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REVIEW

Climate change vulnerability and adaptation in the managed Canadian boreal forest[1]

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Abstract: Climate change is affecting Canada's boreal zone, which includes most of the country's managed forests. The impacts of climate change in this zone are expected to be pervasive and will require adaptation of Canada's forest management system. This paper reviews potential climate change adaptation actions and strategies for the forest management system, considering current and projected climate change impacts and their related vulnerabilities. These impacts and vulnerabilities include regional increases in disturbance rates, regional changes in forest productivity, increased variability in timber supply, decreased socioeconomic resilience, and increased severity of safety and health issues for forest communities. Potential climate change adaptation actions of the forest management system are categorized as those that reduce nonclimatic stressors, those that reduce sensitivity to climate change, or those that maintain or enhance adaptive capacity in the biophysical and human subsystems of the forest management system. Efficient adaptation of the forest management system will revolve around the inclusion of risk management in planning processes, the selection of robust, diversified, and no-regret adaptation actions, and the adoption of an adaptive management framework. Monitoring is highlighted as a no-regret action that is central to the implementation of adaptive forest management.

Key words: adaptation, adaptive capacity, boreal forest, climate change, resilience, vulnerability.

Résumé : Le changement climatique affecte la zone boréale du Canada dans laquelle on retrouve la plupart des forêts aménagées du pays. Les impacts du changement climatique dans cette zone devraient être assez importants pour que l'on y voie la nécessité d'adapter les systèmes d'aménagement forestier au Canada. Ce document examine les mesures et stratégies potentielles d'adaptation à mettre en place pour les systèmes d'aménagement forestier, compte tenu des impacts actuels et futurs des changements climatiques et de la vulnérabilité qui leur sont associés. Ces impacts et ces vulnérabilités comprennent les augmentations régionales des taux de perturbation, les changements régionaux dans la productivité des forêts, la variabilité accrue de l'approvisionnement en bois, la diminution de la résilience socio-économique et l'augmentation de la gravité des problèmes de sécurité et de santé pour les communautés forestières. Les actions potentielles d'adaptation du système d'aménagement forestier sont catégorisées selon qu'elles réduisent les facteurs de stress non climatiques, qu'elles réduisent la sensibilité au changement climatique ou qu'elles maintiennent ou améliorent la capacité d'adaptation des sous-systèmes biophysique et humain du système d'aménagement forestier. Une adaptation efficace du système d'aménagement forestier s'articulera autour de l'inclusion de la gestion des risques dans les processus de planification, de la sélection d'actions d'adaptation robustes, diversifiées et sans regret, et de l'adoption d'un cadre de gestion adaptative. Le suivi (*monitoring*) est mis en évidence comme une action sans regret qui est au cœur de la mise en œuvre de la gestion adaptative des forêts.

Mots-clés : adaptation, capacité d'adaptation, forêt boréale, changement climatique, résilience, vulnérabilité.

1. Introduction

The mean global temperature has increased by almost 1 °C since 1900 (Hansen et al. 2006), owing in large part to human influences, and is expected to continue to increase (IPCC 2001, 2007). Forest ecosystems are tightly coupled with climate both directly through the effects of temperature and precipitation and indirectly through the effects of disturbances. Over the millennia, forests have adapted continuously to changes in climatic conditions through modifications in species composition, vegetation density, and growth patterns (Davis et al. 2005; Carcaillet et al. 2010). However, the rate and magnitude of ongoing climate change are anticipated to be greater than what forests have ever experienced (IPCC 2001, 2007) and may push forests down novel or unanticipated ecological pathways.

Temperature increases are predicted to be particularly significant at northern latitudes (Field et al. 2007; IPCC 2007), resulting in uncertain but potentially major impacts to the forest and the forest sector in Canada's boreal zone. Climate change is already affecting forests in Canada (Lemmen et al. 2008; Lemprière et al. 2008; Johnston et al. 2009; Williamson et al. 2009) through in-

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creases in the frequency and severity of fires (Flannigan et al. 2009), insect and disease attacks (Dukes et al. 2009; Sturrock et al. 2011), and extreme weather events (heavy rain, ice storms, drought, and heat damage; Allen et al. 2010). Community health and safety may also be impacted through, for example, increased vulnerability to wildfires (McFarlane et al. 2011). As these impacts take hold, the ability of the boreal forest ecosystems to provide goods and services such as timber or biodiversity may become increasingly variable. Thus, forest management will occur within complex, dynamic, and uncertain decision-making environments, with a concomitant difficulty in setting or achieving sustainable forest management objectives (Williamson et al. 2008; Ogden and Innes 2009).

Two main strategies have been suggested in response to climate change. The first, **mitigation**, is the anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases (IPCC 2001), in efforts to reduce net greenhouse gas (GHG) emissions and lessen climate change itself. The second, **adaptation**, is the adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harmful opportunities or exploits beneficial ones (IPCC 2001). Adaptive approaches to forest management will increase our capacity to deal with climate change outcomes (Puettman et al. 2008; CCFM 2008; Gray 2012; Edwards and Hirsch 2012; Williamson et al. 2012*b*). The need for adaptation has long been recognized by the scientific community as shown by an early emphasis on adaptation research in the literature (see Box 1)[2]. In addition, the rate of research on both adaptation and mitigation has increased dramatically and in parallel over recent years, a trend evident across all sectors, including Canadian forest research.

This synthesis builds on the growing body of literature in adaptation research as well as on other syntheses in a group of papers on Canada's boreal zone, particularly that of Price et al. (2013) that covers the expected impacts of climate change on boreal forest ecosystems. Specific objectives are to (*i*) identify vulnerabilities of the Canadian boreal forest management system to climate change; and (*ii*) provide a link between the identified vulnerabilities and potential adaptation actions. The review covers the managed portion of the Canadian boreal forest, hereafter referred to as the managed boreal forest.

2. Approach and scope

Our synthesis is structured around a general framework for evaluating vulnerability and identifying adaptation opportunities (Fig. 1). Within this framework, the exposure of the system to climate change and its sensitivity to climate leads to the identification of impacts. Once the impacts are defined, there is an evaluation of the adaptive capacity of the system, i.e., the ability to adjust to changes. This concept applies both to ecological (from the individual species to stand or landscape levels) and human components of the system. The inherent adaptive capacity of ecosystems concerns the mechanisms by which species and their biological communities adjust to environmental fluctuations and changes. In human systems, it includes the capacity to reduce potential damage, take advantage of opportunities, deal with uncertainty, and cope with the consequences of climate change (IPCC 2001). Identification of gaps in the adaptive capacity of either subsystem reveals vulnerabilities, which points to the need for implementing adaptation actions. This may also include the implementation of adaptation actions to capture positive benefits from the opportunities the impacts have created.

The vulnerability assessment approach outlined above is an established methodology that has been used in a variety of forestry contexts (Kobak et al. 1996; Füssel and Klein 2006; Lindner et al. 2010; Wilson and Turton 2010; Seidl et al. 2011; Swanston et al. 2011; Peterson et al. 2011; Halofsky et al. 2011). Its main appeal is that it can be applied at a range of scales, from international and national (IPCC 2001; Lemmen et al. 2008) down to community scales (Williamson et al. 2008). It also provides a systematic way of breaking down the complexity of climate change into manageable pieces that are relevant and meaningful for decision makers. Typically, vulnerability assessments involve the identification of vulnerabilities (and opportunities) from both a current perspective, based on empirical evidence of changes (Smit and Wandel 2006; Johnston and Williamson 2007), and a future perspective, based on climate change impact projections and scenarios (Locatelli et al. 2008, 2010; Hanewinkel et al. 2010).

The forest management system of the managed boreal forest of Canada is defined as an integrated socioecological system (Glaser et al. 2008) that obtains goods and services from forest ecosystems and manages them in a manner that is concordant with sustainable forest management (SFM) principles and objectives (Williamson et al. 2012*b*). Our analysis was conducted separately and sequentially on the biophysical and human subsystems of the boreal forest management system. For the biophysical subsystem, the analysis covers forest habitats, their biological communities focusing mainly on trees, as they constitute the main target of the current management system, and their physical environments and associated disturbances. With regard to the human subsystem, the analysis not only focuses on forest management activities directly impacted by changes to forest ecosystems, but also touches on the health and safety of forest communities. A third potential level in such an analysis, the web of interdependence between the forest management system and other nonforest institutions and structures, such as economic diversification or migration of people, is beyond the scope of this analysis.

