INDICATORS OF SUSTAINABLE FOREST MANAGEMENT IN A CHANGING CLIMATE

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SUMMARY

The theme of sustainability is now woven throughout Canadian forest management and policy. Indeed, Canada was an early adopter of sustainability in forestry, largely through a series of initiatives led by the Canadian Council of Forest Ministers' (CCFM). One such initiative was development and application of a national suite of criteria and indicators of sustainable forest management (C&I-SFM). With appropriate data associated with each of the chosen indicators, the C&I-SFM serve up a comprehensive picture of forest and forest-sector progress on the road called sustainable development.

For almost two decades, C&I-SFM have been applied at a wide range of levels, from international to national to provincial to local. The national set for Canada has been revised once (2003), and a second revision is likely imminent. In the meantime, the CCFM, in its 2008 vision for Canada's forests, stated that all initiatives related to SFM must consider the implications of a changing climate. In the context of a revision to the C&I-SFM, the question becomes this: what are the implications of a changing climate for the ongoing robustness and utility of Canada's national C&I-SFM? This report attempts to address that question.

The approach consisted of devising a systematic set of questions, in other words, an evaluation protocol, to put to each indicator. Some questions pertained to the indicator's relationships with other indicators in the set, some to the expected influences of climate change on the entity represented by the indicator, and finally some that would help us understand the indicator's ongoing relevance to SFM under a changing climate. The research team consisted of experienced forestry professionals and researchers who applied their collective professional judgement, as informed by a thorough canvassing of relevant literature, in answering the questions and developing recommendations for each of the indicators. The preliminary findings, and indeed the entire report, were peer-reviewed by experts from across Canada.

Forty-six indicators were examined using the evaluation protocol. The findings are summarized in the main report and detailed in a companion report. The evaluated indicators were assigned to one of three general outcomes. Twelve indicators were considered to be entirely independent of climate change, meaning that climate change is not expected to affect the phenomena represented by these indicators. The utility and robustness of all the remaining 34 indicators was considered to be influenced by a changing climate. For 23 of these, the team recommends no change to the indicator (unmodified category), and for 11 of them, changes are recommended. Initially it was thought that a potential outcome of the evaluation could be outright abandonment of an indicator in the event that the team found its ongoing utility to be seriously eroded by climate change. However, none of the indicators was found in this situation. Finally, the study identified six new indicators that could help provide a climate-change lens for monitoring and managing forests sustainably in Canada. These are:

a) Connectivity of protected areas;
b) Proportion of tenured forest area with seed transfer guidelines that account for climate change;
c) Average, minimum, and maximum temperature;
d) Area of Crown forest with assisted migration initiatives;

e) Rate and form of precipitation; and
f) Carbon emissions avoided through product substitution.

The study concludes with a set of recommendations that should help improve the overall utility of the C&I-SFM, especially in the context of a changing climate. These recommendations address: (a) moving from predominantly retrospective analysis using C&I-SFM to a balance of retrospective and prospective analysis; (b) linking C&I-SFM much more strongly and directly into forest management and policy processes; (c) undertaking analytical work using a framework of complex adaptive systems; (d) making explicit consideration of climate change in all forest management and policy decisions; and (e) sector-wide collaboration in ongoing improvement to and application of the C&I-SFM.

The report concludes by reminding readers that C&I-SFM are a necessary element of the SFM enterprise. Progress is nigh impossible without using them. Confidence in such progress is indeed impossible without them. It is clear that climate change will affect the entire forest sector, sometimes in insidious ways, sometimes in abrupt and obvious ways, and sometimes even in helpful ways. Considering the complex manner in which climate change will interact with other human influences on forests and the sector, incisive cumulative effects assessment will become increasingly important. Rigorous application of C&I-SFM will help develop the insight needed to assess the real prospects for SFM in Canada under a changing climate.

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DISCLAIMER

The four authors of this report retain all responsibility for errors and omissions. Opinions expressed in the report are entirely our own and not those of any organization.

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James Steenberg is a Research Associate at the School for Resource and Environmental Studies at Dalhousie University. He is an active researcher in forest ecology, resource management, and climate change. He began his research career in 2006, examining post-disturbance regeneration patterns in wilderness parks. James has been researching climate change and sustainable forest management since 2008, collaborating with forest managers at the local water utility during his graduate studies at Dalhousie. He has discussed the implications of climate change for forests at regional, national, and international conferences, and in lectures at Dalhousie University and Saint Mary's University. Since the criteria and indicators research was completed, James has been part of Halifax Regional Municipality Urban Forest Planning Team, conducting research on the urban and peri-urban forests of Halifax and developing the municipal urban forest master plan. In addition to his research career, James has worked in silviculture in BC, AB, and ON, and in forest conservation in NS.

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Peter Duinker is Professor and Director of the School for Resource and Environmental Studies at Dalhousie University's Faculty of Management. He is also Associate Dean Research for the Faculty. He teaches and researches a wide range of topics, most of which deal with forests and environmental assessment. Recent research projects include conservation of old-growth forests in southwest NS, forest restoration in Point Pleasant Park, long-term prospects for Canada's forests and forest sector, attitudes and values of NS woodland owners, and public values for Canada's urban forests. New research projects are underway on urban-forest sustainability and forest adaptation to climate change.

Peter serves on a wide range of committees and boards outside the university. At present he chairs the CSA's Sustainable Forest Management Technical Committee and the Nova Forest Alliance, Nova Scotia's Model Forest. Among the awards Peter has recently received are the CSA's Award of Merit and the CIF's National Scientific Achievement Award.

Peter has extensive histories of work both on criteria and indicators and on climate change. His scholarship on environmental impact assessment and forest management extends to the early 1980s, and featured indicator-related studies at every turn. He was involved in the consultations leading to the original CCFM criteria and indicators, and served as an expert advisor during the process to revise the national set. Peter has led indicator development and application processes across Canada. Peter's interest in climate change started while a research scholar at the International Institute for Applied Systems Analysis in Austria in the late 1980s. His first paper on the topic was published in 1990. Since then, he has examined the interactions between climate change and forests in a wide variety of forest management and policy settings. Peter managed the Atlantic Canada office of the Canadian Climate Impacts and Adaptation Research Network (C-CIARN) for six years, and was a member of the Advisory Committee to C-CIARN Forest.

Laird Van Damme

Laird Van Damme holds a Master of Science in Forestry and is a Registered Professional Forester with 26 years of experience as a practicing forester, educator, and consultant. His primary areas of practice are in the disciplines of silviculture, forest management, and forest research. He has also worked on business development projects across Canada and with some international experiences in Chile, China, and Ghana. In addition to business development, he has authored several forest management plans and published numerous scientific/professional papers. Mr. Van Damme has had several years of teaching and administration responsibilities for silviculture courses and remains an adjunct professor at Lakehead University. He has worked on several climate change committees (e.g. C-CAIRN) and projects, and has led business development activities in anticipation of carbon market developments.

Ken Zielke

Ken Zielke has 30 years of forest management experience, with 20 years consulting throughout British Columbia. Prior to that he taught silviculture and forest ecology at Selkirk College and worked in the West Kootenay Region. During his career, Ken contributed to numerous key provincial challenges and strategic initiatives. Over the past 15 years he worked with the British Columbia provincial government, and corporations in the province, the United States, and Australia to help them manage for biodiversity objectives in natural forest systems. Since 2008, he has been working on a two-phase Climate Change Vulnerability Assessment and Adaptation Strategy for the Kamloops Timber Supply Area, most recently working with UBC researchers on a meta-modeling approach to test initial strategies based on expert opinion. With this climate change knowledge he also assisted in a recent re-evaluation of Canadian's National SFM Criteria and Indicators framework, and is currently helping the provincial government to design and implement a new approach to forest management planning.

INDICATORS OF SUSTAINABLE FOREST MANAGEMENT IN A CHANGING CLIMATE

1. INTRODUCTION

1.1. Criteria and Indicators of Sustainable Forest Management

The theme of sustainability is now woven throughout Canadian forest management and policy. The international appeal of the concepts of sustainability and sustainable development began to take shape with the World Commission on Environment and Development (WCED), also known as the Brundtland Commission, convened by the United Nations (UN) in 1983, and its report, *Our Common Future* (WCED, 1987). Sustainable development was widely accepted across nations and disciplines, but had particularly strong application in the management of natural resources, including agriculture and forestry. Sustainable development of forests was further enshrined at the UN Conference on Environment and Development (UNCED) in 1992, also known as the Rio Summit, and its statement of *Forest Principles* and Chapter 11 of Agenda 21 of the conference's action plan (UNCED, 1992). The sustainability commitments made at the Rio Summit were integral to the adoption of the sustainable forest management paradigm in Canada.

Canada was an early adopter of sustainability in forestry, beginning with the Canadian Council of Forest Ministers' (CCFM) national forest strategy, *A National Forest Sector Strategy for Canada* (CCFM, 1988), and the National Forum on Forests and Sustainable Development in 1990 (CCFM, 1990). The CCFM subsequently released national strategies in 1992, 1998, and 2003, and a vision statement in 2008 (CCFM, 1992; CCFM, 1998; National Forest Strategy Coalition, 2003; CCFM, 2008). Also important were the Forestry Canada state-of-the-forest reports to Parliament (Forestry Canada, 1991; 1992; 1993). The CCFM defines sustainable forest management (SFM) as "Management that maintains and enhances long-term health of forest ecosystems for the benefit of all living things while providing environmental, economic, social, and cultural opportunities for present and future generations" (CCFM, 2008, p. 15).

A key initiative to emerge from the *Forest Principles* commitments to sustainable development in forestry established at the Rio Summit was criteria and indicators (C&I; UNCED, 1992). C&I provide a means to define the broad and ambitious concepts of sustainability in the context of forest management and to establish measurable goals to gauge progress towards sustainability (Wijewardana, 2008). We will define C&I as they are used in the Canadian forest sector, and specifically by the CCFM. A criterion is a collection or homogeneous category of values by which SFM is assessed (CCFM, 1995; Montréal Process, 1995). An indicator is some identified system component or variable that can be objectively and empirically measured to assess the status of a criterion or progress towards a goal associated with the SFM values of a criterion (CCFM, 1995; Prabhu et al., 1999; Duinker, 2001). It is also important to delineate the difference between action indicators and state indicators. Action indicators are so called because they track both the quality and quantity of management actions, such as the rate of compliance with soil disturbance standards. State indicators pertain to the state of a system of interest. One type of state indicator is the condition/response indicator, which tracks the response of phenomena to management action, such as the population levels of forest-associated species. Another is the context indicator, which also tracks system variables, but ones that cannot be directly influenced by management, such as the gross domestic product (GDP; Duinker, 2001).

There have been several international agreements and initiatives for C&I-SFM, such as the Montréal Process, the Helsinki Process (now called Forest Europe), and the International Tropical Timber Organization Process, which altogether involve almost 150 countries. The use of C&I-SFM to define and measure SFM progress has also been refined and implemented at the local, forest-management-unit scale (Duinker, 2001). A primary mechanism for this has been forest certification processes such as that of the Canadian Standards Association (CSA); the SFM standard (Z809) of 1996 relies on indicators directly linked to the CCFM criteria (CSA, 2009). There have been three significant national/international-scale C&I-SFM initiatives in Canada (Duinker, 2011): the CCFM's national framework of C&I-SFM (CCFM, 1995; CCFM, 2003), the Montréal Process and Santiago Declaration (Montréal Process, 1995), and the local-level indicators initiative of Canada's Model Forest Program (von Mirbach, 2000).

The Working Group on C&I for the Conservation and Sustainable Management of Temperate and Boreal Forests, called the Montréal Process for short, was formed in 1994, also in response to the Rio Summit principles, with 12 member countries comprising 83% of the world's temperate and boreal forests (Sato, 2009). In 1995 in Santiago, Chile, the member countries endorsed a framework of C&I-SFM to define and measure SFM and inform policy-makers through what is known as the Santiago Declaration (Montréal Process, 1995). Prior to the formation of the Santiago Declaration, the CCFM initiated a C&I Task Force to develop a national framework of C&I-SFM and meet our commitments to SFM made at the Rio Summit and in the 1992 national forest strategy (CCFM, 1992). The steering committee consisted of federal, provincial, and territorial governments and representatives from industry, academia, environmental/interest groups, and Aboriginal communities. In 1995, it released a national framework of C&I-SFM with six criteria and 83 indicators (CCFM, 1995). The C&I-SFM were first reported on in the 1997 technical report (CCFM, 1996) and then the 2000 national assessment report (CCFM, 2000), and a public review process was initiated soon after in 2001. The revised C&I-SFM, consisting of six criteria and 46 indicators, were released in 2003 and reported on in 2005 (CCFM, 2003; CCFM, 2006).

The 2003 C&I framework and 2005 national status report yielded vital insight into SFM progress in Canada, but did not address the threat of climate change to Canada's forests. There have been considerable advancements in the state of knowledge pertaining to climate change and forests since the last revision of the national C&I-SFM, so a review of the implications of climate change for Canada's ability to define and measure SFM progress would be timely and auspicious.

To address the implications of climate change for the Canadian forest sector and SFM, the CCFM created the Climate Change Task Force (CCTF) in 2008. The CCTF has since undertaken a major initiative on climate-change adaptation. Phase 1 of the initiative was completed in 2009 with a report on the vulnerability of Canadian tree species to climate change (Johnston et al., 2009). Phase 2 is currently underway, and focuses on the assessment of vulnerability of SFM to climate change and options for adaptation. As part of the phase 2 Adaptation Initiative, with funding from British Columbia's (BC) Future Forest Ecosystems Scientific Council (FFESC), the CCTF called for this review of the national framework of C&I-SFM in the context of climate change.

1.2. Climate Change and Forests

Climate change is likely to have profound effects on Canada's forest ecosystems and may disrupt the sustainable flow of their goods and services (Williamson et al., 2009; Johnston et al., 2010). Forest composition is expected to sustain considerable change over the next century, due primarily to climate-driven northward and upward shifts in the range and distribution of tree species (McKenney et al., 2007; Iverson et al., 2008). The effects of climate change on forest composition may cause severe and unexpected reordering of forest ecosystems, due to the changes in competitive and successional processes (Steenberg et al., 2010). Indeed, a frequently overlooked effect of climate change on forest composition is shifts in abundance and relative dominance of species and vegetation types, such as an increase in the abundance of deciduous shrubs and a decrease in bryophytes and lichens in the Arctic (Strum et al., 2001).

Another critical area of influence is the effects of climate change on the phenology of forest biota. A meta-analysis by Parmesan and Yohe (2003) of the global effects of climate change on the phenology of herbs, shrubs, trees, birds, butterflies, and amphibians revealed a mean 2.3-day shift towards earlier spring events. Climate-change impacts on tree phenology, such as the timing of spring budburst or seed-crop production, could have significant effects on forest ecosystem structure and function (van der Meer et al., 2002). However, there are also more complex implications arising from changes in phenologies. For example, climate warming is anticipated to affect the synchrony of forest insect herbivores and plants (Bale et al., 2002).

