m	d		d	m	
Drought	d	m	m	m	m	m	m	m				d	m	
Growth														
Regeneration	d	d				d								
Productivity	d	d				d	d		d		d		d	
Mortality	d	d				d	d		d	d	d		d	
Physical changes														
Permafrost	d	d			d	d	d	d		d				
Glaciers	d	m			d	d								
Snow and ice	d	m		d	d	d	d					m		
Water temperature	d	d		d	d	d	d							
Water quality	d	d	d	d	d	d	d	d						
Water flow	d	m	d	d	d	d	d	d						
Wetlands and lakes	d	d	d	d		d	m	d						
Phenology														
Animal	d	d		d		d	d	m					d	
Plant	d	d		d		d	d	m					d	
Natural disturbances														
Fire	d	d	d	d	d	d	d		d	d	d		d	
Flood	d	d		d	d	d	d						d	
Wind	d	d		d	d	d	d						d	
Mass wasting	d	d		d	d	d	d						d	
Insects	d	m	d	d	d	d	m		d	d	d		d	
Pathogens	d	m	d	d		d	m				d		d	
Soils														
Nutrients	d				d	d		d					d	
Erosion	d	d			d	d	d	d					d	
Distribution														
Tree line	d	d	d	d	d	d	d	d					d	
Animal	d	d	m	d		d	d	m	d	d			d	
Plant	d	d	m	d		d	d	m	d	d			d	
Tree species	d	d	m	d	d	d	d	d	d	d	d		d	
Invasive plant species	d	m	m	d		d	d	d					d	
Economy/Society														
Timber supply	d	d			d	d	d		d	d			d	
Nontimber forest products	d	d			d	d			d				d	
Costs	d	d				d			d	d			d	
Other impacts	d	d	d		d	d	d		d	d				

NTL, national; BC, British Columbia; AB, Alberta; SK, Saskatchewan; MB, Manitoba; PR, Prairies; ON, Ontario; QC, Quebec; ATL, Atlantic; NB, New Brunswick; NS, Nova Scotia; NL, Newfoundland and Labrador; YT, Yukon; NU, Nunavut.

(*Continued*)

Table A1. (*Continued*)

United States	PEW	EPA	USDA	NASA	USGS	TNC	USFW	NTL	AL	CA	NC	ME	MD	MA	MI
Climate drivers															
Growing season	d	m		m		d		d	d		d			d	
Temperature	d	m	d	m		d		m	m	m	m			m	
Precipitation	d	m	d	m		d		m	m	m	m			m	
Extreme weather		m				d		m	m	m	m			m	
Drought	d	m	d			d		d	d	d	d		d	d	
Growth															
Regeneration								d	d						
Productivity	d		d	m				d	d	d					
Mortality	d		d					d	d	d	d				
Physical changes															
Permafrost	d							d	d						
Glaciers	d			m	d			d	d	d					
Snow and ice	d			m	d			d	d					d	
Water temperature	d			m	d			d	d	d	d			d	
Water quality		m		m	d			d	d	d	d			d	
Water flow	d	m	d	m	d			d	d	d	d			d	
Wetlands and lakes	d	m	d	m	d			d	d	d	d		d	d	
Phenology															
Animal	d		d	m	d	d		d	d	d	d				
Plant	d		d	m	d	d		d	d	d	d		d	d	
Natural disturbances															
Fire	d		d		d	d		d	d	d	d		d		
Flood	d					d		d	d	d	d		d		
Wind	d		d					d	d		d				
Mass wasting	d							d	d						
Insects	d		d			d	d	d	d	d					
Pathogens	d		d			d	d	d	d	d					
Soils															
Nutrients			d					d	d		d				
Erosion			d			d		d	d						
Distribution															
Tree line	d	d	d			d	d	d	d	d	d			d	
Animal	d	d	d	d	d	d	d	d	d	d	d		d	d	
Plant	d	d	d	d	d	d	d	d	d	d	d		d	d	
Tree species	d	d	d				d	d	d	d	d		d	d	
Invasive plant species		d	d				d	d	d	d	d			d	
Economy/Society															
Timber supply	d							d	d						
Nontimber forest products									d						
Costs									d						
Other impacts										d					

(Continued)

PEW, Pew Research Center; EPA, Environmental Protection Agency; USDA, United States Department of Agriculture; NASA, National Aeronautics and Space Administration; USGS, U.S. Geological Survey; TNC, The Nature Conservancy; USFW, U.S. Fish & Wildlife Service; NTL, summary of US national; AL, Alabama; CA, California; NC, North Carolina; ME, Maine; MD, Maryland; MA, Massachusetts; MI, Michigan.