3. The managed Canadian boreal forest

3.1. What it is

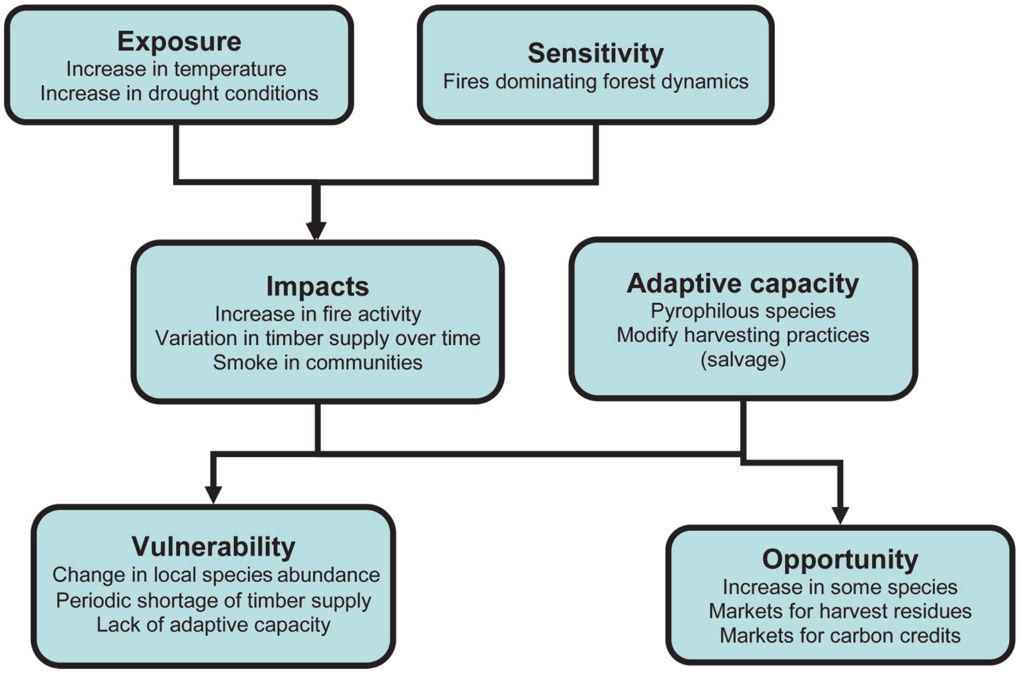
About 70% of Canada's forest land is in the boreal zone; and within this zone, the mostly contiguous forests of limited tree species diversity cover an area of 270 Mha (Brandt et al. 2013). There are eight ecozones that intersect with Canada's boreal zone, five of which have a significant proportion of landbase under forest management (same definition as Stinson et al. 2011, i.e., managed forest was defined "using an area-based approach (IPCC 2003) and included (*i*) lands managed for the sustainable harvest of wood fibre (e.g., saw logs, pulp logs, etc.) or wood-based bioenergy, (*ii*) lands under intensive protection from natural disturbances (e.g., fire and insect suppression to protect forest resources), and (*iii*) protected areas, such as national and provincial parks that are managed to conserve forest ecological values."): the Taiga Plains (TP), Boreal Cordillera (BC), Boreal Plains (BP), Boreal Shield West (BSW), and Boreal Shield East (BSE) (Fig. 2). In these five ecozones, approximately 136 Mha[3] of the boreal forest are considered to be part of the managed boreal forest area (adapted from Stinson et al. 2011; Fig. 2; Table 1). It is within this portion of the Canadian boreal forest that adaptation of management to climate change is likely to be most feasible from an operational and financial perspective.

The climate within the managed boreal forest is cold, with mean annual temperatures generally below or close to 0 °C (normals of 1961–1990). Precipitation decreases from more than 1500 mm in the areas bordering the Atlantic Ocean to just over 400 mm at the prairie–forest ecotone in central Canada. These broad climate gradients and differences in underlying geology result in variations

[2]Supplementary data are available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/er-2013-0064.

[3]The total area of the managed forest is 145 Mha (Kurz et al. 2013), but this value includes all the managed forest whereas our data are for the five main boreal ecozones under management.

Fig. 1. Vulnerability assessment diagram. Exposure and sensitivity to climatic conditions combine, resulting in impacts of climate change. Forests have an innate adaptive capacity, which can be enhanced through forest management practices and other adaptation options. Similarly, components of the human sphere (individuals, communities, organizations, and institutions) have different levels of adaptive capacity. The combination of potential impacts and adaptive capacity results in vulnerabilities or allows the identification of opportunities. For example, in the boreal forest, significant changes in temperature and precipitation are forecast (Exposure); this can translate into a change in fire regime affecting the forest (Sensitivity). An increase in fire activity can affect forest composition, timber supply availability or increase smoke emissions around communities (Impacts). As boreal forests are disturbance-dominated systems, species have the ability to adjust to these changes in fire activity; forest management can also adjust by increasing salvage logging (Adaptive capacity). Locally, large-scale disturbances may create a shortage in timber supply (Vulnerability). At the same time, an increase in demand for bioenergy can provide new markets for residual biomass (Opportunity).



in composition and dominance of tree species across the boreal zone (Bonan 1989). The relatively cold climate also results in the presence of permafrost. In fact, 44% of the managed boreal zone is located in the discontinuous permafrost zone (DPZ) where between 10% and 90% of the area lies on permafrost (Price et al. 2013; Fig. 2; Table 1). Natural disturbances, and in particular wildfires and insect outbreaks, have long shaped the boreal forest (Table 1; Bonan 1989; Johnson 1992) and contributed to the patchwork of stand age (Bergeron et al. 2006). Between 1990 and 2008 in the managed boreal forest, the annual area burned averaged 580 000 ha, while annual area affected by moderate or severe outbreaks of insects was about 970 000 ha (Table 1; Stinson et al. 2011).

3.2. Socioeconomic drivers

The economy of the boreal zone is largely based on the extraction or use of natural resources and its activities contribute significantly to the GDP and the employment of Canadians (NRCan 2011; Patriquin et al. 2007, 2009; Bogdanski 2008). For 2004, Bogdanski (2008) estimated that the boreal timber-based forest sector generated approximately $41 billion in total annual revenues and employed about 127 000 people. In 2011, based on the proportion of Canada-wide harvest occurring in the boreal forest, we estimated that the boreal forest sector contributed $11.5 billion of GDP and employed about 117 000 people (NRCan 2012). In terms of infrastructure, in 2011, 21% of Canadian mills were located in the boreal zone (sawmills, pulp and paper, and pellet mills; Brandt et al. 2013), whereas around 50% of the active mines and 60% of the installed energy capacity were in the boreal zone (Brandt, unpublished data).

About 3.7 million people live in the boreal zone in hundreds of small to medium-sized communities (Fig. 2). Some of these are Aboriginal communities. According to the 2001 census, 90% of these had members who used nontimber forest resources, 40% had members who hunted, fished, or gathered wild plants, and approximately 15% had members who trapped (Bogdanski 2008). Average population density is 0.76/km^2 of land (Brandt et al. 2013).

Canadian boreal forests also deliver a broad range of other public and common-property goods and services not directly related to the ones used by the traditional wood products industry. These include regulating, cultural, and supporting services that are significant for Canadians, such as clean air and water, carbon sequestration, wildlife habitat, aesthetically pleasing vistas and locations, recreation opportunities, or that have spiritual, traditional, subsistence and cultural values notably for the Aboriginal communities.

3.3. Forest management activities

Forest management in the boreal zone involves a broad range of agents and organizations, each with different roles and responsibilities (Table 2). Ninety-three percent of the boreal forests of Canada are on public land, 77% are under the management responsibility of the provinces or territories while 16% are under federal jurisdiction (Natural Resources Canada 2012). Forest management objectives and policies for public forest lands are defined by the Forestry Act and legislation enacted by provincial and territorial governments. Private companies typically enter into agreements with provincial governments to gain timber-harvest rights to public lands, conditional upon undertaking certain management activities and meeting specific management standards and criteria. As fires are an intrinsic part of boreal forests, public and private resources are dedicated to protecting people, infrastructures, and timber from these events. Nongovernmental organizations, communities, and municipalities interact with