The forests in Canada's climatic extremes are particularly vulnerable to the changing climate and the advance of treelines at high altitudes and latitudes is a widely speculated and now observed impact (Aitken et al., 2008). Conversely, in warmer climes where forests are limited by moisture, such as in the western Canadian interior, a decrease in growing-season precipitation is expected to cause widespread forest decline and dieback (Hogg et al., 2008).

Another frequent prediction is that climate change will significantly influence the growth and productivity of terrestrial biota, including trees (Schimel et al., 2001; McMahon et al., 2010). However, there is a tremendous amount of uncertainty around the effects of climate change on forest productivity (Heimann & Reichstein, 2008), as they will likely be extremely variable by region, with continued increases in productivity at high altitudes and latitudes (Chaplin et al., 1995) and decreases in productivity in nutrient- and moisture-limited areas (Friend, 2010). A key determinant of the magnitude of change in forest composition and structure will be the effects of climate change on natural disturbance regimes (Dale et al., 2001).

Increases in temperature and precipitation, along with more frequent and extreme weather events, are all symptoms of the changing climate, and are expected to dramatically alter natural disturbance regimes within forest ecosystems (Intergovernmental Panel on Climate Change (IPCC), 2007). Natural disturbance events like wildfire, insect and disease outbreaks, windstorms and hurricanes, floods, and droughts are generally expected to increase in frequency and magnitude, which will have major consequences for forest ecosystem dynamics (Dale et al., 2001; Williamson et al., 2009). The effects of climate change on natural disturbance regimes have already been observed in Canada with more-severe fire seasons (Flannigan et al., 2009) and the devastating mountain pine beetle (*Dendroctonus ponderosae*) outbreak in western Canada (Kurz et al., 2008).

The biophysical impacts of climate change will certainly have implications for the social, economic, and cultural benefits from forests. Many studies have found that climate change will likely influence the production, consumption and international trade of timber products (Perez-Garcia et al., 2002; Kirilenko & Sedjo, 2007; Jonsson, 2009). A significant finding of these studies is that the global increase in timber supply is expected to cause a decline in prices, which subsequently will lead to an overall increase in consumption of forest products and economic welfare of the global forest sector (Irland et al., 2001; Perez-Garcia et al., 2002). The situation will of course be highly variable among countries. In a Canadian context, Perez-Garcia and colleagues (2002) predicted that despite the likely positive gains in timber supply due to climate change, the declining prices of timber products will lead to a decrease in total harvest rates in order to minimize economic losses to the forest sector. Moreover, Canada has a high cost of production for timber products, which is also predicted to negatively influence forest-sector economic welfare (Perez-Garcia et al., 2002).

Forest-based services and non-timber forest products are at risk from climate change as well. The recreational values of forests, particularly those in protected areas, will likely be affected due to more-frequent forest disturbances, as the mountain pine beetle epidemic has done for Banff and Kootenay National Parks (McFarlane et al., 2006). Moreover, protected areas may be considerably challenged in their future functioning due to the loss of biogeographic stability, which is fundamental to their purpose and planning (Scott & Lemieux, 2005). Social impacts of climate change will be more diverse and uncertain than the aforementioned biophysical ones (Duinker, 1990). Forest-dependent communities and Aboriginal populations are considered to be particularly vulnerable to global environmental change because of their dependence on forest resources and the close relationship they have with the natural environment (Beckley, 2000; Ford & Smit, 2004; Furgal & Seguin, 2006). Given these diverse and highly uncertain implications of a changing climate for SFM, it is exceedingly likely that our ability to define and monitor SFM progress using C&I-SFM will need to be critically analyzed for its robustness and suitability in the face of climate change.

1.3. Project Purpose and Objectives

C&I-SFM constitute a valuable science-based tool both to define the full spectrum of values associated with forests and their management and to measure and gauge the degree to which forests are being managed sustainably (CCFM, 2003; Duinker 2011). As of the 2008 vision statement, the CCFM has mandated that future climate change and variability must be considered in every aspect of SFM (CCFM, 2008). This must therefore include the methods by which we measure our progress towards SFM. The national framework of C&I-SFM was developed to have the quality and utility to track SFM progress with confidence. Because significant climate change in Canada is expected during the next century, and because climate is a strong driver and determinant of forests and the forest sector (Williamson et al. 2009), it is paramount that C&I-SFM have sufficient robustness to be both meaningful and valid in a changing climate. Some indicators will no doubt be independent of climate change, whereas others may need adjustment to retain ongoing relevance and rigour, and yet others may need to be abandoned. Given the imminence of climate change and the urgency of anticipatory adaptation, the CCFM made the timely decision to commission a review and evaluation of the C&I-SFM under a changing climate. This review was implemented in 2010-2011 by the CCFM's CCTF as part of the Phase 2 Adaptation Initiative.

The purpose of this project was to critically evaluate each of the CCFM indicators, as defined within the revised 2003 C&I framework (CCFM, 2003), for its suitability in defining and monitoring SFM in a changing climate. To approach this, we defined the following objectives:

- Review and evaluate each indicator in the national set for a) its relationships with climate, b) its systemic relationships with other indicators in the set, c) its robustness and utility in the face of climate change, and d) future prospects for the indicator including possible abandonment, improvement, or continued use unchanged;

- Make recommendations on improvements to the national indicator set as warranted to account for a changing climate, including possible additions to the indicator set, as well as recommendations on adjustments to the current approach to gauging SFM under a changing climate; and

- Communicate our findings in a full report as well as one or more journal papers.

The main analytical tool in this project was the evaluation protocol, which was applied to each of the 46 indicators from the 2003 framework. In the evaluation we attempted to decipher the often complex, uncertain, or ambiguous effects of climate change on indicator functioning and ability to gauge SFM progress. A key mechanism for analyzing the effects of climate change on the indicators was a set of indicator traits, which define the characteristics of a valid, relevant, and effective indicator (Duinker, 2001; CSA, 2009). In this report, we summarize the findings and recommendations from the evaluation of the 46 SFM indicators. We also discuss some broad, conceptual implications of climate change for the ability to define, implement, and monitor SFM in Canada. The findings in this study are meant to open a dialogue among forest practitioners and policy-makers on how best to address the changing climate in the development and application of C&I-SFM. They are not prescriptions for the final incorporation of climate change into the CCFM national C&I framework. We did not attempt to evaluate the 46 SFM indicators for their current effectiveness irrespective of climate change.

2. METHODS

2.1. Indicator Evaluations

For the review, we developed a three-stage evaluation protocol (Fig. 1). Stage one, the linkages assessment, was designed to delineate and examine the systemic relationships between indicators within the C&I framework. In stage two, the independent climate-change assessment, we assessed the implications of climate change for individual indicator effectiveness. Finally, in stage three, the integrated climate-change assessment, we evaluated any changes in indicator effectiveness associated with indirect climate-change influence via the relationships with other indicators. After evaluation, each indicator was assigned to one of four categories: a) uninfluenced indicators, which have no discernable interaction with climate change, both directly or indirectly, b) unmodified indicators, which are either unchanged by their interaction with climate change or where no possible modifications seem appropriate, c) modified indicators, which required modification to maintain or enhance their effectiveness under climate change, and d) abandoned indicators, which were degraded by climate change to the point where they were no longer valid or useful. A fifth category was also created for new indicators in response to climate change. The newly created indicators did not to replace existing indicators unless they were recommended for abandonment.

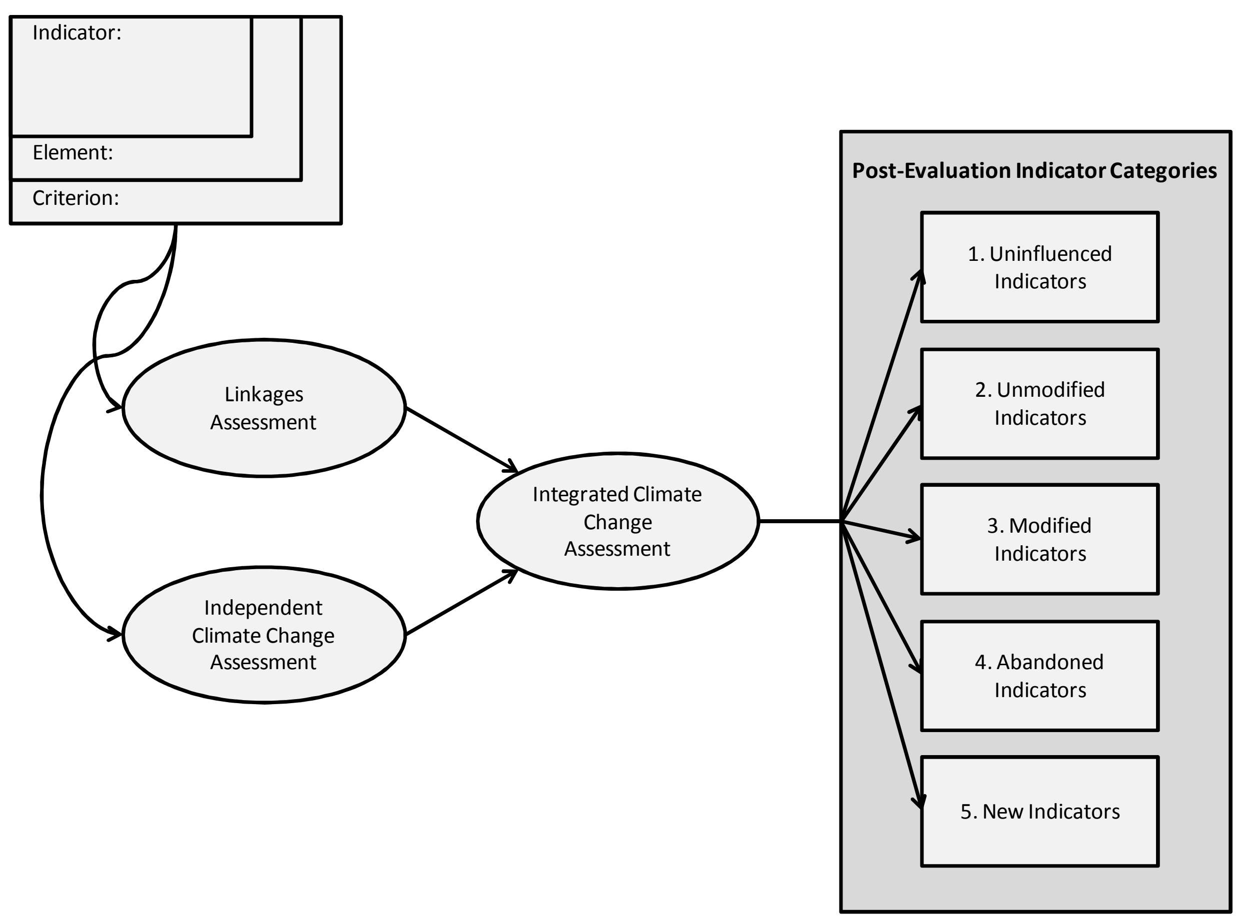

Figure 1. Design of the evaluation protocol used to assess the effects of climate change on each indicator in the CCFM's national framework of C&I-SFM.

2.1.1. Linkages Assessment

The development of C&I-SFM has often been seriously impeded in past initiatives because they failed to address relationships or linkages between indicators and between disciplines (Yamasaki et al., 2002). Indicators that have been developed in the confines of one discipline, whether in the biophysical, social, or economic realm, will be insufficient to address adequately the integrative nature of SFM that they are meant to define and measure. It stands to reason that an evaluation of the potential influence of climate change on C&I-SFM should avoid these same pitfalls. We therefore incorporated systems-analytical thinking into the approach to our analysis and explored the linkages among all indicators prior to the assessment of climate change.

The current CCFM C&I-SFM do not thoroughly address the complex linkages that exist among indicators within the framework. As such, our goal in the linkages assessment was to ascertain the extensive network of relationships among the SFM indicators so that these linkages could be incorporated into our climate-change assessments. Climate change was not addressed in this assessment, but rather this was a preliminary stage of evaluation prior to the independent and integrated climate-change assessments. Climate change may lead to further and unanticipated interactions among indicators, as well as cumulative effects from multiple interactions. These questions were also addressed in the integrated climate-change assessment. The method for determining the linkages between indicators was to systematically and conceptually assess every indicator's influence on a given indicator, and the influence of that given indicator on all others. Influences and the relationships between indicators were analyzed using the CCFM's 2003 framework and 2005 assessment report, as well as the scientific literature.

Influence could be positive, if an increase in the value of an indicator contributes to an increase in the value of another. For example, an increase in the additions of forest area (Indicator 2.2) would likely be associated with an increase in the distribution of forest-associated species (Indicator 1.2.3). Influence could be negative, if an increase in the value of an indicator contributes to a decline in the value of another. For example, a decline in the population levels of forest-associated species (Indicator 1.2.2) would likely equate to an increase in the risk status assigned to forest-associated species (Indicator 1.2.1). Finally, influence could be bi-directional in nature, which was the most common instance, given the complexity and uncertainty around linkages between indicators and the systems they monitor. For example, a change in forest type and age class (Indicator 1.1.1) may cause an increase or decrease in the population levels of forest-associated species (Indicator 1.2.2) because of the different habitat requirements for different species and taxonomic groups.

We also analyzed relationships and potential overlap with the ecological indicators developed in BC, under the Forest and Range Evaluation Program (FREP) and Future Forest Ecosystems Initiative (FFEI) partnership project (Eddington et al., 2009) under the FFESC. These 16 indicators and three criterion-like categories were developed to monitor key species and ecological processes in BC's forests and rangeland under climate change, and were a catalyst for the CCTF's initialization of this project. Box 1 shows the three questions applied to each indicator in the linkages assessment.

Box 1. Linkages Assessment Questions

1.1. Which indicators are influencing and influenced directly by the indicator in question? Is the indicator more of a driver of change in other indicators, or being driven by other indicators?

1.2. List the indicators described as 'relevant indicators under other criteria' in the 2003 C&I-SFM. Is there any conflict with the interactions described in the matrix?

1.3. Are there any overlaps or gaps in the relationship with indicators defined in the Eddington et al. (2009) report?

2.1.2. Independent Climate-Change Assessment

The impetus for our project was founded on the developing knowledge of climate change and forests, and the recognition that climate change may impede our ability to define and monitor SFM in Canada. Assessment of the effects of climate change on each individual indicator, independent of its linkages with other indicators, was done to ensure a detailed and uncluttered examination of all possible avenues of effects, prior to the integrated assessment. While the relationships with other indicators may open further possibilities for climate change to influence an indicator, we assumed that these relationships would never reduce or reverse the potential influence of climate change. Thus, the independent climate-change assessment was the logical second stage of evaluation. In the evaluation protocol, we refer to direct effects as the influence of climate change on the particular indicator under evaluation, while indirect effects refer to climate-change influence via interactions with other indicators, as defined in the linkages assessment.