Table A1. (*Continued*)

United States	MN	NH	OR	PA	VT	VA	WA	WI	WY	NE US	GrL	NMw US	US ROCK
Climate drivers													
Growing season	d				d		d	d		m	d		d
Temperature	m	m	m		m	d		d	d	d		d	d
Precipitation	m	m	m		m	d		d	d			d	d
Extreme weather	m	m			m	d		d		m	d		d
Drought	d	d	d		d	d	d	d	d	d		d	d
Growth													
Regeneration													
Productivity		d			d			d			d		d
Mortality	d	d			d			d					d
Physical changes													
Permafrost													
Glaciers			m		d		m						
Snow and ice			d	d			d	d	d	m	d		
Water temperature	d					d			d		d		
Water quality	d						d		d		d		
Water flow	d		d		d	d	d	d	d	m	d		
Wetlands and lakes			d					d	d				
Phenology													
Animal	d				d					d	d		d
Plant	d	d			d					m	d		d
Natural disturbances													
Fire	d	d	d		d		d	d	d				d
Flood	d	d	d		d		d				d		
Wind	d	d	d		d		d	d					
Mass wasting			d				d	d					
Insects			d		d	d	d	d	d	d	d	d	d
Pathogens			d		d		d						d
Soils													
Nutrients								d		m	d		
Erosion								d					
Distribution													
Tree line			d	d	d	d	d	d		d	d		d
Animal			d	d	d	d	d	d		d	d		d
Plant	d	d	d		d	d	d	d			d		d
Tree species	d	d	d			d	d	d	d		d		d
Invasive plant species	d	d	d			d	d	d	d	d			d
Economy/Society													
Timber supply		d		d					d	d			
Nontimber forest products													
Costs							d						
Other impacts										d			

MN, Minnesota; NH, New Hampshire; OR, Oregon; PA, Pennsylvania; VT, Vermont; VA, Virginia; WA, Washington; WI, Wisconsin; WY, Wyoming; NE US, northeastern United States; GrL, Great Lakes; NMw US, northern and midwestern United States; US ROCK, US Rocky Mountains.

(*Continued*)

Table A1. (*Continued*)

Europe	PAN-EU	AL	BEL	BGR	CRT	CZE	EST	FIN	FRA	GER	HUN	IRL	NLD	NOR	RUS	SWE	UK
Climate drivers																	
Growing season	m					d		d	d	d		d	d	d		d	m
Temperature	m		m	m	m	m	m	m	m	m	m	m	m	m	m	m	m
Precipitation	m		m	m	m	m	m	m	m	m	m	m	m	m	m	m	m
Extreme weather	m		m	m	m		m	m	m	m	m	m	m	m	m	m	m
Drought	d		m	m			d	d	d		d	d	d	d	d	d	
Growth																	
Regeneration											d						
Productivity	d		d	d		d								d	d	d	
Mortality	d		d	d		d		d						d	d	d	
Physical changes																	
Permafrost	d							d						d	d		
Glaciers	d								d						d		m
Snow and ice	d				m		m		d					d	d	d	
Water temperature	d											d	d			d	
Water quality	d		d				d					d	d			d	
Water flow	d		d		m	d	d			d		d	d	d		d	
Wetlands and lakes	d									d			d	d			d
Phenology																	
Animal	d		d		d			d	d	d						d	m
Plant	d		d		d			d	d	d						d	m
Natural disturbances																	
Fire	d	d		d	d		d								d	d	
Flood	d		d	d						d				d	d	d	
Wind	d			d			m									d	
Mass wasting	d									d				d		d	
Insects	d	d	d	d			d	d	d	d				d	d	d	d
Pathogens	d		d				d	d						d	d	d	d
Soils																	
Nutrients	d						d			d	d				d	d	d
Erosion	d			d	d	d		d		d						d	d
Distribution																	
Tree line	d		d	d				d			d			d	d	d	m
Animal	d		d		m			d		d	d			d		d	m
Plant	d		d		m			d		d					d	d	m
Tree species	d	d	d	d	d	d		d		d				d	d	d	m
Invasive plant species	d							d						d		d	d
Economy/Society																	
Timber supply	d	d					d	d				d		d		d	m
Nontimber forest products	d							d				d					
Costs	d																
Other impacts								d						d		d	

PAN-EU, pan-European; AL, Albania; BEL, Belgium, BGR, Bulgaria; CRT, Croatia; CZE, Czech Republic; EST, Estonia; FIN, Finland; FRA, France; GER, Germany; HUN, Hungary; IRL, Ireland; NLD, Netherlands; NOR, Norway; RUS, Russia; SWE, Sweden; UK, United Kingdom (includes MONARCH).