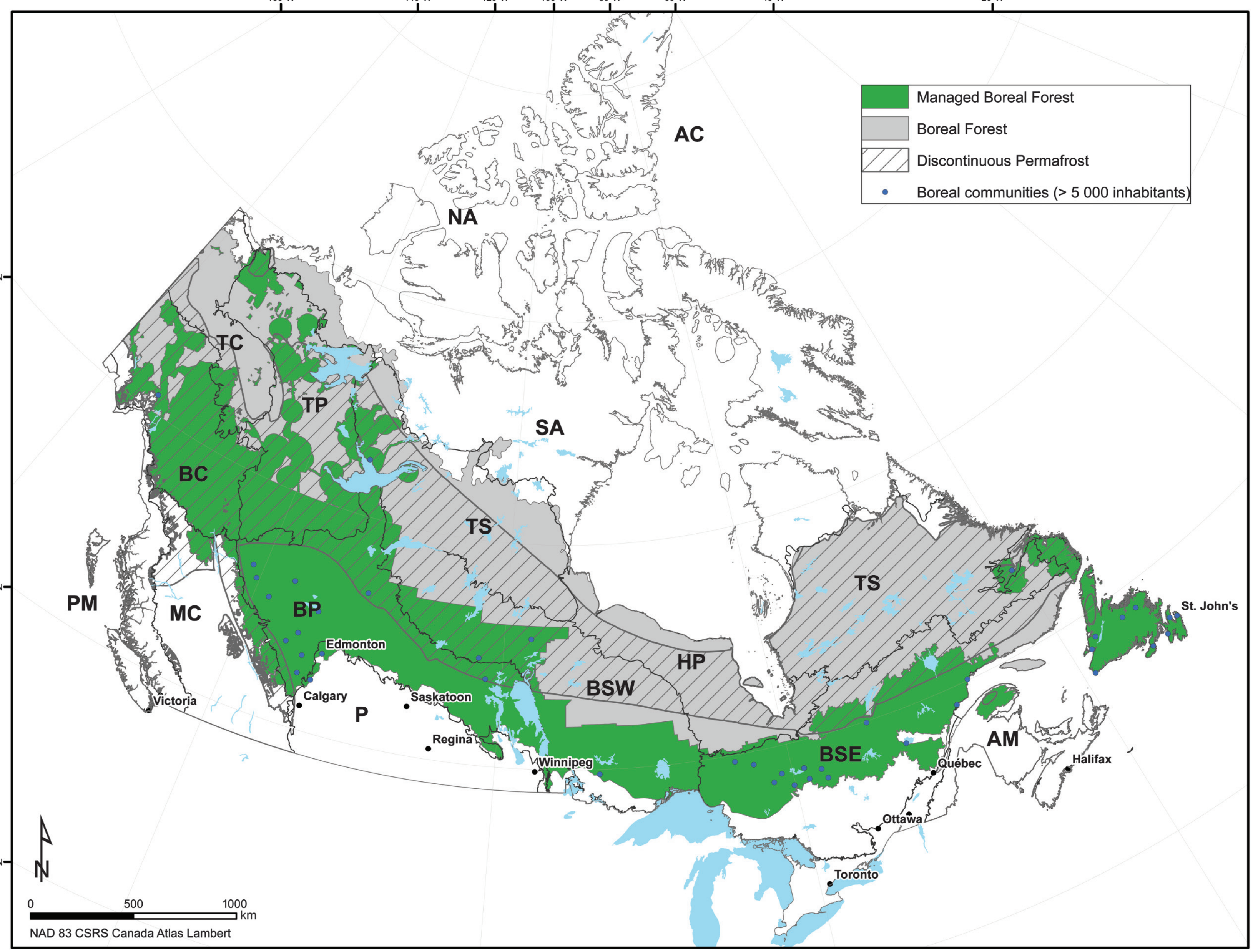


Fig. 2. Location of the managed (in green) and unmanaged (in gray) boreal forest of Canada, together with the boreal ecozones (modified from Ecological Stratification Working Group 1995) and the discontinuous permafrost. Boreal communities of more than 5000 inhabitants are also shown. AC, Arctic Cordillera; AM, Atlantic Maritime; BC, Boreal Cordillera; BP, Boreal Plains; BSE, Boreal Shield East; BSW, Boreal Shield West; HP, Hudson Plains; MC, Montane Cordillera; NA, Northern Arctic; P, Prairies; PM, Pacific Maritime; TC, Taiga Cordillera; TP, Taiga Plains; TS, Taiga Shield; SA, Southern Arctic (adapted from Stinson et al. 2011 and Brandt 2009). Note that the southern limit of the boreal forest does not coincide with the southern limits of the boreal ecozones.

Table 1. Annual area affected by recent disturbances in the five main ecozones of the managed boreal forest of Canada (annual mean for 1990–2008; adapted from Stinson et al. 2011) and proportion located in the discontinuous permafrost zone.

	Boreal Cordillera	Taiga Plains	Boreal Plains	Boreal Shield West	Boreal Shield East	Total
Managed area (km²)	159 630	200 131	352 596	254 846	390 511	1 357 713
Fire						
Area (km²)	539	973	1695	1566	1013	5787
Proportion (%)	0.34	0.49	0.48	0.61	0.26	0.43
Insects*						
Area (km²)	480	1582	7084	136	409	9691
Proportion (%)	0.30	0.79	2.01	0.05	0.10	0.71
Harvesting						
Area (km²)	60	349	2032	586	418	3446
Proportion (%)	0.04	0.17	0.58	0.23	0.11	0.25
Discontinuous permafrost zone (DPZ)						
Proportion (%)	100	82	28	42	19	44
Proportion of harvest within the DPZ† (%)	100	100	22	7	12	27

*Moderate and severe levels of mortality or defoliation.
†Information derived from remote sensing data covering the period of 2001–2011 (Luc Guindon, personal communication).

Table 2. Main agents and organizations of the boreal forest management system in Canada.

SFM participants	Role and responsibilities
Provincial and territorial governments	Enact forest legislation and develop forest management policy, environmental policy, and regulations; long-term planning; timber management; allocate timber rights; forest renewal; ensure compliance with acts and regulations; forest fire protection; forest health; public consultation; applied research
Forest industry	Implement SFM policies according to tenure obligations (conduct inventories, consult with other land users, forest management planning); conduct forest harvesting operations, monitoring, and regeneration in compliance with third-party certification; carry out research
Certification bodies	Set standards for SFM and certify and audit forestry operations
Canadian Council of Forest Ministers	Provide a forum for cooperation and leadership by provinces, territories, and the federal government on SFM issues
Government of Canada	Carry out forest research; support trade, environmental, economic, and industrial development and transformation; regional development; oversee national institutions; deliver disaster relief
Aboriginal peoples / First Nation governments	Contribute to forest management through new Aboriginal tenure arrangements, consultation processes, and traditional land uses
Municipal governments / Forest-based communities	Delivery of SFM via community-based tenures and through consultation with industry
Universities	Education of forestry professionals; research
Environmental non-governmental organizations	Partner with industry or other organizations on initiatives regarding protection of environmental values, conservation and use of the boreal forest for improved prosperity of dependent populations

Note: SFM, sustainable forest management.

higher level institutions to define land-use and resource management objectives and provide resources for on-the-ground operations.

Forest management laws and regulations in Canada have evolved during the past 30 years from a focus on sustained timber yield to one of sustainable forest management (SFM) that aims at maintaining environmental, social, and economic benefits for current and future generations (Burton et al. 2003; Gauthier et al. 2009*b*). At the national level, the Canadian Council of Forest Ministers (CCFM 1995) defines SFM according to six criteria shown in Table 3 in relation to the types of services provided by the forest. The majority of firms operating in the boreal zone also have products that are certified by third parties (Forest Stewardship Council, Sustainable Forestry Initiative, or Canadian Standards Association) as coming from forest areas that are managed according to SFM standards. At the end of 2012, there were 148 Mha certified in Canada with an estimated 60% (i.e., 88.8 Mha) belonging to the boreal forest (Forest Products Association of Canada 2012).

The managed Canadian boreal forest is composed of generally remote, closed-canopy stands of low productivity, and its management tends to be extensive rather than intensive. Annually, the harvest in the five main ecozones covers about 344 600 ha (1990–2008 average or 0.25% of the forest area per year) of which around 27% is located in the DPZ (Table 1; adapted from Stinson et al. 2011).

3.4. Climate change and forest management

In 2008, the CCFM released a vision statement identifying climate change as one of the main priorities of national strategic importance to Canada's forest sector (CCFM 2008). Its Climate Change Task Force has now released several reports and information products to support adaptation (CCFM 2009; Johnston et al. 2009; Edwards and Hirsch 2012; Gray 2012; Price and Isaac 2012; Williamson et al. 2012*b*; Johnston and Edwards 2013; Williamson and Isaac 2013). The value of the current CCFM criteria and indicators of sustainability with regard to climate change was assessed

Table 3. Canadian sustainable forest management criteria (Canadian Council of Forest Ministers (CCFM) 1995) and their linkages with ecosystem services and human well-being (adapted from Locatelli et al. 2010).

CCFM criteria	Ecosystem services
Conservation of biological diversity	Support services
Maintenance and enhancement of forest ecosystem conditions and productivity	Support services, provision of services
Conservation of soil and water resources	Regulation and provision of services
Forest ecosystem contributions to global ecological cycles	Regulation of services
Multiple benefits of forests to society	Cultural services and human well-being
Accepting society's responsibility for sustainable development and creating institutions that ensure sustainable management of forests	All ecosystem services and human well-being

(Steenberg et al. 2013). Finally, a number of national assessments describing climate change vulnerabilities of the forest sector have also been produced (Lemprière et al. 2008; Lemmen et al. 2008; Williamson et al. 2009; NRTEE 2011).

Actions to adapt SFM to climate change in Canada are underway but are currently at an early stage (Ogden and Innes 2007, 2008, 2009; Yamasaki et al. 2008; Campbell et al. 2009). For instance, several provinces have on-going initiatives to study the effects of climate change on their respective forest sectors and identify adaptation strategies. At more localized levels, at least 15 initiatives have been launched to investigate forest sector vulnerability in various parts of Canada (Johnston 2012; Johnston and Edwards 2013; Ogden and Innes 2008). The forest industry is also considering how to include climate change considerations in forest management planning. Millar Western Forest Products Ltd. in Alberta, for example, has incorporated climate change impacts into their last 20-year forest management plan (Yamasaki et al. 2008). It is possible that the economic downturn that started in 2008–2009 has made it more challenging for the private sector and government organizations to undertake more substantive actions on climate change adaptation. Nonetheless, these transitional times may represent an opportunity to start mainstreaming adaptation in all spheres of the forest management system of the Canadian boreal forest.