The three questions applied to an indicator under evaluation (Box 2) were designed to detail a linear process for discovering how an indicator could potentially be degraded by climate change. The bulk of this assessment was the literature review of likely effects of climate change on the phenomenon measured by an indicator. Following this, we examined how an indicator may or may not be influenced by the changing climate.

Box 2. Independent Climate-Change Assessment Questions

2.1. Provide in detail a qualitative description of what are the expected direct effects of climate change on the indicator, using a broad representation from the literature.

2.2. Given expected changes in Canada's climate*, describe if and how the indicator's ability to signal progress towards SFM remains unchanged.

2.3. If an indicator's ability to signal progress towards SFM will be changed, describe if and how the indicator may become worse or better at signalling SFM progress.

*This study did not take into account any specific climate-change scenario, emissions scenario, or general circulation model. Expected changes in Canada's climate are based on the forest science literature and the choices and assumptions made in the studies cited.

2.1.3. Integrated Climate-Change Assessment

In the integrated climate-change assessment, the efforts of the two previous assessments were combined to explore both the direct and indirect effects of climate change on the indicators in order to assign indicators to one of the four final post-evaluation categories or create a new indicator. More specifically, a key focus of the integrated climate-change assessment was the indirect effects of climate change on the indicators through the complex network of interactions among them.

The integrated assessment consisted of twelve questions (Box 3) that were applied to each indicator. The first three questions (3.1 to 3.3) were designed as an in-depth analysis of the indicator's dynamics, by discovering exactly what other processes and variables the indicator is a driver for, what the determinants of the indicator are, and how these determinants interact cumulatively to influence the indicator. The following seven questions (3.4 to 3.10) were designed to explore the likely indirect and direct influence of climate change on an indicator, and resulted in the ultimate assignment of the indicator to the post-evaluation categories. The final two questions were somewhat separate from the assessment, but we felt were useful additions to the evaluation. Given the review of the entire C&I framework in light of the changing climate, new opportunities to improve our ability to model and monitor SFM in Canada may come to light. As such, we addressed potential opportunities in Question 3.11. In the final Question 3.12, we briefly addressed the regional variability in the influence of climate change on indicators in the C&I framework. The results of the independent and integrated climate-change assessments are presented jointly in the Section 3.2.

Box 3. Integrated Climate-Change Assessment Questions

3.1. What are the key determinants of the indicator (i.e. what causes it to change when it does change);

a) Among other indicators in the C&I framework?

b) Among determinants not within the C&I framework?

3.2. For what other entities is this indicator a key determinant (i.e. when it changes, what other indicators are influenced to change);

a) Among other indicators in the C&I framework?

b) Among determinants not within the C&I framework?

3.3. To what degree can we now, on the basis of extant knowledge, establish how the key determinants interact cumulatively in influencing the indicator?

3.4. Is the indicator largely unrelated to any other, as described by the linkages assessment and evaluation of key determinants? If so, and the indicator was defined as uninfluenced by climate change in the independent assessment, then it can be placed in category one.

3.5. Do the indirect effects of climate change via the linkages with other indicators influence the indicator's ability to signal SFM, regardless of which category was assigned in the independent climate-change assessment?

3.6. If the indicator's ability to signal SFM progress remains the same under a changing climate, can we conclude no negative influence and leave it unchanged? These indicators can be placed in category two.

Box 3. Integrated Climate Change Assessment Questions (Continued)

3.7. If the indicator's ability to signal SFM progress deteriorates when one assumes a changing climate, then what modifications are possible or warranted to improve its ability sufficiently for it to remain among the C&I-SFM? These indicators can be placed in category three.

3.8. If no modifications seem possible or warranted, are we prepared to recommend abandonment of the indicator? These indicators can be placed in category four.

3.9. If we recommend abandonment, can we identify any new and closely allied indicators that might suit our needs better under climate change? Are there any other reasons for the creation of an additional indicator? These indicators can be placed in category five.

3.10. Have extant climate-change impacts made this indicator more pertinent to SFM (e.g. 2.3 and the mountain pine beetle)? These indicators can be placed in category five or considered for conversion from a supporting to a core indicator (where applicable).

3.11. How should the surviving indicator (the original, modified, or new) be modelled and monitored so that stronger SFM signals may be generated?

3.12. Does this indicator track an entity whose relationship with climate is regionally variable?

2.2. Interpreting the Effects of Climate Change on Indicator Effectiveness

To understand and characterize the complex interactions of climate change with the ability of an indicator to track SFM progress, we analyzed the effects of climate change through seven indicator traits used to define their effectiveness (Johnson, 2000; Duinker, 2001; CSA, 2009). These traits included measurability, feasibility, predictability, relevance, responsiveness, understandability, and validity.

- **Measurability** refers to the degree to which a phenomenon can be objectively and empirically measured on a continual basis. More often than not, biophysical indicators are far more easily measured than socioeconomic and socio-political indicators. A simple example of the effects of climate change is that the predicted warmer temperatures and consequent increase in parasites, among other factors, will decrease moose populations (Thompson et al., 1998). Then, that smaller population, as an indicator, would become physically more difficult to count and less feasible to measurable. Levels of effort must go up, and levels of uncertainty rise as well. Conversely, climate change is predicted to lead to more invasive, alien species (Dukes et al., 2009), and those more-abundant species would become more feasible to count.

- **Feasibility** refers to how practical it is to measure an indicator, and how obtainable data are or expensive data collection is. Feasibility is inextricably linked to measurability, and is more of a limiting factor for indicator effectiveness, especially at the national scale. Any change in the measurability of an indicator caused by climate change will subsequently correspond to a change in feasibility for the same reasons. A population of moose that has become sparser under climate change will be more expensive and time consuming to measure and monitor over a period of time.

- **Responsiveness**, also called sensitivity, is the degree to which a phenomenon responds to management actions in known ways, and is a vital factor for indicator effectiveness. The same diminished population of afflicted moose might become far less sensitive to forest management actions due to increasing competition with deer, more parasites, physiological stress, and habitat alteration from more frequent natural disturbances (Thompson et al., 1998). The cumulative effects of these climatically introduced stressors would mean that the moose population is now far less proportionally affected by forest management activities in its habitat and therefore a poor signal of SFM.

- **Relevance** is an indicator's relationship to a defined SFM value within a criterion and the insight it provides into the sustainability of that value. The relevance of an indicator may increase or decrease with climate change. The expanding low-emissions industries of forest biomass and bioenergy have become more relevant due to climate change and major mitigation initiatives (Hall, 2002). A decline in relevance corresponds to a diminishing ability to interpret how changes in an indicator correspond to a given SFM value. Any decline in relevance due to climate change would only arise from a decline in responsiveness.

- **Predictability** is a more obscure trait than the others, but is fundamental in the context of SFM and adaptive management because it is the expected future range of an indicator by which we derive management goals and indicator targets (Duinker, 2001). Monitoring is inherently focused on the present and past, so the ability to predict, forecast, or model an indicator into the future is vital to gauging whether indicators will be within acceptable ranges or progressing towards desired targets. Climate change is not only a significant driver of change in forest ecosystems and SFM, but is also tremendously uncertain. Consequently, the predictability of indicators is highly sensitive to climate change, with a range of reductions in predictability expected.

- **Understandability** is a fairly obvious trait, as the SFM signal generated by an indicator must be clear and approachable to decision-makers and forest stakeholders. We have made the assumption that the understandability of an indicator is independent of climate change.

- **Validity** is the final trait of indicator effectiveness, and refers to the overall soundness of the science behind an indicator. Validity is a broad and overarching trait of indicator effectiveness, in some ways reflecting a synthesis of most of the other traits.

Each of the 46 indicators in the C&I framework have strengths and weaknesses against these traits. In our assessment, we focused entirely on the effects of climate change on the indicator traits, not the current effectiveness of the SFM indicators.

A final word on the study approach is in order. The study relied on the qualitative professional judgement of the four authors, three of whom (Duinker, Van Damme, and Zielke) are experienced forest-system analysts and one (Steenberg) a junior forest-systems analyst. We all have experience studying the links between climate change and sustainable forest management. The evaluation protocol was developed by us to represent a logical analytical framework that would enable other analysts to check our results. The relevant literatures on climate change and forest-sector responses were canvassed for insights to help address the questions. Because professional judgements can easily conflict and experts often disagree with each other in making such judgements, it is entirely possible for other experts to arrive at other outcomes and conclusions. Our team has converged on the findings in this report, and the multiple peer reviews we obtained have been vital in sharpening our judgement.

3. INDICATOR EVALUATION RESULTS

Table 1. The 2003 CCFM C&I framework.

1	**Biological diversity**
1.1	*Ecosystem diversity*
1.1.1	Area of forest by type and age class, and wetlands in each ecozone
1.1.2	Area of forest by type and age class, wetlands, soil types, and geomorphological features in protected areas in each ecozone
1.2	*Species diversity*
1.2.1	The status of forest-associated species at risk
1.2.2	Population levels of selected forest-associated species
1.2.3	Distribution of selected forest-associated species
1.2.4	Number of invasive, exotic forest-associated species
1.3	*Genetic diversity*
1.3.1	Genetic diversity of reforestation seed-lots
1.3.2	Status of *in situ* and *ex situ* conservation efforts of native tree species within each ecozone
2	**Ecosystem condition and productivity**
2.1	Total growing stock of both merchantable and non-merchantable tree species on forest land
2.2	Additions and deletions of forest area, by cause
2.3	Area of forest disturbed by fire, insects, disease, and timber harvest.
2.4	Area of forest with impaired function due to ozone and acid rain
2.5	Proportion of timber harvest area successfully regenerated
3	**Soil and water**
3.1	Rate of compliance with locally applicable soil disturbance standards
3.2	Rate of compliance with locally applicable road construction, stream crossing, and riparian zone management standards
3.3	Proportion of watersheds with substantial stand-replacing disturbance in the last 20 years
4	**Role in global ecological cycles**
4.1	*Carbon cycle*
4.1.1	Net change in forest ecosystem carbon
4.1.2	Forest ecosystem carbon storage by forest type and age class
4.1.3	Net change in forest products carbon
4.1.4	Forest sector carbon emissions
5	**Economic and social benefits**
5.1	*Economic benefits*
5.1.1	Contribution of timber products to the gross domestic product
5.1.2	Value of secondary manufacturing of timber products per volume harvested
5.1.3	Production, consumption, imports, and exports of timber products
5.1.4	Contribution of non-timber forest products and forest-based services to the gross domestic product
5.1.5	Value of unmarketed non-timber forest products and forest-based services
5.2	*Distribution of benefits*
5.2.1	Forest area by timber tenure
5.2.2	Distribution of financial benefits from the timber products industry
5.3	*Sustainability of benefits*
5.3.1	Annual harvest of timber relative to the level of harvest deemed to be sustainable
5.3.2	Annual harvest of non-timber forest products relative to the levels of harvest deemed to be sustainable
5.3.3	Return on capital employed
5.3.4	Productivity index
5.3.5	Direct, indirect, and induced employment
5.3.6	Average income in major employment categories
6	**Society's responsibility**

6.1	*Aboriginal and treaty rights*
6.1.1	Extent of consultation with Aboriginals in forest management planning and in the development of policies and legislation related to forest management
6.1.2	Area of forest land owned by Aboriginal peoples
6.2	*Aboriginal traditional land use and forest-based ecological knowledge*
6.2.1	Area of forested Crown land with traditional land use studies
6.3	*Forest community well-being and resilience*
6.3.1	Economic diversity index of forest-based communities
6.3.2	Education attainment levels in forest-based communities
6.3.3	Employment rate in forest-based communities
6.3.4	Incidence of low income in forest-based communities
6.4	*Fair and effective decision-making*
6.4.1	Proportion of participants who are satisfied with public involvement processes in forest management in Canada
6.4.2	Rate of compliance with sustainable forest management laws and regulations
6.5	*Informed decision-making*
6.5.1	Coverage, attributes, frequency, and statistical reliability of forest inventories
6.5.2	Availability of forest inventory information to the public
6.5.3	Investment in forest research, timber products industry research and development, and education
6.5.4	Status of new or updated forest management guidelines and standards related to ecological issues

3.1. Linkages Assessment

The biophysical indicators of Criteria 1 through 4 were found to be far more interrelated with other indicators in the framework than the socioeconomic and socio-political indicators of Criteria 5 and 6 (Fig. 2). Indicators from the Biological Diversity Criterion and Ecosystem Condition and Productivity Criterion had by far the most interactions, on average. These indicators also had the most overlap with the FFEI indicators described by Eddington et al. (2009). Some notable exceptions from these trends were Indicators 5.3.1 and 5.3.2, the former being the most inter-related indicator in the framework with 31 interactions (Fig. 3). Indicators 6.4.2 and 6.5.4 were also highly interrelated socio-political action indicators. Indicators 6.1.1, 6.5.1, and 6.5.2 were the only indicators in the C&I framework found to have no interactions with others. Criterion 6 also contained indicators with the fewest interactions, on average.

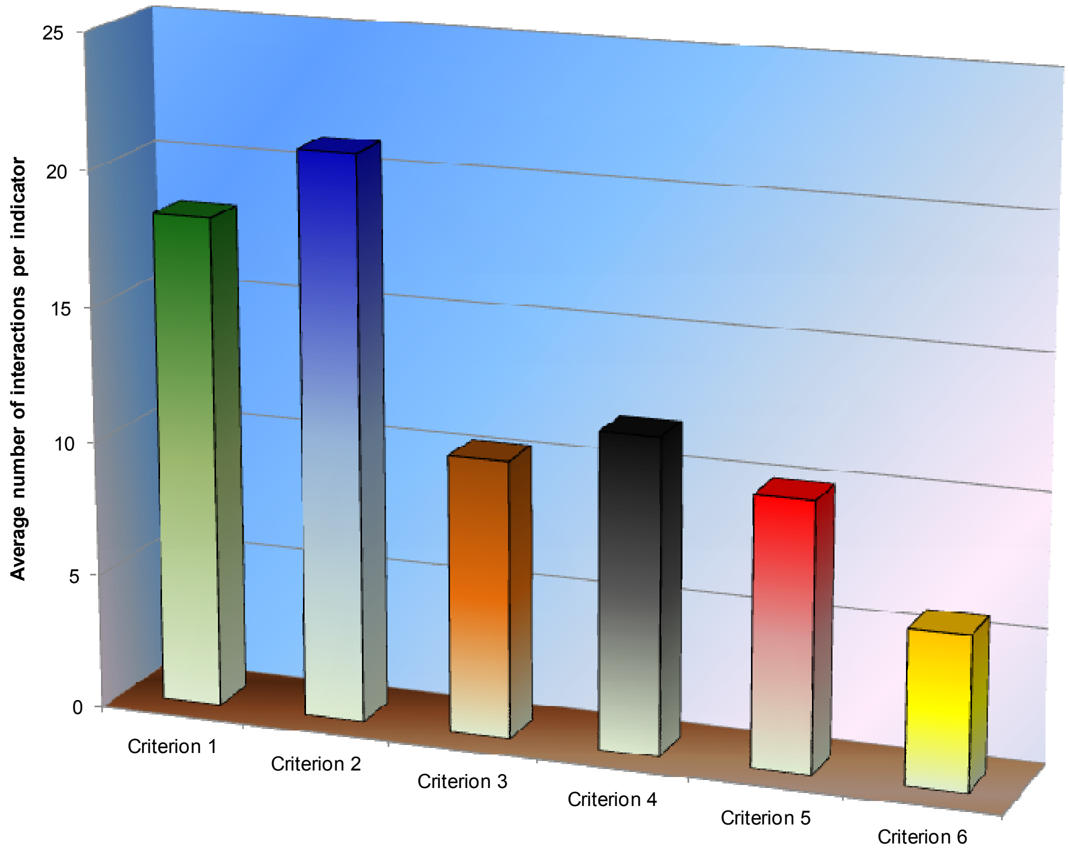

Figure 2. The average number of interactions per indicator in each criterion.