(*Continued*)

Table A1. (*Concluded*)

Other countries/ global	AMER	ASIA	AUS	IND	IDN	CHN	GLOB ORGS	FAO UN IUFRO	IPCC	CBD	UN DEV COUN
Climate drivers											
Growing season				d				m	m	d	
Temperature	m		m	m		m		m	m	d	m
Precipitation	m		m	m		m		m	m	d	m
Extreme weather			m	m		m		m	m	d	m
Drought			d	d		m		m	m	d	m
Growth											
Regeneration								d		d	
Productivity						d		d		d	
Mortality						d		d		d	
Physical changes											
Permafrost								d		d	
Glaciers				d		m		d		d	
Snow and ice				d				d		d	d
Water temperature				d				d		d	
Water quality				d				d		d	
Water flow	d		d	d	d	m		d	d	d	d
Wetlands and lakes								d		d	
Phenology											
Animal								d		d	
Plant						d		d		d	
Natural disturbances											
Fire			d					d	d	d	
Flood			d					d	d	d	d
Wind								d		d	
Mass wasting								d		d	
Insects						m		d		d	
Pathogens						m		d		d	
Soils											
Nutrients						d		d		d	
Erosion					d	d		d		d	
Distribution											
Tree line				d		d		d	d	d	
Animal				d				d	d	d	
Plant				d		d		d	d	d	
Tree species	d	d		d		d		m	d	d	m
Invasive plant species				d				d		d	d
Economy/Society											
Timber supply								d		d	
Nontimber forest products								d		d	
Costs								d		d	
Other impacts						d		d		d	

AMER, Americas; AUS, Australia; IND, India; IDN, Indonesia; CHN, China; GLOB ORGS, global organizations; FAO, Food and Agriculture Organization; UN, United Nations; IUFRO, International Union of Forest Research Organizations; IPCC, Intergovernmental Panel on Climate Change; CBD, Convention on Biological Diversity; UN DEV COUN, United Nations developing countries.

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APPENDIX 4. ABBREVIATIONS AND ACRONYMS

ANUSPLIN: Australian National University Splines

BBS: Breeding Birds Survey

BioSIM: biosimulation

C: carbon

CBD: Convention on Biological Diversity

CFS: Canadian Forest Service

ClimateWNA: Climate Western North America

CMI: Climate Moisture Index

CO_2: carbon dioxide

EC: Environment Canada

ECOLEAP: Extended Collaboration to Link Ecophysiology and Forest Productivity

EEA: European Environment Agency

EPA: United States Environmental Protection Agency

FAO: Food and Agriculture Organization of the United Nations

FWI: Canadian Forest Fire Weather Index System

GPP: gross primary production

IPCC: Intergovernmental Panel on Climate Change

IUFRO: International Union of Forest Research Organizations

LANDIS: landscape disturbance and succession (model)

LiDAR: light detection and ranging

MONARCH: Modelling Natural Resource Responses to Climate Change

N: nitrogen

NASA: National Aeronautics and Space Administration

NASDAQ: National Association of Securities Dealers Automated Quotations

NEON: National Ecological Observatory Network

NFI: National Forest Inventory

NGO: nongovernmental organization

NPP: net primary productivity

PDSI: Palmer Drought Severity Index

PRISM: Planning Tool for Resource Integration, Synchronization, and Management

PSPs: permanent sample plots

REDD+: United Nations Collaborative Programme on Reducing Emissions from Deforestation and forest degradation in Developing countries plus conservation, the sustainable management of forests, and enhancement of forest carbon stocks

SGM: Semi-Global Matching

SMI: soil moisture index

UNFCCC: United Nations Framework Convention on Climate Change

USDA: United States Department of Agriculture

USFW: U.S. Fish & Wildlife Service

USGS: U.S. Geological Survey