4. Assessing vulnerabilities

As mentioned earlier, the forest management system can be separated into two components: the biophysical and human subsystems. Impacts of climate change on forest ecosystem properties alter the ability of the human subsystem to benefit from forest-related services. Modifications in the forest ecosystem thus become drivers of change within the assessment of socioeconomic vulnerabilities of the human subsystem (Fig. 3). In response, adaptation actions undertaken through the human subsystem may target processes or dynamics in either the biophysical or human subsystem.

4.1. Exposure to climate change and other stressors

Issues related to climate and climate projections for the boreal forests of Canada are covered in detail by Price et al. (2013). In brief, increases in mean annual temperature have already been greater in the western and northern ecozones of the boreal zone, with daily minimum temperatures rising faster than corresponding maximum temperatures, particularly in winter (McKenney et al. 2006). Precipitation has increased in the eastern portion of the boreal zone, and significant droughts have affected the central boreal zone at the prairie–forest ecotone (Hogg et al. 2005). Projections suggest rapid increases in temperature and precipitation in all five managed boreal ecozones. The mean annual temperature is projected to increase by 3.3–5.4 °C compared with current normals (1961–1990) by 2071–2100, with the largest variation in the Boreal Shield West ecozone. Projected increases will be more rapid in winter, as high as 7 °C for the Taiga Plains and Boreal Shield West ecozones by 2071–2100, resulting in a shortening of the snow cover season (IPCC 2007; Price et al. 2013). The length of the growing season is expected to increase gradually by 9–10 days from 2011 to 2040 and 21–46 days from 2071 to 2100, with the greatest increase in the Boreal Cordillera and Boreal Shield East.

Projections also suggest increases in precipitation during the growing season, especially in the Boreal Cordillera or Boreal Shield East ecozones (Price et al. 2013). In the drier western boreal ecozones (Taiga and Boreal Plains), modest predicted increases in precipitation will not totally compensate for the increased evapotranspiration under predicted higher temperatures. This drying effect is predicted to be less important in the Boreal Cordillera and Boreal Shield West, and even more modest in the Boreal Shield East.

The frequency and intensity of extreme weather events is likely to increase in the boreal zone. Projected changes in 90th percentile surface winds (i.e., the intense winds that could be expected to cause forest damage) in western Canada suggest increases (particularly in fall) for the Boreal Cordillera, but no significant changes appear likely for the Boreal Plains or Taiga Plains (Haughian et al. 2012). Locally, extreme climate events such as droughts, wind damage, and ice storms are impacting Canadian boreal forests (Lemmen et al. 2008; Lemprière et al. 2008; Allen et al. 2010), but only long-term tracking will enable us to position such events outside the extreme-event variability of the recent past and within climate change trends.

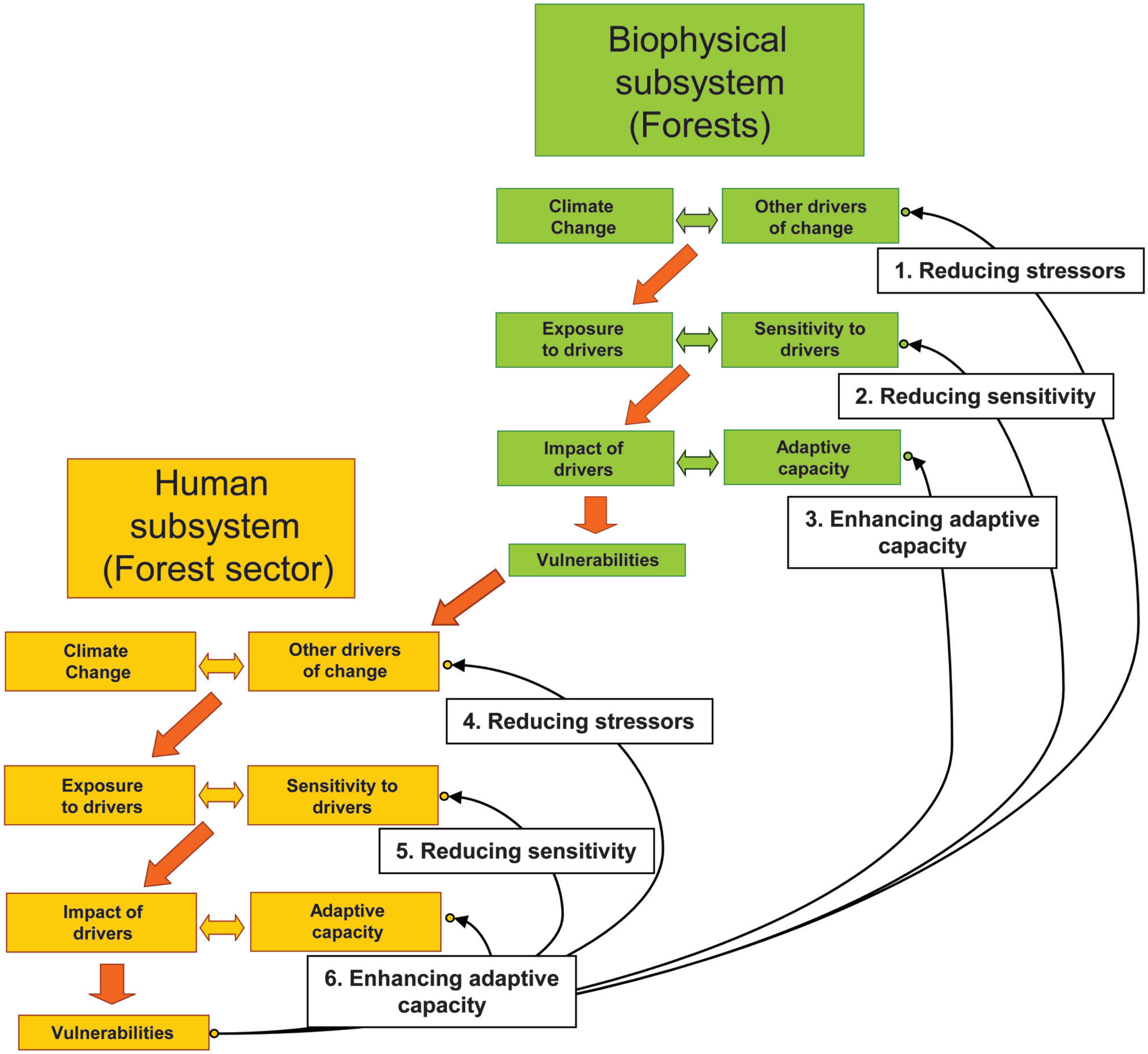
In addition to climate change, both the biophysical and human subsystems are exposed to and affected by other stressors. For instance air pollution, which affects photosynthesis of tree species (Bytnerowicz et al. 2007; Matyssek et al. 2012), can be such a stressor. Landscape fragmentation is increased through cumulative impacts of land-use activities, including forest harvesting, urbanization, transportation infrastructure, energy, and mineral development. Market forces and global events affect world economies and impact the socioeconomic sector over different time scales as well. Such stressors may have a greater impact on some aspects of the forest management system than climate change itself, at least in the short term, but may compound climate change impacts through reduced forest or institutional adaptive capacity (Millar et al. 2007; Mery et al. 2010).

4.2. Impacts on the biophysical subsystem

Forests are the biophysical subsystem of the forest management system. Canada's boreal forest ecosystems are sensitive to climate directly through several processes acting at various temporal and spatial scales (permafrost melting, tree growth, reproduction, establishment, mortality, species composition, and stand structure) and indirectly through the influence of disturbances (fire, insects, wind, diseases, etc.). In this section, we concentrate on the potential impacts of climate change on permafrost, abiotic and biotic disturbances, tree growth and mortality, stand structure and composition, and finally ecosystem state, with a summary by forest property affected provided in Table 4. A detailed analysis of the impact of climate change on the boreal zone is provided in Price et al. (2013).

The increase in mean annual temperature across the boreal forest is leading to the degradation and disappearance of perma-

Fig. 3. Analytical framework for the identification of vulnerabilities within the forest management system, as represented by its two components: the biophysical (forests) and the human (forest sector) subsystems. Changes leading to vulnerabilities in the forest subsequently influence the human subsystem and its resulting vulnerabilities. These vulnerabilities, in turn, can be addressed by one of the six target areas for adaptation options.



frost (Price et al. 2013). Black spruce stands on organic permafrost soils, which are ecosystems with large reservoirs of carbon and habitat for caribou, are becoming increasingly vulnerable to permafrost degradation with human and natural disturbances. Once disturbed, these sites are susceptible to more rapid melt and waterlogging (Price et al. 2013). A rapid change in vegetation can then be observed where sites can be transformed into wetlands or where black spruce can be replaced by white spruce or deciduous trees (Wirth et al. 2008; Johnstone et al. 2010).