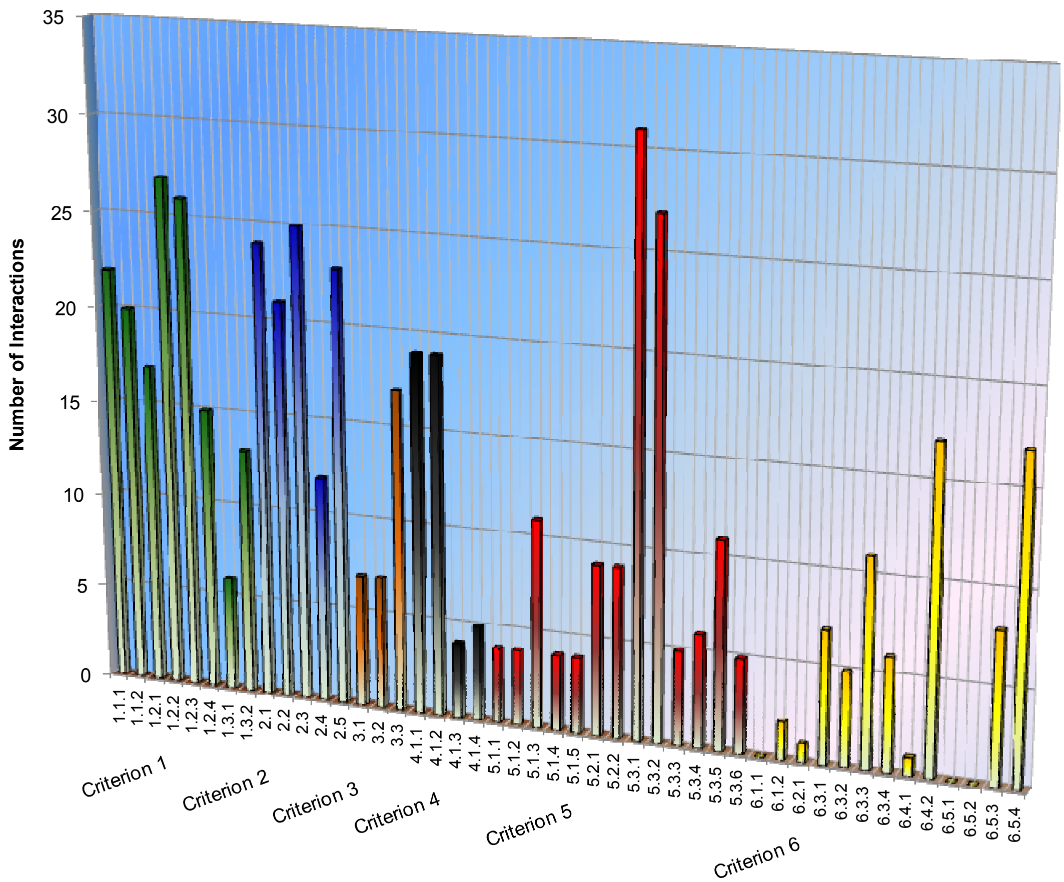

Figure 3. Total number of interactions for each indicator.

In the linkages assessment, indicators were described as being either a key driver of change or largely driven to change by other indicators. The distribution of these two types of indicators (Fig. 4) was fairly random within all criteria except for Criterion 3, which consisted entirely of driver indicators, and Criterion 4, which consisted entirely of indicators that were driven to change. A key agent determining this distribution was the presence or absence of action indicators versus state indicators, and is discussed in Section 4. It is also important to note that the majority of indicators that were found to be uninfluenced by climate change were also largely unrelated to other indicators in the framework. This emphasises the role of indirect climate-change influence and the importance of this linkages assessment and systems-analytical thinking within C&I-SFM.

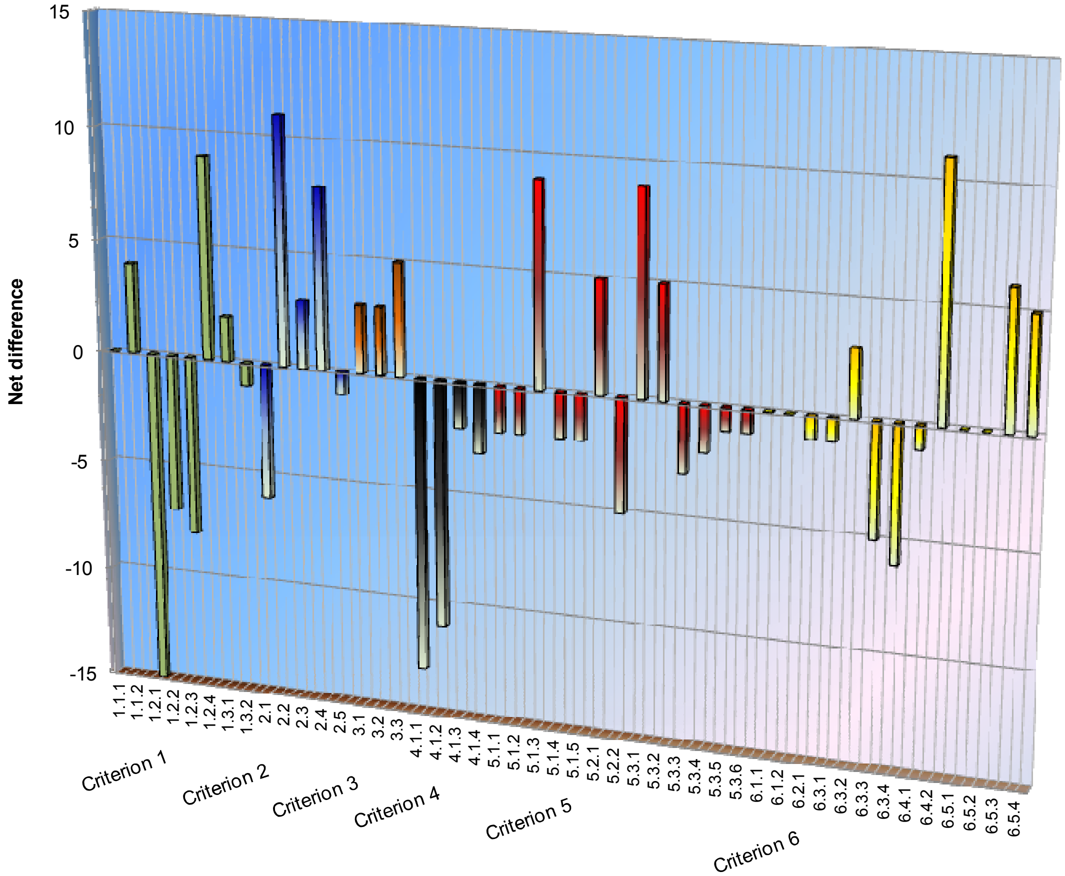

Figure 4. The net difference between the number of other indicators influenced by a given indicator and the number of other indicators influencing a given indicator. A positive number implies that the indicator is more of a driver of change than driven to change, and a negative number implies the opposite.

A component of the linkages assessment was comparing the CCFM indicators with the ecological indicators created by Eddington and colleagues (2009) under the partnership of the FFEI and BC's FREP. The purpose of developing these indicators was for the "development of a strategy for monitoring forest and rangeland species and ecosystem processes to anticipate and effectively respond to climate change" (Eddington et al., 2009, p. 5). This sub-national framework of three criterion-like categories (Ecosystem Drivers, Natural Disturbances, and Biodiversity) and 16 indicators was designed specifically for the province of BC and had a strong focus on data availability and collaboration with existing monitoring networks.

There were several high-order differences between the FFEI indicators and the CCFM C&I framework. First, the former were all biophysical state indicators and therefore only overlapped with the four biophysical criteria of the CCFM's framework, mainly Criteria 1 and 2. Another important distinction was that outside of the five Biodiversity indicators, the FFEI indicators were primarily designed to track major drivers of forest ecosystems that will be influenced by climate change, rather than the response of these systems to natural drivers, management, political and socioeconomic change, and of course climate change. Thus, the FFEI indicator set serves largely as an early warning system for climate-change impacts, rather than monitoring the forest sector to gauge whether SFM values are being satisfied. This distinction is critical - while there was some overlap with CCFM indicators, the two frameworks are significantly different in their intent.

Despite the distinctions above, there was notable overlap in the data needs of the two indicator sets where they spatially overlap in BC. If collaboration were to be sought between the CCFM C&I national assessments and the sub-national FFEI monitoring initiative, overlap in the data needs for the following CCFM indicators should be considered: 1.1.1, 1.1.2, 1.2.2, 1.2.3, 1.2.4, 1.3.2, 2.1, 2.3, 3.3, 4.1.1, and 4.1.2. More-detailed descriptions of the comparisons are available in the separate Indicator Evaluations report containing the 46 indicator evaluations.

3.2. Independent and Integrated Climate Change Assessments

The completed evaluations of all indicators from the CCFM's national framework of C&I-SFM can be found in the separate Indicator Evaluations report. The following six sections summarize the evaluations of the 46 indicators and are organized by Criterion.

3.2.1. Criterion 1

The biophysical indicators within Criterion 1 (Table 2) were highly susceptible to the changing climate, as biological diversity at all scales is intrinsically linked to the surrounding climate. Indicators 1.1.1 and 1.1.2 represent the Ecosystem Diversity Element, tracking forest type, age, and area, and wetlands in and out of protected areas, and were both assigned to the unmodified category. Both these indicators were broad and encompassing in what was measured in the 2005 assessment, with a total of 20 measured variables (CCFM, 2005). The anticipated effects of climate change on species distribution, natural disturbance regimes, and hydrological processes, as well as the sheer breadth of what was measured by the Indicators suggests that Indicator 1.1.1, and to a lesser degree Indicator 1.1.2, were among the indicators most afflicted by climate change, with a decline in the predictability, responsiveness, and relevance of the Indicators. However, these indicators are at foundation of SFM monitoring, which negates any alternative approaches to measurement and therefore any possible modifications that could mitigate the deterioration of these indicator traits.

Table 2. Evaluation results for Criterion 1, Biological Diversity.

Indicator	Outcome	New/Modified Indicator
1.1.1 Area of forest by type and age class, and wetlands in each ecozone	Unmodified	-
1.1.2 Area of forest by type and age class, wetlands, soil types, and geomorphological features in protected areas in each ecozone	Unmodified/ New Indicator	Connectivity of protected areas
1.2.1 The status of forest-associated species at risk	Unmodified	-
1.2.2 Population levels of selected forest-associated species	Modified	Population levels of selected forest-associated species*
1.2.3 Distribution of selected forest-associated species	Unmodified	-
1.2.4 Number of invasive, exotic forest-associated species	Modified	Area of forest disturbed by native and alien invasive forest-associated species

Indicator	Outcome	New/Modified Indicator
1.3.1 Genetic diversity of reforestation seed-lots	Uninfluenced/ New Indicator	Proportion of tenured forest area with seed transfer guidelines that account for climate change
1.3.2 Status of *in situ* and *ex situ* conservation efforts of native tree species within each ecozone	Unmodified	-

*The Indicator was modified in how it is measured, not what it measures, so its naming was left unchanged.

Indicator 1.1.2 is highly related to 1.1.1 and vulnerable to all the aforementioned climate-change impacts. But because its function in signalling progress towards SFM is to yield insight into the ability to protect representative forest areas (CCFM, 2006), we found it to be further compromised by climate change due to the core assumption of biogeographic stability in the protected areas system. Because of this loss of biogeographic stability and the shifting ranges and relative abundance of species, we recommended the creation of an additional indicator to track the connectivity of protected areas. Given the degree to which Indicators 1.1.1 and 1.1.2 are interrelated with other indicators in the framework and the fact that they track physical forest-ecosystem conditions within Canada and its terrestrial ecozones, they are arguably one of the most fundamental pieces of information pertaining to biological diversity. Therefore, we saw no possible justification in abandoning these indicators in light of climate change.

The Species Diversity indicators were also found to be affected quite extensively by climate change, resulting in the modification of Indicators 1.2.2 and 1.2.4. Indicator 1.2.1 was somewhat anomalous, as the status of forest-associated species that it tracks refers to the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) risk status (CCFM, 2006). Therefore, the indicator's capacity under climate change is dependent on the COSEWIC status assessment and designation process. Fortunately, climate change is being more frequently considered in this process and Indicator 1.2.1 was subsequently assigned to the unmodified category.

Indicators 1.2.2 and 1.2.3 are similar in concept but quite different in terms of what is measured and tracked. Indicator 1.2.2 currently tracks population levels of ten mammal species and 31 bird species, while Indicator 1.2.3 tracks four species with detailed case studies (CCFM, 2006). Consequently, we feel that the decline in predictability, responsiveness, and relevance of these indicators was unacceptable and warranted modification to Indicator 1.2.2, but not to Indicator 1.2.3. Since climate change may cause both increases and decreases in the population levels of some forest-associated species, both directly and indirectly and often in an unpredictable manner, their ability to signal SFM is compromised. Species monitored by Indicator 1.2.2 in the future will need to be either relatively uninfluenced by climate change, or have a climate-change response that is adequately researched and understood. This will certainly result in the abandonment of some of the 41 species currently monitored. The more-focused and in-depth approach to the measurement of Indicator 1.2.3 suggested a smaller decline in the strength of its SFM signal, and it was left unmodified.