Fire has long been the defining disturbance of the boreal forest, but its frequency and severity are changing and predicted to intensify under future climatic conditions (Flannigan et al. 2005, 2009). The predictions also suggest large variations in changes to the fire regime across the boreal zone of Canada (Flannigan et al. 2005, 2009; Price et al. 2013). The mean annual area burned is expected to increase considerably in the Boreal Plains and Boreal Shield West ecozones, a little less in the Taiga Plains and moderately less in the Boreal Shield East. The length of the fire season is also expected to increase (Flannigan et al. 2009; Boulanger et al. 2013).

The severity and duration of biotic disturbances (outbreaks of insects, fungi, and other pathogens) are also related to climatic factors. For instance, insect population dynamics can be controlled by cold winter temperatures that cause high mortality (Taylor et al. 2006; Bentz et al. 2010) or tree phenology that influences the synchronicity between tree and insect life cycles (Nealis and Régnière 2004). Moisture is an important factor in the dynamics of fungal epidemics; pathogens that cause foliar diseases are usually sensitive to precipitation and humidity. Other pathogens are more likely to affect trees that are already stressed by changing climatic factors (Sturrock et al. 2011).

The complexity of interactions involved in forest pest dynamics makes the long-term prediction of their impacts uncertain (e.g., Régnière et al. 2010). Although some forest pests may decline in a warmer world (Régnière 2009), recent mountain pine beetle and spruce beetle outbreaks in western Canada and southern Yukon,

Table 4. Main impacts and potential vulnerabilities identified for the managed boreal forest of Canada.

Component of the forest management system	Boreal impacts and vulnerabilities	Details	Ecozones* affected
Biophysical subsystem	Decrease in forest productivity	Changes in regeneration capacity and growth rate, dieback, and high mortality; due to water limitations	Where water is limiting; drought tolerant species may be favoured
	Changes in forest structure and tree species composition	Pioneer species increase their abundance due to increased disturbance rate and forest management	All regions: local changes very likely; regional extirpation unlikely
		Replacement of black spruce by other species on degraded permafrost	
	Species invasion	Potential for introduction of invasive species; changes in the distribution of native species	Unknown
		Possible impact on forest resilience	
	Forest resilience	Threat to biodiversity: e.g., increasing risk of detrimental effects on species that depend on mature and old-growth ecosystems (e.g. woodland caribou) when combining increased natural disturbance rate with harvesting	Unknown
		Change in forest ecosystem state: change from forest to prairie	Southern fringe of Boreal Plains and Boreal Shield West
		Change in forest ecosystem state: change from black spruce forest to open woodland or wetland	High risk where disturbance frequency is high; occasionally happening due to short intervals between successive disturbances; changes to wetland may happen in areas of permafrost loss
		Decreased health and viability of forest ecosystems due to cumulative impacts of multiple stressors	Unknown
Human subsystem	Change in timber supply quantity and quality	Change in tree growth	Likely to be reduced where water is limiting; Boreal Plains, Taiga Plains, and Boreal Shield West; may increase where temperature was limiting
		Change in regeneration capacity, dieback, and high mortality	Where water is limiting; drought tolerant species may be favoured; where disturbance rate is high
		Change in species composition	All regions / various levels
		Increase in disturbances: high variation in timber supply during tactical planning periods	All regions / various levels
		Increase in salvage logging: type and quality of fibre impacted	All regions / various levels
	Decrease in non-timber forest goods and services	Outdoor recreation activities; increase in summer outdoor recreation opportunities; decrease in winter outdoor recreation opportunities; berries and mushrooms	Unknown
	Limits in accessing the resource	Shorter winter harvest seasons, road washouts, etc.	Various locations across the boreal / already occurring
		Constrained access due to fire danger	All regions / various levels
	Increasing cost related to management of disturbances	Fire protection, fill planting, spraying against pests, etc.	All regions / various levels
		Need to redirect activities to salvage logging	All regions / various levels

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Table 4 (*concluded*).

Component of the forest management system	Boreal impacts and vulnerabilities	Details	Ecozones* affected
	Increasing uncertainty	Forest managers may have to deal with large-scale disturbance events, surprises with an increasing frequency, unknown future forest productivity, global market variation, etc.	All regions / various levels
	Reduction in socioeconomic resilience	A lack of adaptive capacity to current and (or) future changes may make the forest management system vulnerable to unforeseen or rapid changes	Unknown
		Changes in timber supply, harvesting operations, and industry profitability will likely have secondary effects in terms of forest sector employment and income in many small resource-based communities; impacts of climate change and limited adaptive capacity will be concentrated in forest-based and First Nations communities	All regions / various levels
	Increasing safety and health issues	Increase in extreme-weather events; forest fires at the wildland–urban interface are likely to increase; increases in smoke emissions leading to related health problems.	All regions / various levels

*See Fig. 2 for the ecozone locations.

respectively, and their link to warmer weather (Carroll et al. 2004; Taylor et al. 2006; Garbutt et al. 2006) are indicative of how some insect pests may benefit from warmer conditions. Climate change is expanding the area climatically suitable for these two beetles (Régnière 2009), which have now moved out of their historical range (Rice et al. 2007; Cullingham et al. 2011). Moreover, both species have caused extensive mortality in affected forests (Westfall and Ebata 2010; Garbutt et al. 2006).

The expected increase in climatic stressors (such as drought) can act locally as a catalyst for an increase in disease outbreaks, although any pathosystem involves complex interactions among the environment, host, and pathogens (Sturrock et al. 2011). Interaction between drought- and insect-induced mortality is also a potential cause of extensive mortality in some coniferous species of the boreal forest (Berg et al. 2006; Kurz et al. 2008*a*; Allen et al. 2010; Peng et al. 2011). Finally, the potential for outbreaks of non-native pests and pathogens will likely increase, as the global exchange of goods intensifies and the cold climatic conditions presently limiting their spread become warmer with climate change (Langor et al., Manuscript in preparation).

Tree growth in the boreal zone is limited by low temperatures and a short growing season (Jarvis and Linder 2000). In general, tree growth is predicted to increase in the Boreal Shield East, a region where water availability is projected to increase enough to compensate for the increase in temperature (Lemprière et al. 2008; Price et al. 2013). Growth in some species populations may already be benefiting from elevated temperature and possibly elevated CO_2, notably in the northern parts of the managed boreal forest (e.g., Girardin et al. 2011*a*, 2011*b*), but stand age may weaken this effect (Girardin et al. 2012). From a genetics standpoint, however, growth is also related to tree phenophases, such as the timing of budburst and budset. These key adaptive traits (Howe et al. 2003) are influenced by both heredity and climatic conditions (Li et al. 1997*a*, 1997*b*; Pelgas et al. 2011), and it is likely that hereditary change will be much slower than climate change. Consequently, the positive impacts of elevated temperatures on growth might not be fully realized for a few tree generations (Aitken et al. 2008).

In regions where water availability is low relative to species requirements, growth could be impaired by the predicted changes (Girardin et al. 2008; Lapointe-Garant et al. 2010; Hogg and Bernier 2005). Growth decreases will most likely occur in the Taiga Plains, Boreal Plains, and Boreal Shield West, where water availability is projected to decrease (Table 4; Price et al. 2013). Already, in the pristine boreal forests of Eastern Canada just north of the managed forest, Girardin et al. (2014) have shown a decline in tree growth co-occurring with a retreat in sea ice, a pattern that exemplifies how water stress can affect forest productivity. These climate–growth relationships contrast with those observed in the past where the decline was associated with cooler temperatures. On the other hand, in southern Yukon (Chavardes et al. 2012), results suggest that an increase in temperature and precipitation has also changed the growth–climate relationship in white spruce. Depending on the future seasonality and interaction between temperature and precipitation, this might be beneficial to the productivity of that species. The predicted increase in rates and severity of landscape-level disturbances, including drought, has however the potential to offset any increases in tree-level growth (Kurz et al. 2008*b*) anywhere in the boreal forest.

Cold conditions in the boreal forest limit the northern expansion of species such as balsam fir, white spruce, and black spruce (Messaoud et al. 2007; Meunier et al. 2007) by affecting seed production (mainly maturation of the seed) and viability at the northern limits of their ranges (Sirois 2000). Warming temperatures are already starting to remove physiological barriers to the northward expansion of tree species ranges (Caccianiga and Payette 2006). Decreased water availability or increased evaporative demand may also push the prairie–forest ecotone northward into the Boreal Shield West of central Canada (Table 4). Increased drought and heat-induced stress in these regions have already been linked to increased mortality in trembling aspen (Hogg et al. 2002, 2008).

Natural disturbances may also interact with the direct climate effects mentioned earlier in the paper on tree regeneration and survival in ways that will accelerate changes in forest structure, composition, and function at the stand and landscape levels (Pickett and White 1985; Overpeck et al. 1990). In their absence, species range expansions can be a slow process because of the inherent inertia or resistance associated with long-lived plants already occupying a site, even though they may be maladapted to the current climate (Levine et al. 2004; Gillson et al. 2008). Stand-replacing disturbances favour either range expansion or change in relative species abundance by removing the competitive resistance of ecosystems to compositional change (Lodge 1993), although this process may be less important for shade-tolerant species (Martin et al. 2009). Increases in forest fire burn severity linked to climate change are already leading locally to the replacement of spruce by deciduous species in Alaska (Johnstone et al. 2010; Barrett et al. 2011; Beck et al. 2011). Time intervals between successive disturbances that are shorter than the time required to replenish seed and propagule pools have been shown to lead to forest regeneration failure (Jasinski and Payette 2005; Girard et al. 2008). In such extreme cases, an increased frequency of disturbances may transform closed-canopy forests into open woodlands (Table 4).

4.3. Vulnerability of the biophysical subsystem

The vulnerability of boreal forest ecosystems to climate change depends on the extent of their adaptive capacity at the tree and landscape levels. Boreal forest tree species, with their widespread populations, high fecundity, and high levels of genetic diversity (Hamrick et al. 1992), are expected to have a relatively high adaptive capacity in the face of climate change (Aitken et al. 2008). Black spruce, for instance, shows a high level of genetic diversity (Isabel et al. 1995; Perry and Bousquet 2001) similar to that of many other major boreal forest species. Clinal variation (adaptive variation) exists for a number of boreal tree species, suggesting a local adaptation potential, but it is rather limited (e.g., Li et al. 1997*a*, 1997*b*) owing to the relatively little time during the Holocene for genotypic differentiation to occur. One example of adaptive responses found in black spruce is an earlier budset at higher latitudes that confers better frost tolerance (Morgenstern 1969*a*, 1969*b*; Bannister and Neumer 2001). Likewise, local adaptation to aridity resulting from natural selection was recently found for black spruce (Prunier et al. 2011). Nonetheless, as mentioned earlier in the paper, given the projected degree and speed of environmental changes, populations may be maladapted for a few generations (Parmesan 2006; Aitken et al. 2008) under future climate conditions and may not fully capitalize on improved growth conditions.

As a result of natural selection, the degree of resistance or tolerance to fire through specific reproductive mechanisms varies both within and among species. In general, black spruce, trembling aspen, and paper birch have an intermediate degree of vulnerability to repeated fires, and drought conditions for establishment in the case of black spruce (Le Goff and Sirois 2004; Jasinski and Payette 2005; Moss and Hermanutz 2009). In the deep soils of the Boreal Plains ecozone, trembling aspen is likely the least vulnerable species to fire because of its ability to reproduce vegetatively from its root system. At the other extreme, balsam fir is fire intolerant and dominates in the Boreal Shield East where fires are infrequent (Bouchard et al. 2008; Cyr et al. 2012). Jack pine and lodgepole pine are fire adapted, with early sexual maturity and serotinous, fire-resistant cones. In both species, the proportion of trees with serotinous cones is higher in populations occurring in regions where the fire regime is dominated by extensive lethal fires than in those where the fire regime is characterized by local nonlethal fires (Muir and Lotan 1985; Gauthier et al. 1996). Genetic and phenotypic variability of resistance to pests also contributes to adaptive capacity. For example, populations of boreal tree species that cope with recurring insect outbreaks tend to have adaptive traits such as well-established seedling banks (Baskerville 1975; Duchesneau and Morin 1999), prolific propagule production (Greene et al. 1999), or physiological and phytochemical mechanisms of pest resistance and resilience (Keeling and Bohlmann 2006).

Despite their relatively high adaptive capacity, Canadian boreal forests are vulnerable to impacts of climate change (Table 4), in large part because of the relative homogeneity and connectedness of boreal landscapes, but also simply because of the speed at which climatic conditions will change. Overall, the increase in disturbances combined with forest management may reduce the area of old forest (Cyr et al. 2009), thereby impacting regional biodiversity (Venier et al., Manuscript in preparation) and the system's resilience in the face of environmental changes (Millar et al. 2007; Campbell et al. 2009).

Holocene results suggest that the regional extirpation of tree species is unlikely. In fact during the Holocene, the relative species abundance fluctuated in response to wide changes in climate and disturbance regimes, but the overall species pool remained mostly unchanged (Carcaillet et al. 2010). The projected increase in forest disturbances may, therefore, lead to an increase in pioneer species abundance and a decrease in late seral species abundance without any loss of tree species. For some regions, the predicted increase in fire frequency for the next 100 years will not be outside the natural range of variability observed during the Holocene (Bergeron et al. 2010), highlighting even more the unlikeliness of tree species loss.

In terms of resilience, the boreal forest is locally vulnerable to loss of forest cover resulting from permafrost degradation, successive disturbances, or drought. In the Boreal Shield East (BSE, Fig. 2), forest cover loss resulting from successive disturbances (Jasinski and Payette 2005; Girard et al. 2008) could be amplified by climate change and other synergistic impacts, but should remain a local phenomenon. More critically, however, in the Boreal Shield West, drought and increased fire frequency will likely move the prairie–forest ecotone northward into the area that currently supports boreal forests (Hogg and Bernier 2005; Table 4).

Potential vulnerabilities of the wildlife, soil, or water resources that are also part of boreal forest ecosystems are not addressed in this review but can be found in Price et al. 2013; Maynard et al. 2014; Venier et al., Manuscript in preparation; and Webster et al., Manuscript in preparation. It is clear that climate change impacts on other boreal organisms, resources, or processes can be expected, which can also lead to impacts on forest ecosystems. For instance, the virulence of some tree pathogens may increase with more favourable temperature or precipitation levels, resulting in increased mortality of host trees (Sturrock et al. 2011). The abundance of invasive shrub species that can counteract forest regeneration may also be favoured by stand opening after disturbances and a changing climate (Dukes et al. 2009). Such unpredictable and unprecedented events may tip systems toward new states (Price et al. 2013). Outcomes of interactions between different ecosystem processes and drivers of change such as climate, land use, and air pollution are also difficult to predict (Lawler et al. 2010). Difficulty stems from the complexity of interactions between multiple ecosystem components across a hierarchy of scales that makes forests adaptive when challenged with new stresses (Anand et al. 2010). These considerations indicate the need to track indicators of forest ecosystem integrity and responses to global change to detect changing trends, avoid surprises, and develop adaptation actions to face these changes as they occur.

4.4. Impacts on the human subsystem

The impacts of climate change on the human (forest sector) subsystem of the management system are related to the sensitivity of its processes to climate. Currently, climate-sensitive aspects are present in the area of forest management planning, forest operations, and market or nonmarket forest benefits and values such as recreation, water regulation, and community health and safety.

In forest management planning, achieving SFM objectives, as currently defined by the CCFM criteria and indicators (Table 3), may be challenged by climate change, especially when done without considering climate-driven variability and changes (Mote et al. 2003; Ogden and Innes 2007; Johnston et al. 2009). Environmental objectives such as those linked to the maintenance of specific aspects of biodiversity may be unreachable, at least regionally, with existing management objectives and practices that do not account for climate change (Hebda 1998; Gray 2005; Environment Canada 2011). For example, regional mitigation measures that attempt to preserve woodland caribou are currently being jeopardized by the cumulative impacts of climate change (Latham et al. 2011) and other natural and anthropogenic disturbances (Venier et al., Manuscript in preparation). Maintenance of boreal forest carbon stocks will also be difficult to achieve if fire regimes intensify across the boreal forest (Metsaranta et al. 2010; Kurz et al. 2013).

Achievement of SFM economic objectives will be challenged by climate change through its impacts on forests. Intensification of boreal forest disturbance regimes will likely negatively impact timber supply. Current model projections suggest an increase in area burned across the boreal forest, but most rapidly across the Boreal Shield West in conjunction with drought (Flannigan et al. 2005; Hogg and Bernier 2005; Bergeron et al. 2010). Such changes will reduce both timber quality and quantity. Forest-based employment or recreational activities may be difficult to maintain in areas where timber supply decreases substantially or recreational areas are affected by fire. Increases in disturbance frequency and intensity will also have implications for the cost and extent of forest protection (Wotton et al. 2010).

Tree growth may be increased by climate change in the absence of additional limiting factors (Chen et al. 2006; Euskirchen et al. 2006; Lemprière et al. 2008; Johnston et al. 2010), with positive impacts on the quantity of timber available for commercial use. However, the large uncertainties in growth predictions could overwhelm projected changes in growth (Coulombe et al. 2010), thus reducing the capacity to credibly incorporate tree growth increases into timber supply modelling (Table 4).

Climate change also has implications relative to the cost, design, and required intensity of future forest management. Increased uncertainty will make forest planning more complex and thus more costly (Ogden and Innes 2007; Johnston et al. 2009). For instance, forest renewal through tree planting will require more complex methods of seed selection and planting decision-making (Pedlar et al. 2011). Increased climate variability will likely increase the risk of regeneration failures (Girard et al. 2008).