Invasive, alien, forest-associated species will likely become more abundant and detrimental to forest ecosystems and the sustainable flow of their resources under climate change. Therefore, Indicator 1.2.4 not only suffered a considerable decline in its predictability, but also an increase in its relevance. The impetus behind the switch to measuring area disturbed rather than the number of species was that it could be more easily aligned with a directional goal statement; the minimization of forest area disturbed by invasive species. Moreover, the mountain pine beetle is an example of how climate change may destabilize the population dynamics of native forest-associated biological disturbance agents. As such, we also modified the indicator to track both native and alien invasive species.

Indicator 1.3.1 offers a relatively simple measure of genetic diversity by assessing the number parents used for collecting seed of regeneration seed-lots, and as an action indicator, it was largely uninfluenced by climate change and was assigned to the uninfluenced category. However, the rate and magnitude of climate change in Canada may lead to a decline in the genetic diversity of tree species. One potential adaptation to this is adjusting jurisdictional seed-transfer guidelines to promote assisted migration of more southerly genetic resources. This issue has serious implications for the relevance of Indicator 1.3.1, yet the current structure of the indicator does not reflect this. We therefore recommended a new indicator for the Genetic Diversity Element to track seed-transfer updates on public land.

Indicator 1.3.2, another action indicator, has two key components, *in situ* and *ex situ* conservation efforts for native tree species, which were afflicted by climate change in differing ways. The *ex situ* component of the Indicator was relatively uninfluenced by climate change. The *in situ* component shares the same assumption of biogeographic stability as Indicator 1.1.2, and thus was reduced in its ability to monitor SFM progress. We saw no possible modifications that would mitigate the decline in this indicator's effectiveness. However, it is reasonable to assume that many of the *in situ* and especially the *ex situ* conservation efforts will adapt to incorporate the additional threats of climate change. In this case, the current design of Indicator 1.3.2 is sufficient to monitor these potential adaptations.

3.2.2. Criterion 2

Indicators within Criterion 2 were the most directly affected by climate change, resulting in recommendations for two modifications and two new indicators (Table 3). These five biophysical state indicators are also all relatively well researched in the climate-change literature and far more tractable than most of the indicators within Criteria 5 and 6. Therefore, the evaluation of, and recommendations for, these indicators were more in-depth and developed than many of the more conceptual and ambiguous socioeconomic and socio-political indicators.

Table 3. Evaluation results for Criterion 2, Ecosystem Condition and Productivity.

Indicator	**Outcome**	**New/Modified Indicator**
2.1 Total growing stock of both merchantable and non-merchantable tree species on forest land	Modified/ New Indicator	Total growing stock of both merchantable and non-merchantable tree species on forest land*/ Average, minimum, and maximum temperature
2.2 Additions and deletions of forest area, by cause	Unmodified	-
2.3 Area of forest disturbed by fire, insects, disease, and timber harvest.	Modified	Area of forest disturbed, by cause
2.4 Area of forest with impaired function due to ozone and acid rain	Unmodified	-
2.5 Proportion of timber harvest area successfully regenerated	Unmodified/ New Indicator	Area of Crown forest with assisted migration initiatives

*The indicator was modified in how it is measured, not what it measures, so its naming was left unchanged.

Indicator 2.1 tracks merchantable volume and was found to gain in relevance from observed and anticipated effects of climate change, but was also expected to decline in predictability and measurability. The SFM signal generated by Indicator 2.1 was slightly diminished, not because of how we interpret growing stock and its relation to SFM in a changing climate (i.e. its relevance), but because of how it is often measured and the predictability of these measurements. The measurement has a reliance on pre-established relationships and processes in forest ecosystems that are based on historically stable climates. Thus, inventory and modelling methods will need to be modified to account for a variable climate. The creation of a new indicator to track temperatures was also recommended because of its importance for phenology, tree growth performance, and forest productivity.

Indicator 2.2, though having numerous interactions with climate change, was not found to be overly diminished in its effectiveness. Climate change may directly influence forest area through species migration and dieback and indirectly through new afforestation and carbon sequestration policies, which increased the relevance of Indicator 2.2 in a changing climate. Moreover, the proliferation of remote-sensing technologies may improve the feasibility of monitoring the indicator in the future. The decline in predictability was found for nearly every biophysical state indicator, and in this case we felt it did not overly diminish the Indicator's SFM signal and we assigned it to the unmodified category.

Indicator 2.3 greatly increased in its relevance to SFM because of the more frequent and severe natural disturbance events, as is already being observed across Canada. The decline in predictability of Indicator 2.3 was concerning, given the major influence of Indicator 2.3 on other indicators in the C&I framework, though we saw no possible modifications that could minimize this decline in predictability. However, given the increased relevance of natural disturbance in a changing climate, we did recommend modifying the Indicator to incorporate other major forms of natural disturbance.

Indicator 2.4 tracks forest area disturbed by ozone and acid rain, and was far more linked with anthropogenic emissions from fossil-fuel combustion than the resulting climatic change. However, there was some decline in the predictability of the indicator due to the influence of changing precipitation rates and temperatures with acid rain and tropospheric ozone, respectively. Despite this drop in predictability, we felt that Indicator 2.4 would remain largely unchanged in its ability to signal SFM progress and we assigned it to the unmodified category.

Indicator 2.5 was also left unmodified, but resulted in the recommendation of a new indicator. We surmised that the indicator experienced major declines in predictability and responsiveness because of the anticipated impacts of climate change. The relevance of Indicator 2.5 to SFM also increased given the vulnerability of forest regeneration to climate change. We felt that the best approach to address the introduced uncertainty and relevance from climate change was to create a new indicator as opposed to modifying the original Indicator 2.5, which was assigned to the unmodified category. The newly created indicator tracks assisted migration initiatives on public land, since this is an adaptation to climate-change impacts on natural regeneration that is growing in relevance. However, assisted migration is still a new and developing science and practice, with many uncertainties. Consequently, further research into its effectiveness and appropriateness is needed.

3.2.3. Criterion 3

Criterion 3 contains three indicators, the least of the six criteria. Indicators 3.1 and 3.2 are action indicators tracking compliance rates with various standards, and were found to be uninfluenced by climate change (Table 4). Indicators 3.1 and 3.2, along with Indicator 1.3.1 (another action indicator), were the only biophysical indicators to be uninfluenced by climate change. Some observed and potential climate-change impacts are relevant to Criterion 3, such as changes in decomposition rates of dead organic matter, soil disturbance arising from less frozen-ground conditions, and changes in hydrological processes, but they were not captured by Indicators 3.1 and 3.2.

Table 4. Evaluation results for Criterion 3, Soil and Water.

Indicator	Outcome	New/Modified Indicator
3.1 Rate of compliance with locally applicable soil disturbance standards	Uninfluenced	-
3.2 Rate of compliance with locally applicable road construction, stream crossing, and riparian zone management standards	Uninfluenced	-
3.3 Proportion of watersheds with substantial stand-replacing disturbance in the last 20 years	Unmodified/ New Indicator	Rate and form of precipitation

Indicator 3.3 has considerable overlap with Indicator 2.3, and naturally was influenced to some degree by the effects of climate change on natural disturbance regimes. The most notable effects of climate change on the indicator were a decline in predictability. However, the SFM values associated with Criterion 3 and Indicator 3.3 are the maintenance of soil and water resources, not ecosystem condition and productivity. Therefore, we chose to leave the indicator unmodified and created a new indicator in response to the likely impacts of climate change on hydrological processes. This new indicator may also satisfy some of the current misalignment of the indicator with its described goal of monitoring major changes in water yield, timing, and peak flow (CCFM, 2003).

3.2.4. Criterion 4

All four indicators in Criterion 4 are within the Carbon Cycle Element, tracking the Canadian forest’s contribution in global carbon cycling. Criterion 4 is unique in the framework in that it expressly addresses climate change (CCFM, 2003), and its indicators were all found to track phenomena that can potentially mitigate climate change and were all therefore more relevant in the face of global environmental change (Table 5). Two out of four indicators were modified, a new indicator was created, and all were influenced by climate change to some degree. Indicators 4.1.1 and 4.1.2 both track the carbon stored in forest ecosystems and are similar in design. As such, they both were subject to the same recommendations for modification. These indicators suffered from the same decline in measurability, and arguably in validity, as Indicator 2.1. Climate change is predicted to affect the physiological growth rate of trees and the productivity of forests, as well as decomposition rates of dead organic matter, which invalidates some of the core assumptions of how we measure net changes in forest carbon. Consequently, Indicators 4.1.1 and 4.1.2 were both assigned to the modified category.

Table 5. Evaluation results for Criterion 4, Role in Global Ecological Cycles.

Indicator	Outcome	New/Modified Indicator
4.1.1 Net change in forest ecosystem carbon	Modified	Net change in forest ecosystem carbon*
4.1.2 Forest ecosystem carbon storage by forest type and age class	Modified	Forest ecosystem carbon storage by forest type and age class*
4.1.3 Net change in forest products carbon	Unmodified/ New Indicator	Carbon emissions avoided through product substitution
4.1.4 Forest sector carbon emissions	Unmodified	-

*The Indicator was modified in how it is measured, not what it measures, so its naming was left unchanged.

Indicator 4.1.3 tracks carbon stored in forest products and was much more relevant in a changing climate, though we did not modify the Indicator. Instead, given the growing recognition of forest products carbon and the carbon emissions avoided through product substitution to mitigate climate change, we recommended the creation an additional indicator to track emissions avoided through product substitution. However, it will be important to examine what we classify as forest products in the future measurement of this indicator, considering the growing relevance of bioproducts, biofuels, and other forest-derived products.

Indicator 4.1.4 also increased in relevance because of the contribution of forest-sector emissions to climate forcing by anthropogenic greenhouse gas emissions. Future uncertainty around the magnitude and rate of climate change and society's response, namely the employment of policy tools for emissions reductions, also confounded the predictability of Indicator 4.1.4. However, unlike more complex and inclusive indicators like Indicators 1.1.1 and 2.3, Indicator 4.1.4 is relatively simple and transparent, so we felt no modifications were necessary to maintain its SFM signal.

3.2.5. Criterion 5

Indicators within Criterion 5 track the social and economic benefits derived from forests, and were far more difficult to evaluate in light of climate change (Table 6). While on average the indicators within Criteria 5 and 6 were less influenced by climate change, it was far more difficult to expose and quantify the full suite of direct and indirect effects of climate change on social systems and the indicators that track them, in comparison to those that track ecological systems (Beckley, 2000). The economic indicators of Element 5.1 were influenced by climate change to varying degrees. Indicator 5.1.1 and 5.1.4 are simple economic measures similar in design that track the contribution of timber products, non-timber forest products, and forest-based services to the GDP. Indicator 5.1.4 was modified to include the contribution of biotechnologies, bioproducts, and carbon credits to the GDP. Indicator 5.1.1 was similarly modified to include the contribution of bioenergy generated from forest biomass to the GDP. This subsector is increasing in relevance as a low-emissions substitute for fossil fuels in light of climate change.

Table 6. Evaluation results for Criterion 5, Economic and Social Benefits.

Indicator	Outcome	New/Modified Indicator
5.1.1 Contribution of timber products to the gross domestic product	Modified	Contribution of timber products to the gross domestic product*
5.1.2 Value of secondary manufacturing of timber products per volume harvested	Unmodified	-
5.1.3 Production, consumption, imports, and exports of timber products	Unmodified	-
5.1.4 Contribution of non-timber forest products and forest-based services to the gross domestic product	Modified	Contribution of non-timber forest products and forest-based services to the gross domestic product*
5.1.5 Value of unmarketed non-timber forest products and forest-based services	Unmodified	-
5.2.1 Forest area by timber tenure	Modified	Forest area by timber tenure*
5.2.2 Distribution of financial benefits from the timber products industry	Unmodified	-
5.3.1 Annual harvest of timber relative to the level of harvest deemed to be sustainable	Unmodified	-
5.3.2 Annual harvest of non-timber forest products relative to the levels of harvest deemed to be sustainable	Unmodified	-
5.3.3 Return on capital employed	Uninfluenced	-
5.3.4 Productivity index	Uninfluenced	-
5.3.5 Direct, indirect, and induced employment	Unmodified	-
5.3.6 Average income in major employment categories	Uninfluenced	-

*The Indicator was modified in how it is measured, not what it measures, so its naming was left unchanged.

Indicator 5.1.2 suffered a decline in predictability due to the indirect effects of climate change on the supply of wood fibre. The linear dependence of secondary manufacturing on the supply of primary manufactured products make fluctuations in this indicator easily understandable, despite the likelihood that climate change will influence the flow of primary timber products. Therefore, Indicator 5.1.2 was assigned to the unmodified category.

Indicator 5.1.3 is highly dependent on external factors, especially ones external to the C&I framework and to Canada, which run the gamut from the price of fuel to consumer preferences and trade patterns. These relationships obscured the influence of climate change on quality, quantity, and type of wood available, and subsequently the production, consumption, and trade of timber products, thereby diminishing the SFM signal generated by Indicator 5.1.3. However, Canada is the world's biggest exporter of forest products (CCFM, 2006), so monitoring international trade is critical to SFM. Furthermore, Indicator 5.1.3 was found to be highly influential on other socioeconomic indicators within Criterion 5. So while no modifications were deemed appropriate, we were not ready to abandon the indicator and it was assigned to the unmodified category. Indicator 5.1.5 tracks the value of unmarketed forest-based services and products. This indicator has existing challenges in its measurability and feasibility. However, the influence of climate change alone does not warrant any action, and the indicator was left unmodified.

Indicator 5.2.1 tracks the type and distribution of forest tenures on public land, and is an important indicator for the distribution of benefits from the forest sector. The ability of Indicator 5.2.1 to signal SFM progress may be slightly diminished if it does not incorporate emergent societal demand for climate-change mitigation and adaptation on public land. This was largely addressed by the creation of new indicators under Criteria 1 and 2. We did however recommend modifying the Indicator so that the proportion of tenured area with agreements that specifically address climate change would also be measured. Indicator 5.2.2 tracks the distribution of financial benefits specifically, and was assigned to the unmodified category, as most of the economic impacts of climate change were far removed from the indicator and only marginally reduced its predictability.

Indicators 5.3.1 and 5.3.2 are two of the most influential and important indicators in the framework as they track the flow of timber and non-timber forest products from forest ecosystems in Canada. Both indicators were influenced by climate change but were left unmodified. The anticipated impacts of climate change and the already observed alterations to annual allowable cut (AAC) in response to the mountain pine beetle outbreak meant a considerable decline in the predictability of these indicators. However, these two indicators, Indicator 5.3.1 especially, are at the core of SFM in Canada, and we saw no possible modifications or alternative indicators to alleviate the decline in predictability of these two vital measures. Moreover, because they interact so heavily with the biophysical indicators and are therefore influenced by climate change indirectly, it was hoped that much of the decline in the effectiveness of these two indicators would be addressed by the new and modified indicators within Criteria 1 through 4.