Climate change may locally constrain access to forest resources, resulting in uneven access to merchantable timber and increased fibre delivery costs for processing facilities. Operators are already reporting a shortened winter harvesting season (Ogden and Innes 2009; Johnston et al. 2010). Projections suggest that the duration and predictability of frozen ground conditions will continue to decrease (Barrow et al. 2004). Road washouts appear to be more common regionally, possibly as a result of changes in precipitation regimes, and are forcing the revision of road design and culvert requirements (as reported for Europe in Kolström et al. 2011). Access to forests can also be constrained in summer by restrictions on operations when fire danger ratings reach critical levels; these restrictions are likely to increase with an increase in fire frequency.

An increased disturbance frequency may increase operating costs and decrease fibre quality if forest operations are required in turn to increase their salvaging activities (Table 4). Salvaging damaged timber affects the economics of forest operations as a result of changes in the location and timing of harvesting, access, wear and tear on machinery, and quality of products (Nappi et al. 2004; Schmiegelow et al. 2006; Saint-Germain and Greene 2009). Salvage logging can also add another layer of impacts to forest ecosystems by reducing coniferous natural regeneration or negatively affecting biodiversity (Donato et al. 2006; Greene et al. 2006; Lindenmayer et al. 2008).

Other nontimber economic activities will also be impacted by climate change, but estimating their net economic impact is challenging in large part because of the uncertainty in the direction or magnitude of these changes. For example, the net effect of climate change on outdoor recreation is unclear because climate change could benefit summer recreational opportunities while being detrimental to winter ones (Browne and Hunt 2007). Estimating climate change impacts on the receipts from harvestable berries and mushrooms is equally challenging. Climate change may also affect the subsistence economies of Aboriginal communities through positive or negative changes in game and edible plant species abundance.

At a broader scale, changes in global markets, such as the increased demand for bioenergy and projected increases in global timber supply (Sohngen and Sedjo 2005), in particular from producers located in the southern hemisphere (Perez-Garcia et al. 2002), will impact the forest sector operating in the boreal zone. Opportunities may exist, however, for the timber industry to recast long-term wood products as climate change mitigation options, thereby capturing new markets in the construction sector (Skog and Nicholson 1998; Lemprière et al. 2013).

Climate change also has the potential to impact many nontimber and nonmarket goods and services that are important to society (Williamson and Watson 2010). The impacts for the boreal zone overall are difficult to estimate, however, in part because the common metrics used to estimate such impacts cannot capture many social and cultural values derived from forest ecosystems (Hauer et al. 2001; Adger et al. 2007). Impacts may include losses in spiritual, cultural, and use values. A changing environment in which impacts are outside the bounds of natural variability may also reduce the value of Aboriginal peoples' traditional knowledge and negatively affect their traditional uses of boreal ecosystems (Turner and Clifton 2009).

Finally, forest-based communities face additional climate impacts because of their strong ties to surrounding forest landscapes, proximity to fire-prone forests, and strong economic reliance on the forest industry. Potential impacts include loss of employment, loss of property and infrastructure to extreme events such as flooding (Williamson et al. 2007), and more fundamentally, increased personal health and safety risks from wildfires and wildfire smoke.

4.5. Vulnerability of the human subsystem

The vulnerability of the human component of the forest management system to climate change depends on the extent of its adaptive capacity to impacts. Although exact location and timing of impacts is unknown, it is clear that the human subsystem will need to adapt to current and future changes and events. In that context, it is important to assess the existing ability of the human subsystem to adapt to a rapidly changing climate (Williamson et al. 2012*a*; Johnston et al. 2011). Globally, theories on how to assess adaptive capacity, including elements related to awareness and risk perception, are in nascent stages and currently there is no commonly accepted method or approach (Lindner et al. 2010; Engle 2011; Kolström et al. 2011; Williamson and Isaac 2013).

In Canada, empirical research on the adaptive capacity of the forest sector in the boreal zone has been initiated (Beckley et al.

2008; Johnston et al. 2008; Williamson et al. 2008, 2012*a*). The ability of private and public institutions to adapt to climate change is highly variable (Table 4). Even within larger organizations, climate change considerations have just begun to be mainstreamed into policy, planning, and decision-making on account of knowledge and capacity issues (i.e., staff, resources, systems). Organizational culture, structure, or networking may not provide the flexibility or innovation potential necessary to deal with an increasingly complex, uncertain, and dynamic decision-making environment (Konkin and Hopkins 2009). In surveys of more than 50 forest organizations across Canada (Johnston et al. 2010, 2011), high levels of education, professional knowledge, and access to technologies were factors that were perceived as contributing positively to their adaptive capacity. On the other hand, lack of financial resources, flexibility in the management framework, and information about future impacts at relevant scales were also pointed out as barriers to adaptation in forest management policy and planning (Ogden and Innes 2009; Johnston et al. 2010, 2011).

The speed of anticipated changes will affect the level of vulnerability. Slow and gradual changes in timber supply may leave enough time for forest managers to adapt. Sudden and large-scale events may overwhelm the adaptive capacity of organizations and institutions, as has been the case with the mountain pine beetle outbreak in central British Columbia (Konkin and Hopkins 2009). Small, rural, resource-based, or First Nations communities in Canada can be particularly vulnerable to climate change outcomes because of their high exposure to changes and their sometimes limited adaptive capacity (Davidson et al. 2003; Lemmen et al. 2008).

5. Adaptation actions

Adaptation is intended to maintain forest-derived services to people, either through actions in the biophysical (forests) or human (forest sector) subsystems of the forest management system through changes in forest policies, practices, or operations. All adaptation actions can either be reactive or proactive. Reactive adaptation refers to actions taken after the impact has occurred. Planned or proactive adaptation refers to actions taken in anticipation of negative outcomes or for capturing emerging opportunities. Planned adaptation in a forest management context is a desirable approach because it can reduce exposure to risk. Reactive adaptation is nevertheless the more commonly used approach in forestry (Keenan 2012; Schoene and Bernier 2012). A more detailed typology of adaptation response types is provided in Ogden and Innes (2008) and applied to local management plans.

Adaptation actions, whether reactive or proactive, act on one of three possible components of the society–forest interaction: the biophysical subsystem (forest ecosystem), the human subsystem (forest sector), and society at large. In the last case, adaptation efforts could involve changing the needs, the use, or the dependence on forest ecosystem services (Spittlehouse 2005). The review of actions related to this third component, such as the diversification of local economies and the movement of people, exceeds the scope of this review. In this review, we focus on actions related to forest management and targeting either the biophysical or human subsystems. These actions may aim at reducing system stressors, reducing system sensitivity to climate change, or maintaining or enhancing the adaptive capacity of either subsystem (Fig. 3).

Our ability to influence the adaptive capacity of boreal forest ecosystems (the biophysical subsystem) is limited by the relatively small yearly footprint of forest management activities and the nearly uncontrollable nature of large-scale natural disturbances (Wotton et al. 2010). In contrast, we define and control all activities related to the human subsystem, and this is, therefore, where most adaptation options lie. Analyzing adaptation options through the categories proposed in Fig. 3 shows the various avenues through which organizations can implement changes. These six avenues for adaptation are discussed in the following sections and are presented in Table 5. This exhaustive list is also available in Table S1[2] in a format that permits filtering and sorting as required by the user. Within both tables, adaptation actions are also classified into six broad areas of vulnerability: (1) disturbances and species invasion, (2) forest productivity, (3) forest resilience, (4) access to the forest, (5) lack of adaptive capacity, and (6) socioeconomic resilience. This classification links the main vulnerabilities highlighted in the previous sections to potential adaptation options.

5.1. Reducing stressors on the biophysical subsystem

Although trees and forests have the ability to naturally adapt to changing conditions, climatic and nonclimatic stressors can reduce their adaptive capacity and decrease their capacity to provide services to society under future change. The identification and reduction of nonclimatic stressors (Ogden and Innes 2007; Joyce et al. 2008; Blate et al. 2009) are an important category of adaptation actions that can include the reduction of atmospheric pollutants, the reduction of forest landscape fragmentation due to land use (including coordination of road construction and other associated infrastructures by the forestry, energy, and mining sectors), and protection against nonnative pests and plant species through port-of-entry surveillance and control measures (Table 5). The reduction of nonclimatic stressors requires coordinated partnerships among multiple agencies, stakeholders (industries, land planners, communities, environmental agencies, and nongovernmental organizations), and governments at all levels (Burton et al. 2010).

Because of the significance of climate change impacts, it is also clear that climate change mitigation actions contribute to effective adaptation (Konkin and Hopkins 2009). In this sense, measures that increase stored carbon in landscapes or forest sector participation in carbon offset schemes could, therefore, be considered as adaptation actions aimed at reducing stressors on the forest (in this case, induced climate change). Further details on mitigation actions can be found in Lemprière et al. (2013).