Indicators 5.3.3 and 5.3.4 are two traditional economic indicators used the gauge the economic welfare of an industry. Both indicators are largely unrelated to other indicators in the C&I framework and were both determined to be uninfluenced by climate change. Indicators 5.3.5 and 5.3.6 track employment variables in the forest sector. Indicator 5.3.6 tracks the distribution of income in employment categories and was deemed uninfluenced by climate change. Indicator 5.3.5 sustained a decline in predictability due to short- and long-term fluctuations in employment deriving from climate change. It also increased in relevance in light of emerging subsectors like carbon markets and bioenergy, as well as job creation from assisted migration and research to discover new forest practices and products. Indicator 5.3.5 is also a widely accepted and used indicator of economic and social welfare, so modifications to the indicator would be both unfavourable and unrealistic, despite the influence of climate change on its effectiveness.

3.2.6. Criterion 6

Criterion 6 indicators of social responsibility were the most uninfluenced by climate change of all the criteria of SFM (Table 7). As previously mentioned, these social indicators were far more difficult to evaluate for their interaction with climate change, as all or any effects of climate change were indirect and frequently ambiguous. However, many of these indicators were genuinely independent of climate and climate change and eight of the 13 indicators are action indicators. Several of the indicators were evaluated in groups, which was done not because they were considered less important but because they were closely related and largely independent of climate change.

Table 7. Evaluation results for Criterion 6, Society's Responsibility.

Indicator	Outcome	New/Modified Indicator
6.1.1 Extent of consultation with Aboriginals in forest management planning and in the development of policies and legislation related to forest management	Uninfluenced	-
6.1.2 Area of forest land owned by Aboriginal peoples	Unmodified	-
6.2.1 Area of forested Crown land with traditional land use studies	Unmodified	-
6.3.1 Economic diversity index of forest-based communities	Unmodified	-
6.3.2 Education attainment levels in forest-based communities	Uninfluenced	-
6.3.3 Employment rate in forest-based communities	Unmodified	-
6.3.4 Incidence of low income in forest-based communities	Unmodified	-
6.4.1 Proportion of participants who are satisfied with public involvement processes in forest management in Canada	Uninfluenced	-
6.4.2 Rate of compliance with sustainable forest management laws and regulations	Uninfluenced	-
6.5.1 Coverage, attributes, frequency, and statistical reliability of forest inventories	Uninfluenced	-
6.5.2 Availability of forest inventory information to the public	Uninfluenced	-
6.5.3 Investment in forest research, timber products industry research and development, and education	Modified	Investment in forest research, timber products industry research and development, education, and climate change adaptation and mitigation
6.5.4 Status of new or updated forest management guidelines and standards related to ecological issues	Modified	Status of new or updated forest management guidelines and standards related to ecological issues*

*The Indicator was modified in how it is measured, not what it measures, so its naming was left unchanged.

Indicators 6.1.1, 6.1.2, and 6.2.1 are action indicators that track Aboriginal rights, land use, and traditional knowledge, and were all left unmodified. Indicator 6.1.1 was deemed to be uninfluenced by climate change. Indicators 6.1.2 and 6.2.1 both had some decline in their predictability due to the effects of climate change, most notably tree-line advance in Canada's northern regions and the threats to traditional knowledge arising from environmental change. However, no modifications were considered to be necessary for these two indicators to remain effective SFM signals.

The four socioeconomic indicators used to track forest-dependent community well-being in Element 6.3 were also evaluated jointly. Indicators 6.3.1, 6.3.3, and 6.3.4 were all influenced by climate change in a near-identical fashion. The short- and long-term ecological, economic, and social impacts of climate change will reduce the predictability of these three socioeconomic state indicators. However, these three indicators are well established measures of community well-being and resilience (Beckley, 2000), so it is more than likely that these will remain a vital tool in monitoring SFM progress in relation to society's responsibility in managing the economic and social benefits of forests in Canada as the climate changes. They were therefore all assigned to the unmodified category. Indicator 6.3.2 tracks education attainment levels, and was determined to be uninfluenced by climate change, as it tracks a climatically insensitive phenomenon.

Indicator 6.4.1 tracks satisfaction with the public engagement process in forest management in Canada. The indicator was almost entirely unrelated to climate change and had no decline in its ability to signal SFM progress. However, the growing public awareness of climate-change issues, especially those that pertain to forest management, may surface more frequently in advisory committee processes and increase the relevance of the Indicator. Indicator 6.4.2 is another action indicator, and tracks compliance rates with SFM laws and regulations, which makes it closely related to Indicators 3.1 and 3.2. There was a very low potential for the indicator to decline under climate change, and it was determined to be uninfluenced.

Indicators 6.5.1 and 6.5.2, evaluated jointly, are action indicators that track the quality and availability of forest inventory data, and did not sustain any declines in their ability to signal progress towards SFM. It seems likely that the indicators will increase in relevance due entirely to their role in the measurement of other major climate-change impacts, especially given recent improvements to inventory capacities with new remote-sensing technologies. However, we still regarded both these indicators as fundamentally uninfluenced by climate change.

Indicators 6.5.3 and 6.5.4 were the only indicators within Criterion 6 where some form of change was recommended. Indicator 6.5.3 is a fairly influential socioeconomic action indicator tracking investment in the forest sector. The indicator had a considerable increase in its relevance, largely because of the likelihood for new major research initiatives into climate-change adaptation and mitigation, like Natural Resources Canada's Regional Adaptation Collaborative initiatives (Natural Resources Canada, 2011). We therefore modified the indicator to also measure investment into climate-change adaptation and mitigation. Indicator 6.5.4 is another broad and encompassing indicator that because of its breadth and relatedness with other indicators was influenced by climate change. Specifically, this action indicator increased in relevance because of the myriad of ecological issues expected and currently arising from climate change. In response to this, we modified the indicator so that the development of new standards and guidelines pertaining to ecological issues would also address those ecological issues caused by the changing climate.

4. DISCUSSION

4.1. Summary of Findings

In total, there were 12 uninfluenced indicators, 23 unmodified indicators, 11 modified indicators, and no abandoned indicators. The detailed evaluation of each of the 46 indicators can be found in the separate Indicator Evaluations report. The study identified six new indicators that could help to provide a climate-change lens for monitoring and managing forests sustainably in Canada. These are:

g) Connectivity of protected areas;
h) Proportion of tenured forest area with seed transfer guidelines that account for climate change;
i) Average, minimum, and maximum temperature;
j) Area of Crown forest with assisted migration initiatives;
k) Rate and form of precipitation; and
l) Carbon emissions avoided through product substitution.

All six of the recommended new indicators were created within the biophysical criteria: two within Criterion 1, two within Criterion 2, one within Criterion 3, and one within Criterion 4. The recommended indicator modifications were more evenly distributed, with six of the 20 biophysical indicators modified within Criteria 1 through 4, and five of the 26 social indicators modified within Criteria 5 and 6. It was expected that the combination of some existing indicator deficiencies with the effects of climate change would have resulted in the abandonment of some of the indicators. However, our project was restricted to the analysis of the influence of climate change alone on indicator effectiveness. This is further discussed in Section 4.2 and 4.5.

A general theme of these evaluations was that indicators most often responded to climate change with a decline in their predictability. This response, though not beneficial for the overall effectiveness of the C&I framework, is more desirable than a complete lack of response of the indicators. The inherit dependence of forest ecosystems and their management on climate predisposes them to vulnerability to climatic fluctuation. If many of the SFM indicators, especially the biophysical ones, were largely uninfluenced it would suggest that the indicators do not fully respond to system variation or are not entirely aligned with the SFM values defined for their respective criteria. This was largely the case for Criterion 3. It could also be stated that climate change certainly will make defining and measuring SFM more difficult, but there is no comparable or adequate replacement for C&I-SFM, which are already integrated into many scales of forest management and policy development (Duinker, 2011).

A decline in indicator predictability was in fact the most common outcome for state indicators. Many of these indicators, the biophysical ones in particular, were left unmodified. However, the finding that the majority of indicators were not modified is logical. These indicators represent fundamental components of forests and SFM that are entirely embedded in the surrounding climate and have no surrogates to replace them as indicators. For example, the growing stock of trees (Indicator 2.1) is highly sensitive to temperature and precipitation, but a good surrogate indicator does not exist nor would it be favourable. These declines in predictability occurred because of the uncertainty and variability of future climate change, and rather than necessitating modification to individual indicators, they instead strongly reinforce the need for prospective insight into C&I-SFM (see Section 4.4.1).

4.1.1. Common Patterns in Climate-Change Influence on Indicators

Upon completion of the evaluations, we discerned some key patterns in the influence of climate change on the SFM indicators. First, developing ecological and economic indicators tends to be a less challenging task than developing social indicators (Bridge et al., 2001). Social indicators from Criterion 6, and to a lesser degree Criterion 5, are therefore faced with existing challenges in indicator development and effectiveness, which will in all likelihood be exacerbated by climate change. The biophysical indicators from Criteria 1 through 4 were found to be strongly affected by predicted and observed climate change, while the influence of climate change on the socioeconomic and socio-political indicators in Criteria 5 and 6 were difficult to assess because of their dependence on human behaviour and decision-making. Also, the vast majority of climate-change influence on the social indicators was indirect, and dependent on linkages with biophysical indicators.

Another key division in the climate-change evaluations was between action indicators, which track the quality and quantity of management actions, and state indicators, which track how systems react to management action and external drivers. The state indicators were more prone to a decline in their ability to track SFM progress, while action indicators were often uninfluenced, or even improved in the face of climate change. It is useful to examine this division through the indicator traits. Every state indicator was found to decline in predictability to some degree because of climate change. Many of them also had substantive declines in responsiveness and relevance, which often resulted in the modification of the indicator. The action indicators were most often found to have an increase in relevance under climate change; frequently because of the capacity of the actions they track to influence climate-change mitigation or adaptation. However, action indicators were also found to be insufficient in capturing the threats of climate change to SFM values identified by the criterion than contains them. For example, Indicators 3.1 and 3.2 are action indicators designed to track phenomena associated with the SFM values pertaining to water and soil. We know that climate change will affect soil and water to varying degrees (Jones et al., 2009; Johnston et al., 2010), yet both of these indicators were uninfluenced by climate change. This division may emphasize the advanced utility of state indicators in place of action indicators, if possible, despite the propensity for state indicators to decline in effectiveness under climate change.

4.2. Study Challenges and Limitations

In our review of the indicators of SFM, we formulated an approach consisting of systems-analytical thinking, and the professional judgement of our combined team of forest practitioners and researchers to arrive at our decisions and recommendations. We felt that this approach would yield the most meaningful and valid insight into C&I-SFM under a changing climate, but it is of course not without its share of unique challenges, biases, and limitations. Applying systems-analytical thinking to the national indicator set was an important addition to this project. Since this type of approach to evaluating C&I is new, the approach of systematically evaluating indicator pairs for interaction was far more dependent on professional judgement than any existing approach. The quantification of indicator interactions is therefore meant more as a comparative tool for summarizing and displaying the system of relationships between the SFM indicators than an empirical analysis of indicator influence and interaction.

A major challenge to the indicator evaluations and especially the indicator modifications pertained to how these national indicators are currently defined and constructed, which we believe also is largely related to issues of scale. Some of the indicators consist of single objective and measurable variables that are easily aligned with a desired management direction or target – an important attribute of SFM indicators (Duinker, 2001). A prime example of this is Indicator 2.5, the proportion of timber harvest area successfully regenerated. Conversely, Indicator 1.2.2, population levels of forest-associated species, tracks 41 species in the national assessment, and is in essence a cluster of indicators. Indicator 6.5.4, the status of new or updated forest management guidelines and standards related to ecological issues, is an exceedingly broad and inclusive indicator that is not easily aligned with a management target.

The above distinctions are important as they heavily influence the type of modifications made to an indicator due to climate change, as well as the analysis of linkages between indicators. More specifically, we made two types of modifications to the indicators in our recommendations. The first arose when we needed to alter the foundational concepts of an indicator, by making contributions or omissions to the phenomenon tracked by an indicator because of the changing climate. An example of this is the modification to Indicator 6.5.3 to include investment in climate-change adaptation and mitigation in addition to scientific research, industry research and development, and education. The second type of modification arose when we had no need to change what phenomenon an indicator tracks, but instead had to change how the phenomenon was measured. An example of this is again Indicator 2.1, which is measured and subsequently modelled under the assumption of a stable climate.

4.3. The Nature of Climatic Influences on Forests and the Forest Sector

It has long been known that climate is a controlling or driving force influencing the broadest range of humans' relationships with the earth. However, only in recent decades have we come to understand and realize the implications of such profound influences, partly as a result of real and expected climate change and partly as a result of advances in science. The first papers linking climate change to forests and the forest sector began appearing only in the 1980s, such as the early work of Pastor and Post (1988) and Solomon (1986), and now the literature is burgeoning with ideas, theories, scenarios, empirical data, and warnings about the potentially dire consequences of continued climate change on forest ecosystems and our management and use of them (Williamson et al., 2009; Johnston et al., 2010).

In the context of gauging SFM using C&I, we make the following observations about the influences of climate change on forests and the forest sector:

a) The impacts of climate change will be ubiquitous. No tree nor stand nor forest in Canada's outdoors will escape the influences of climate change. This does not mean that the influences everywhere will be large; indeed, many may be subtle yet crucial.

b) The impacts of climate change will have strong spatial variability. Canada is a huge landmass, stretching from the mid-latitudes to the Arctic, and covering 80 degrees of longitude at its widest. Our forests, inclusive of sparsely wooded land, cover some 400 million hectares – 10% of the world's forest (CCFM, 2006). The current huge diversity of forest ecosystems in Canada attests to the variability of the past and present climates across the country. What climate change will look like across Canada has great diversity, so the impacts on forests will be likewise diverse, from province to province, ecozone to ecozone, and management unit to management unit.

c) The impacts of climate change are characterized by dozens of cause-effect pathways from climatic variables as causal agents to forest-ecosystem characteristics as effect receptors. For example, if moose are the effects receptors, then some cause-effect pathways are direct (e.g., heat stress on moose), and some are indirect (e.g., climatically driven changes in vegetation patterns and consequent changes in habitat quality for moose). The interaction of the multitude of cause-effect pathways leads to a complex situation of cumulative effects. We have every reason to believe that such cumulative effects will not be simply additive, but rather may exhibit compensatory or synergistic behaviours.

d) For many valued elements of forests, as embodied by the C&I-SFM, climate change is but one of a plethora of driving forces. It is impossible to have confidence in understanding the effects of climate change on these forest values if we do not examine them in the context of the other drivers. The essential purpose of implementing C&I-SFM is to discover whether activities related to SFM are having, or can be expected to have, desired outcomes in terms of forest values. The question then becomes, at its simplest, how climate change might affect forest ecosystems and the forest sector in the context of SFM-related activities. To further complicate matters, we must also consider other drivers, such as invasive alien species, land-use change, mammal harvests, and so on. The need for incisive cumulative effects assessment has never been greater (Greig and Duinker, 2011).

e) Both climate change and forests, in their full complexity, are characterized by a range of both slow, intermediate-pace, and fast processes, ranging from the rapid reproduction of forest insects to the slow growth of centuries-old Douglas fir. Any initiative trying to understand the implications of the myriad cause-effect relationships between climate change and forest ecosystems will need to take such temporal complexity into account.

These observations make it clear that a consideration of how climate change might affect the utility of C&I-SFM, at any level from local to national, is fraught with immense complexity and uncertainty. The possibility of making incorrect judgements due to the partiality of systems analysis, even qualitative, is huge. However, we must not let this curtail our efforts and enthusiasm for deeper understanding. Strong systems thinking, with an eye to cumulative effects, is mandatory.

4.4. Improving Consideration of Climate Change in Sustainable Forest Management

There is often a gap between research and practice regarding climate change and its potential influences on forests and the forest sector. Greater uptake of the existing knowledge pertaining to climate change and forests is an important future step in SFM. Based on our analysis, we recommend the following approaches to the consideration of climate change into SFM.

4.4.1. Moving from Retrospective to Prospective Insight

Most of the work to date using C&I to illuminate progress in SFM has been empirical. Thus, the data assembled give insight into the past/present status of the phenomena under investigation. In our view, looking backward is a necessary but insufficient exercise to guide SFM. A look backward has most meaning in the context of what was desired or expected when major SFM decisions were taken and implemented. Desires and expectations require prospective analysis that explicitly deals with the future (Duinker, 2011). Prospective analysis can be both quantitative (based on predictive or forecasting models) and qualitative (based on narrative scenarios) (Cornish, 2004).

In the context of climate change and SFM, the degrees and kinds of climatic changes we might expect during the rest of the 21st century are far greater than the degrees and kinds of climatic changes we have experienced in recent decades. This means that, while we can get some empirical insights on how climate change has influenced and can influence SFM (e.g., the mountain pine beetle outbreak in western Canada), deeper insights will have to come from prospective analysis. Prospective analyses are pivotal in guiding and directing further empirical work to track real ecosystem and sector conditions under a changing climate. The shift from empirical to prospective work does not alter indicator design but rather dramatically increases the utility of indicators to point out promising management directions under a changing climate.

4.4.2. Linking Criteria and Indicators into Management and Policy Decision-Making Processes

A big part of the rationale for moving to stronger prospective work is the strengthening of linkages between C&I work and management and policy decision-making (Duinker, 2011). The utility of C&I efforts would be so much higher if they were embedded into SFM decision-making processes. The C&I thus become the terms through which decision-makers and other process participants evaluate the relative desirability of alternative approaches to management and policy. Prospective analysis would also be vital to incorporating elements of adaptive management into management and policy development.

Experiences in driving SFM decision processes on the basis of C&I, in whatever constellation, are few but sufficient to give us confidence in making this recommendation. At the local level of the forest-management unit, the forest-management planning processes of both Alberta (Alberta Sustainable Resource Development (SRD), 2006) and Ontario (Ontario Ministry of Natural Resources (OMNR), 2009) prescribe local-level use of SFM indicator sets to guide selection of preferred management strategies. The Z809 SFM standard of the CSA (CSA, 2009) prescribes 34 mandatory indicators, organized under the CCFM's six criteria, to guide selection of a preferred management alternative.

At a provincial level, the work of the New Brunswick Task Force on Forest Diversity and Wood Supply (2008) was based on a forest-modelling effort looking forward to 2050. It projected the effects of seven management alternatives on 19 indicators of forest diversity and wood supply. Going abroad for an example, the State of Minnesota implemented a state-wide environmental impact assessment in which alternative forest-management policies were evaluated in terms of long-term forecasts for a range of indicators of biophysical and socio-economic indicators (Hay, 1994).

In relation to Canada-wide policy discourse, we identify two initiatives, one complete and another contemplated. The scenarios of the SFM Network's Forest Futures Project (Duinker, 2008), designed to enlighten forest-policy discussions across the country, were structured around a suite of eleven indicators grouped into ecological, social and economic clusters. As for possible future policy initiatives, we know that there is discussion about evaluating progress in implementing the CCFM's Forest Vision (CCFM, 2008) in terms of the national C&I-SFM. We see this as a very promising development.

In sum, the more we can link C&I-SFM into forest management and policy decision-making processes, the greater the relevance and utility of the C&I. At the same time, the prospects for understanding how climate change may affect Canada's forests and forest sector will also be vastly improved.

4.4.3. Thinking in Terms of Complex Adaptive Systems

The complexity associated with managing forests sustainably in the face of climate change and the rapidly evolving nature of climate-change research require on-going learning and improvement of forest-management institutions (Van Damme et al., 2003). This is a central concept of adaptive management (Duinker and Trevisan, 2003). Adaptive management is vital to managing forests in a changing climate because it focuses on the recognition and reduction of uncertainty. This is done through a cyclical process of research, forecasting the consequences of alternative forest management strategies, implementation and monitoring, and management review and re-evaluation (Duinker & Trevisan, 2003). Adaptive management is critical to the technical implementation of SFM and relies heavily on the use of simulation modelling and scenarios (Duinker & Trevisan, 2003; Van Damme et al., 2003). As a tool for defining and monitoring SFM progress and multiple scales, C&I could be invaluable in the adaptive management of complex systems in a rapidly changing climate.

4.4.4. Explicit Consideration of Climate Change in Forest Management and Policy

Forest management is by nature a process of managing forest conditions today to achieve goals and objectives over relatively long timeframes into the future. Climate change challenges the entire process by changing the context for the future. While uncertainty about the future context is high with climate change, it is increasingly clear that it must be considered to be able to manage risk as well as to maintain credibility and relevance. Linking forest management and policy to climate change is in its infancy in Canada, yet there are some examples that can be built upon.

Millar Western recently designed a forest management plan to consider climate change (Millar Western Forest Products Ltd., 2008). The company believed that planning elements needed to be discussed within the context of an integrated land management and cumulative impact assessment approach. Scenario outcomes needed to be developed that reflected realistic projections based on non-traditional inputs. To understand the potential changing trajectories of the future forest conditions, the company explored cumulative effects of timber harvesting, climate change, human population, and wildfire incidence relative to changes in climate, human population, and oil-and-gas development activity. Results confirmed that these emerging issues were indeed significant and likely to have a major bearing on future sustainability of the forest.

The Kamloops Future Forest Strategy (KFFS) was initiated as a pilot project by the BC Ministry of Forests and Range in 2007-08 to explore sensitivities to climate change and subsequent future management vulnerabilities in the Kamloops Timber Supply Area (TSA) and suggest adaptive management and policy actions to address these challenges. Interpretation of climate-modelling results for two climate-change scenarios provided a framework that allowed expert opinion to identify issues and possible management actions to prudently maintain management options for plausible climate-change futures. Under the BC FFESC, two similar projects have been initiated in other parts of the BC Interior, and a suite of linked models is being used to test sensitivities and adaptive options designed under the KFFS in the Kamloops TSA.

Among the 13 drivers of change in Canada's forests and forest sector, as used to define the four scenarios developed under the Sustainable Forest Management Network's Forest Futures Project, climate change was a key one (Duinker, 2008). As the response portion of the scenarios was developed and written, climate change was a strong consideration, especially in the two scenarios where climate change was assumed to be strong and essentially overwhelming.

In southeastern BC, scenario-planning methods are currently building on the work done on the Forest Futures Project to explore climate-change impacts on the supply and trade-offs between providing fibre for wood products, maintaining biodiversity, and providing habitat for grizzly bears in an area experiencing a massive mountain pine beetle outbreak (Morgan, 2011).

The challenge for governments, forest companies, and other stakeholders when considering long, slow, and uncertain impacts on management is to try and understand their implications at an early stage and develop policies and management strategies that are prospective rather than retrospective. This is crucial to maintaining system resilience and management options over time.

4.5. Opportunities for Criteria and Indicator Improvement

4.5.1. Collaboration

A national assessment of SFM using C&I is a major endeavour with substantial data needs. Building upon existing monitoring initiatives and networks is a major asset for implementing C&I-SFM (Eddington et al., 2009) and alleviates some of the C&I challenges related to data availability. For example, building on the existing National Forest Inventory (NFI) grid to report by ecozone and management-intensity category may provide some insight into climate-change effects arising from different forest management actions and intensities. The current NFI consists of photo plots and ground plots that could also be used to describe changes in forest cover and carbon stocks over time (CanFI, 2004). Securing inter-agency cooperation in the provinces and territories to measure other indicators, such as wildlife populations and distributions, and using simulation tools with reference to the NFI grid may provide considerable cost advantages in future C&I-SFM assessments.

4.5.2. Indicator Adjustments

Given the process we used to evaluate of each of the 46 CCFM indicators (see separate Indicator Evaluations report), it is possible for us to make some general recommendations on indicator adjustments regardless of climate change. Often the case for indicator modification in this project was founded on existing deficiencies in one or more of the seven indicator traits of effectiveness. The most frequent deficiency appeared to be low understandability, resulting from the broad definition of indicators and 'indicator clusters', as defined in Section 4.2. Again, this is at least partly due to scale, as explicit indicator definition is difficult at the national level given the diversity of Canada's forests and SFM values.

Another recommended course of action for future C&I framework revision would be to adopt state indicators over action indicators, when feasible. The analysis of action-indicator performance under climate change as well as their interaction dynamics in the linkages assessment suggests to us that they are not as effective indicators as the state indicators within the national framework of C&I-SFM (see Section 4.4).

Another ongoing limitation of the indicators is the lack of, or inability to be linked with, a direction or target. This is a vital attribute of indicators that will likely become more critical under climate change and echoes the need for more prospective insight in applications of C&I-SFM. A considerable threat to the utility of indicators to gauge SFM progress under climate change will be an introduced uncertainty and variability in indicator targets. Furthermore, there may be emergent ecological thresholds that are unanticipated because of the interaction of climate change and management actions (Millar et al., 2007), which further complicates target-setting. For example, if reforestation initiatives are focused on a given species mix or vegetation type that is no longer climatically favoured, eventually these thresholds may be exceeded, resulting in time-lags and potential ecosystem collapse. Established targets may be too close or beyond these thresholds introduced by climate change. In addition to clear indicator definition, the latter point reinforces the use of prospective thinking in C&I implementation.

4.5.3. Criterion Addition

As the time for the second revision of the CCFM C&I-SFM approaches, we can expect that climate change will be woven throughout the framework of indicators. However, the magnitude of the effects of climate change on SFM may warrant more substantial action. The uptake of climate change into the awareness of nearly every SFM stakeholder might suggest that we create a seventh criterion pertaining exclusively to climate change. We advance this thought not as a recommendation but rather to open a dialogue in any discussions about revisions to the indicator set. Such discussion might touch upon re-organization of existing indicators and addition of new indicators, including the ones we have proposed.

5. Conclusions

We have examined the C&I-SFM to determine whether climate change can alter the interpretation and handling of the indicators. We have considered how the indicators relate to each other and to a range of significant drivers. We have examined the literature associated with the indicators, and peered into their links with forest management and policy. Save collection of new data on the indicators, we feel we have scrutinized them rather comprehensively.

Progress with development and implementation of C&I-SFM is both laudable so far and wanting in several ways. The fact that the Canadian forest sector embraced C&I-SFM in the early 1990s is a sign of leadership and commitment towards SFM at a world-wide scale. The sector took decisive action, and despite uncertainties, put C&I-SFM in place for, first of all, national reporting, and subsequently provincial reporting and then local reporting. Canada is, without doubt, a world leader in C&I-SFM.

Much additional progress is to be made. The discussions above point to a range of improvements we can make to further the C&I cause. Stronger links into management and policy decision-making processes, and greater emphasis on prospective analyses, will move the C&I-SFM to centre-stage in forest management and policy.

C&I-SFM are, without question, a key component in the pursuit of SFM. Canadian forest and forest-sector stakeholders have embraced them and, using them, tried to determine the degree to which SFM is becoming a reality. Climate change adds considerable complexity and uncertainty to this enterprise. With concerted and coordinated efforts, we can address these complexities and uncertainties in useful ways to improve our ability to gauge progress in SFM.

Is this the full extent of the kinds of thinking Canada's forest stakeholders need to engage in to make the best of SFM under a changing climate? Surely the enterprise of gauging progress – the central motive of C&I - is but one of several essential elements of dealing with climate change in the forest sector. During the next decade or two, if Canada is to cope well with the changing climate, much deeper considerations and decisive actions will be needed across the full spectrum of elements of SFM. For example, given the profound uncertainties that so severely restrict our understanding of the interactions between climate and the forests, targeted research must be significantly accelerated. Comprehensive dialogues will be needed involving all forest and forest-sector stakeholders to determine desired conditions and uses of forests through the 21st century. Long-cherished paradigms of forest management, such as sustained yield, and new ones too, such as emulation of natural disturbance, will need to be rethought as climate change invalidates our assumptions about managing forests in a stable atmospheric future. Perhaps fundamental changes will be needed in how we, collectively, allocate forest resources to specific organizations and user groups (i.e. the tenure and property rights system), how we educate resource professionals, and how we arrange for ecosystem conservation through systems of protected areas. Climate change poses serious challenges not only to our ability to gauge SFM progress using C&I – the challenges permeate the entire system that links forest ecosystems with society, the economy, and the global atmosphere.

6. References

Aitken, S. N., Yeaman, S., Holliday, J. A., Wang, T., & Curtis-McLane, S. (2008). Adaptation, migration or extirpation: Climate change outcomes for tree species. *Evolutionary Applications, 1*, 95-111.

Alberta Sustainable Resource Development. (2006). *Alberta Forest Management Planning Standard*. Edmonton, AB: Alberta SRD.

Bale, J. S., Masters, G. J., Hodkinson, I. D., Awmack, C., Bezemer, T. M., Brown, V. K., Butterfield, J., Buse, A., Coulson, J. C., Farrar, J., Good, J. G., Harrington, R., Hartley, S., Jones, T. H., Lindroth, R. L., Press, M. C., Symrnioudis, I., Watt, A. D., & Whittaker, J. B. (2002). Herbivory in global climate change research: Direct effects of rising temperature on insect herbivores. *Global Change Biology, 8*, 1-16.

Beckley, T. M. (2000). *Sustainability for Whom? Social Indicators for Forest-Dependent Communities in Canada.* Edmonton, AB: SFM Network.

Bridge, S. R. J., Wright, P., & Rios, R. (2001). Criteria and indicators of sustainable forest management: Relationships between multi-scaled initiatives. *Proceedings of the XXI Sessions of the North American Forest Commission.* Honolulu, HI.

Canadian Council of Forest Ministers. (1988). *A National Forest Sector Strategy for Canada.* Ottawa, ON: CCFM.

Canadian Council of Forest Ministers. (1990). *Sustainable Development and Forest Management*. Hull, QC: CCFM.

Canadian Council of Forest Ministers. (1992). *Sustainable Forests: A Canadian Commitment.* Hull, QC: CCFM.

Canadian Council of Forest Ministers. (1995). *Defining Sustainable Forest Management: A Canadian Approach to Criteria and Indicators*. Ottawa, ON: CCFM.

Canadian Council of Forest Ministers. (1996). *Criteria and Indicators of Sustainable Forest Management in Canada – Technical Report 1997*. Ottawa, ON: CCFM.

Canadian Council of Forest Ministers. (1998). *National Forest Strategy (1998-2003)*. Ottawa, ON: CCFM.

Canadian Council of Forest Ministers. (2000). *Criteria and Indicators of Sustainable Forest Management in Canada – National Status 2000*. Ottawa, ON: CCFM.

Canadian Council of Forest Ministers. (2003). *Defining Sustainable Forest Management in Canada – Criteria and Indicators*. Ottawa, ON: CCFM.

Canadian Council of Forest Ministers. (2006). *Criteria and Indicators of Sustainable Forest Management – National Status 2005*. Ottawa, ON: CCFM.

Canadian Council of Forest Ministers. (2008). *A Vision of Canada's Forests – 2008 and Beyond*. Ottawa, ON: CCFM.

Canadian Standards Association. (2009). *CAN/CSA-Z809-08 Sustainable Forest Management*. Mississauga, ON: CSA.

CanFI. (2004). *Canada's National Forest Inventory: Design Overview*. Ottawa, ON: CCFM.

Chaplin, F. S., Shaver, G. R., Giblin, A. E., Nadelhoffer, K. J., & Laundre, J. A. (1995). Responses of Arctic tundra to experimental and observed changes in climate. *Ecology, 76*, 694-711.

Cornish, E. (2004). *Futuring: The Exploration of the Future.* Bethesda, MD: World Future Society.

Dale, V. H., Joyce, L. A., McNuly, M., Neilson, R. P., Ayres, M. P., Flannigan, M. D., Hanson, P. J., Irland, L. C., Lugo, A. E., Peterson, C. J., Simberloff, D., Swanson, F. J., Socks, B. J., & Wotton, B. M. (2001). Climate change and forest disturbances. *Bioscience, 51*, 723-734.

Duinker, P. N. (2001). Criteria and indicators of sustainable forest management in Canada: Progress and problems in integrating science and politics at the local level. *In* A. Franc, O. Laroussinie, & T. Karjalainen (Eds.), *Criteria and Indicators for Sustainable Forest Management at the Forest Management Unit Level*. Joensuu, Finland: European Forestry Institute.

Duinker, P. N. (2008). *Scenarios of the Forest Futures Project: Why and How we Created Them, and How to Use Them.* Edmonton, AB: SFM Network.

Duinker, P. N. (2011). Advancing the cause? Contributions of criteria and indicators to sustainable forest management in Canada. *The Forestry Chronicle, 87*, 488-493.

Duinker, P. N. & Trevisan, L. M. (2003). Adaptive management: Progress and prospects for Canadian forests. *In* P. J. Burton, C. Messier, D. W. Smith, & W. L. Adamowicz (Eds.), *Towards Sustainable Management of the Boreal Forest.* Ottawa, ON: NRC Research Press.

Dukes, J. S., Pontius, J., Orwig, D., Garnas, J. R., Rodgers, V. L., Brazee, N., Cooke, B., Theoharides, K. A., Stange, E. E., Harrington, R., Ehrenfeld, J., Gurevitch, J., Lerdau, M., Stinson, K., Wick, R., & Ayres, M. (2009). Responses of insect pests, pathogens, and invasive plant species to climate change in the forests of northeastern North America: What can we predict? *Canadian Journal of Forest Research, 39*, 231-248.

Eddington, M. M., Innes, J. L., McHugh, A. E., & Smith, A. C. (2009). *Monitoring Forest and Rangeland Species and Ecological Processes to Anticipate and Respond to Climate Change in British Columbia.* Victoria, BC: BC Ministry of Forests and Range.

Flannigan, M. D., Stocks, B., Turetsky, M., & Wotton, M. (2009). Impacts of climate change on fire activity and fire management in the circumboreal forest. *Global Change Biology, 14*, 1-12.

Ford, J. D. & Smit, B. (2004). A framework for assessing the vulnerability of communities in the Canadian Arctic to risks associated with climate change. *Arctic, 57*, 389-400.

Forestry Canada. (1991). *The State of Forestry in Canada: 1990 Report to Parliament*. Ottawa, ON: Forestry Canada.

Forestry Canada. (1992). *The State of Canada's Forests: Second Report to Parliament*. Ottawa, ON: Forestry Canada.

Forestry Canada. (1993). *The State of Canada's Forests: Third Report to Parliament*. Ottawa, ON: Forestry Canada.

Friend, A. D. (2010). Terrestrial plant production and climate change. *Journal of Experimental Botany, 61*, 1293-1309.

Furgal, C. & Seguin, J. (2006). Climate change, health, and vulnerability in the Canadian northern Aboriginal communities. *Environmental Health Perspectives, 114*, 1964-1970.

Greig, L. A. & Duinker, P. N. (2011). A proposal for further strengthening science in environmental impact assessment in Canada. *Impact Assessment and Project Appraisal, 29,* 159-165.

Hall, J. P. (2002). Sustainable production of forest biomass for energy. *The Forestry Chronicle, 78*, 391-396.

Hay, M. R. S. (1994). *Regional Environmental Assessment of Forest Management: Experience in Ontario and Minnesota*. Master's Thesis. Thunder Bay, ON: Lakehead University.

Heimann, M. & Reichstein, M. (2008). Terrestrial ecosystem carbon dynamics and climate feedbacks. *Nature, 451*, 289-292.

Hogg, E. H., Brandt, J. P., & Michaelian, M. (2008). Impacts of regional drought on the productivity, dieback, and biomass of western Canadian aspen forests. *Canadian Journal of Forest Research, 35*, 610-622.

Intergovernmental Panel on Climate Change. (2007). *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press.

Irland, L. C., Adams, D., Alig, R., Betz, C. J., Chen, C., Hutchins, M., McCarl, B. A., Skog, K., & Sohngen, B. (2001). Assessing socioeconomic impacts of climate change on U. S. forests, wood product markets and forest recreation. *Bioscience, 51*, 753-764.

Iverson L. R., Prasad, A. M., Matthews, S. N., & Peters, M. (2008). Estimating potential habitat for 134 eastern US tree species under six climate scenarios. *Forest Ecology and Management, 254*, 390-406.

Johnson, M. R. (2000). *Ecosystem Sustainability and Resource-Based Tourism: Linkages and Indicators.* Master's Thesis. Thunder Bay, ON: Lakehead University.

Johnston, M., Campagna, M., Gray, P., Kope, H., Loo, J., Ogden, A., O'Neill, G. A., Price, D., & Williamson, T. (2009). *Vulnerability of Canada's Tree Species to Climate Change and Management Options for Adaptation.* Ottawa, ON: CCFM.

Johnston, M., Williamson, T., Munson, A., Ogden, A., Moroni, M., Parsons, R., Price, D., & Stadt, J. (2010). *Climate Change and Forest Management in Canada: Impacts, Adaptive Capacity, and Adaptation Options*. Edmonton, AB: SFM Network.

Jones, J. A., Achterman, G. L., Augustine, L. A., Creed, I. F., Folliot, P. F., MacDonald, L., & Wemple, B. C. (2009). Hydrologic effects of a changing forested landscape – challenges for the hydrological sciences. *Hydrological Processes, 23*, 2699-2704.

Jonsson, R. (2009). *Forest Products Markets: External Drivers Affecting Swedish Forests and Forestry – Forest Futures Working Report.* Alnarp, Sweden: Forest Futures.

Kirilenko, A. P. & Sedjo, R. A. (2007). Climate change impacts on forestry. *Proceedings of the National Academy of Science, 104*, 19697-19702.

Kurz, W. A., Stinson, G., Rampley, G. J., Dymond, C. C., & Neilson, E. T. (2008). Risk of natural disturbances makes future contribution Canada's forests to the global carbon cycle highly uncertain. *Proceedings of the National Academy of Sciences, 105*, 1551-1555.

McFarlane, B. L., Stumpf-Allen, R. C. G., & Watson, D. O. (2006). Public perceptions of natural disturbance in Canada's national parks: The case of the mountain pine beetle (*Dendroctonus ponderosae* Hopkins). *Biological Conservation, 130,* 340-348.

McKenney, D. W., Pedlar, J. H., Lawrence, K., Campbell, K., & Hutchinson, M. F. (2007). Potential impacts of climate change on the distribution of North American trees. *Bioscience, 57*, 39-948.

McKenney, D. W., Pedlar, J., & O'Neil, G. (2009). Climate change and forest seed zones: Past trends, future prospects and challenges to ponder. *The Forestry Chronicle, 85*, 258-266.

McMahon, S. M., Parker, G. G., & Miller, D. R. (2010). Evidence for a recent increase in forest growth. *Proceedings of the National Academy of Science, 107*, 3611-3615.

Messier, C., Tittler, R., Kneeshaw, D. D., Gélinas, N., Paquette, A., Berninger, K., Rheault, H., Meek, P., & Beaulieu, N. (2009). TRIAD zoning in Quebec: Experiences and results after 5 years. *The Forestry Chronicle, 85*, 885-896.

Millar Western Forest Products Ltd. (2008). 2007-2016 Detailed Forest Management Plan. Edmonton, AB: Alberta SRD.

Montréal Process. (1995). *Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forests: The Montréal Process.* Hull, QC: Natural Resources Canada, Canadian Forest Service.

Morgan, D. G. (2011). *Exploring the Social-Ecological Resilience of Forest Ecosystem Services.* Master's Thesis. Prince George, BC: University of Northern British Columbia.

National Forest Strategy Coalition. (2003). *National Forest Strategy (2003-2008) – A Sustainable Forest: The Canadian Commitment.* Ottawa, ON: CCFM.

Natural Resources Canada. (2011). *Regional Adaptation Collaboratives*. Retrieved from http://adaptation.nrcan.gc.ca/collab/abosuj_e.php

New Brunswick Task Force on Forest Diversity and Wood Supply. (2008). *Management Alternatives for New Brunswick's Public Forest.* Fredericton, NB: New Brunswick Department of Natural Resources.

Ontario Ministry of Natural Resources. (2009). *Forest Management Planning Manual for Ontario's Crown Forests.* Sault Ste. Marie, ON: OMNR.

Parmesan, C. & Yohe, G. (2003). A globally coherent fingerprint of climate change impacts across natural systems. *Nature, 421*, 37-42.

Pastor, J. & Post, W. M. (1988). Response of northern forests to CO_2-induced climate change. *Nature, 344*, 55-58.

Perez-Garcia, J., Joyce, L. A., McGuire, A. D., & Xiao, X. (2002). Impacts of climate change on the global forest sector. *Climatic Change, 54*, 439-461.

Prahbu, R., Colfer, C. J. P., & Dudley, R. G. (1999). *Guidelines for Developing, Testing and Selecting Criteria and Indicators of Sustainable Forest Management.* Jakarta, Indonesia: CIFOR.

Sato, Y. (2009). *Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forests: The Montréal Process.* Tokyo, Japan: Forestry Agency, Ministry of Agriculture, Forestry & Fisheries.

Schimel, D. S., House, J. I., Hibbard, K. A., Bousquet, P., Ciais, P., Peylin, P., Braswell, B. H., Apps, M. J., Baker, D., Bondeau, A., Canadell, J., Churkina, G., Cramer, W., Denning, A. S., Field, C. B., Friedlingstein, P., Goodale, C., Heimann, M., Houghton, R. A., Melillo, J. M, Murdiyarso, D., Noble, I., Pacala, S. W., Prentice, I. C., Raupach, M. R., Rayner, P. J., Scholes, R. J., Steffen, W. L., & Wirth, C. (2001). Recent patterns and mechanisms of carbon exchange by terrestrial ecosystems. *Nature, 414,* 169-172.

Scott, D. J. & Lemieux, C. J. (2005). Climate change and protected area policy and planning in Canada. *The Forestry Chronicle, 81*, 696-703.

Solomon, A.M. (1986). Transient response of forests to CO_2-induced climate change: Simulation modeling experiments in eastern North America. *Oecologia, 68*, 567-579.

Steenberg, J. W. N., Duinker, P. N., & Bush, P. G. (2011). Modelling the effects of climate change, timber harvest, and natural disturbance on the forests of central Nova Scotia, Canada. Submitted to the Canadian Journal of Forest Research.

Sturm, M., Racine, C., & Tape, K. (2001). Increasing shrub abundance in the Arctic. *Nature, 411*, 546-547.

Thompson, I. D., Flannigan, M. D., Wotton, B. M., & Stuffling, R. (1998). The effects of climate change on landscape diversity: An example in Ontario Forests. *Environmental Monitoring and Assessment, 49,* 213-233.

United Nations Conference on Environment and Development. (1992). *Agenda 21: The United Nations Program of Action from Rio.* New York, NY: UN.

Van Damme, L., Russell, J. S., Doyon, F., Duinker, P. N., Gooding, T., Hirsch, K., Rothwell, R., & Rudy, A. (2003). The development and application of a decision support system for sustainable forest management on the Boreal Plain. *Journal of Environmental Engineering and Science, 2*, S23-S34.

van der Meer, P. J., Jorritsma, I. T. M., & Kramer, K. (2002). Assessing climate change effects on long-term forest development: Adjusting growth, phenology, and seed production in a gap model. *Forest Ecology and Mangement,162*, 39-52.

von Mirbach, M. (2000). *A User's Guide to Local Level Indicators of Sustainable Forest Management: Experiences from the Model Forest Network.* Ottawa, ON: Natural Resources Canada.

Wijewardana, D. (2008). Criteria and indicators for sustainable forest management: The road travelled and the way ahead. *Ecological Indicators, 8*, 115-122.

Williamson, T., Colombo, S., Duinker, P., Gray, P., Hennessey, R., Houle, D., Johnston, M., Ogden, A., & Spittlehouse, D. (2009). *Climate Change and Canada's Forests: Current and Predicted Impacts*. Edmonton, AB: SFM Network.

World Commission on Environment and Development. (1987). *Our Common Future*. Oxford, UK: Oxford University Press.

Yamasaki, S. H., Kneeshaw, D. D., Munson, A. D., & Dorion, F. (2002). Bridging boundaries among disciplines and institutions for effective implementation of criteria and indicators. *The Forestry Chronicle, 78*(4), 487-491.