5.2. Reducing sensitivity of the biophysical subsystem

A combined approach involving strategic changes in management, operations, and silvicultural practices can be used to reduce forest sensitivity to changes in disturbance frequency (Table 5). Operational management actions include practices such as intensive protection against disturbances and fuel reduction treatments (Millar et al. 2007; Ogden and Innes 2007; Locatelli et al. 2008; Blate et al. 2009), fire-smart management (Hirsch et al. 2001), and the use of tree species or genotypes, including genetically modified trees, less susceptible to or adapted to insect attack, drought, or other forecasted detrimental events (Campbell et al. 2009). Management strategies and silvicultural practices that generate heterogeneity in forest structure, composition, and age-class distribution could be used to reduce the vulnerability of forest landscapes to large catastrophic disturbances (Drever et al. 2006; Millar et al. 2007; Ogden and Innes 2007; Bernier and Schoene 2009; Campbell et al. 2009; Girardin et al. 2013). Silvicultural practices can also be developed to promote stand productivity and vigour for better resistance to drought or insect attack (Ogden and Innes 2007; Anderson and Chmura 2009; Jactel et al. 2009). Examples of adaptation actions related to reducing the sensitivity in forest growth are also presented in Table 5.

5.3. Maintaining or enhancing adaptive capacity of the biophysical subsystem

The adaptive capacity, or resilience, of the boreal forest relies on the maintenance of system complexity, ensuring a diversity of responses to changing conditions (Gunderson and Holling 2002; Folke et al. 2002; Jump and Peñuelas 2005; Chapin III et al. 2006;

Table 5. Example of adaptation actions proposed in the literature for the managed boreal forest.

Subsystem	Target areas of adaptation	General vulnerability	Detailed vulnerability	Adaptation option	Reference
Biophysical	Reduce stressors	Species invasion	Invasions by non-native species	Proactively control invasive species (plants, insects, diseases)	Ogden and Innes 2007, 2008; Johnston et al. 2009; Campbell et al. 2009
				Proactively control the origin of trees planted in urban context (select tree species best suited to local conditions and desired ecosystem services); not well adapted and stressed trees are more susceptible to pests and can be a route of entry for exotic pests (impact natural forests)	Tubby and Webber 2010
		Forest resilience	Decreased health and viability of forest ecosystems due to cumulative impacts of multiple stressors	Integrated multi-sector land management to reduce current stress factors and their cumulative impacts: (1) regulate atmospheric pollutants or CO_2 emissions or use forest management as a CO_2 sink; (2) manage tourism, recreation, and grazing impacts; (3) restore degraded areas to maintain genetic diversity and promote ecosystem health; (4) reduce landscape fragmentation	Chapin III et al. 2006; Ogden and Innes 2007, 2008; Blate et al. 2009; Joyce et al. 2008; Konkin and Hopkins 2009; Lemprière et al. 2013
				Work with others to ensure that stressors outside the control of the forest manager are minimized	Ogden and Innes 2007
	Reduce sensitivity	Forest productivity	Decreased forest growth	Modify seed transfer zones	Williamson et al. 2009; Johnstone et al. 2010
				Plant alternative genotypes or new species in anticipation of future climate	Williamson et al. 2009; Johnstone et al. 2010; Ogden and Innes 2007
				Focus silvicultural investments in areas projected to have relatively stable climates	Rose and Burton 2009
				Plant logged sites with species or populations expected to be adapted to the new climate	Campbell et al. 2009
				Employ vegetation control techniques to offset drought	Ogden and Innes 2007, 2008
				Enhance forest growth through forest fertilization	Ogden and Innes 2007, 2008
				Plant seedlings from a range of seed sources, particularly from more southern or lower-elevation populations; plant genetically modified species and identify more suitable genotypes	Ogden and Innes 2007, 2008; Bernier and Schoene 2009; Campbell et al. 2009
				Adapt silvicultural rules and practices to ensure the growth rate of trees is maintained or enhanced; for instance, use pre-commercial thinning or selectively remove suppressed damage or poor quality individuals to increase resource availability to the remaining trees	Ogden and Innes 2007, 2008; Bernier and Schoene 2009; Johnston et al. 2009; Blate et al. 2009
			Populations or species are no longer suited to site conditions	Underplant with other species or genotypes where the current advanced regeneration is unacceptable	Ogden and Innes 2007, 2008; Campbell et al. 2009
				Reduce the rotation age followed by planting to speed the establishment of better adapted species	Ogden and Innes 2007, 2008; Johnston et al. 2009
		Disturbances	Increased frequency and severity of forest disturbances	Develop “disturbance-smart” landscapes	Williamson et al. 2009; Johnston et al. 2010; Ogden and Innes 2007, 2008; Hirsch et al. 2001; Locatelli et al. 2008; Blate et al. 2009

Table 5 (*continued*).

Subsystem	Target areas of adaptation	General vulnerability	Detailed vulnerability	Adaptation option	Reference
				Develop forest harvest and regeneration patterns that generate a diversity of stand ages and compositions over landscapes to reduce forest vulnerability to future insect and disease outbreaks	Drever et al. 2006; Millar et al. 2007; Ogden and Innes 2007; Bernier and Schoene 2009; Campbell et al. 2009
				Actively manage forest pests	Ogden and Innes 2007, 2008
				Vary the shape and size of clearcuts and leave patches or stream buffers to reduce vulnerability to potential for increased windthrow disturbance	Campbell et al. 2009
				Plant species mixes that occur following natural disturbances—avoid practices that generate uniform post-disturbance stands that may be highly vulnerable to future disturbances	Campbell et al. 2009
				Employ silvicultural techniques to promote forest productivity and increase stand vigour to lower the susceptibility to drought or insect attack	Ogden and Innes 2007, 2008; Anderson and Chmura 2009; Jactel et al. 2009)
				Plant genotypes or species that are tolerant of drought, insects, and (or) disease and fire	Ogden and Innes 2007, 2008; Johnston et al. 2009; Campbell et al. 2009
				Use prescribed burning or other fuel treatments to reduce fire risk and reduce forest vulnerability to insect outbreaks	Ogden and Innes 2007, 2008; Johnston et al. 2009; Campbell et al. 2009; Millar et al. 2007; Locatelli et al. 2008; Blate et al. 2009
	Enhance adaptive capacity	Forest productivity	Populations or species are no longer suited to site conditions	Plant broader and new mixes of tree species over landscapes	Campbell et al. 2009
				Plant species over a broader range of environments	Campbell et al. 2009
				Assisted range expansion: regional expansion of northern, inland, or upper elevational limit of species for reforestation to track climatic niches	Millar et al. 2007; O'Neill et al. 2008; Johnston et al. 2009; Pedlar et al. 2011
		Disturbances	Change in forest structure, composition, or cover	Maximize forested areas by quickly regenerating any degraded areas	Ogden and Innes 2007; Johnston et al. 2009; Campbell et al. 2009
				Allow forests to regenerate naturally following disturbances when possible	Ogden and Innes 2007, 2008
			Decrease in forest sinks and increased CO_2 emissions from northern forested ecosystems due to increased frequency and severity of forest disturbances	Enhance forest recovery after disturbances	Ogden and Innes 2007, 2008
			Increased frequency and severity of forest disturbances	Manage for the maintenance of complexity and diversity of responses to changing conditions	Millar et al. 2007; Sarr and Puettmann 2008; Campbell et al. 2009; Johnston et al. 2010
				Maintain or restore natural fire regimes where historical fire cycles have been disrupted by past fire exclusion and made them more vulnerable to severe future fires	Ogden and Innes 2007, 2008; Blate et al. 2009; Campbell et al. 2009
		Forest resilience	Alteration of plant and animal distribution	Minimize fragmentation of habitat and maintain connectivity	Ogden and Innes 2007, 2008; West et al. 2009

Table 5 (*continued*).

Subsystem	Target areas of adaptation	General vulnerability	Detailed vulnerability	Adaptation option	Reference
				Maintain a diverse and heterogeneous landscape (mixture of stand age, composition, and structure) by applying various silvicultural techniques	Ogden and Innes 2007, 2008; Johnston et al. 2010; Bernier and Schoene 2009; Gauthier et al. 2009*b*; Williamson et al. 2009
				Study the synchrony between trees and animals (phenology of the development) both in parasitic and mutualistic relationships with a focus on keystone species	Cleland et al. 2007; Singer and Parmesan 2010
				Minimize density of permanent road networks and decommission and rehabilitate roads to maximize productive forest areas	Ogden and Innes 2007, 2008
				Practice low-intensity forestry and prevent conversion to plantations	Ogden and Innes 2007, 2008
				Protect most highly threatened species ex situ.; for instance, create artificial reserves or arboreta to preserve rare species	Ogden and Innes 2007, 2008; Johnston et al. 2009
				Assist changes in the distribution of species by introducing them into new areas	Ogden and Innes 2007, 2008; Johnston et al. 2009
				Maintain representative forest types across environmental gradients in reserves; protect forest largely undisturbed by human activities; protect climate refugia at multiple scales	Ogden and Innes 2007, 2008; Rose and Burton 2009
				Identify and protect functional groups and keystone species	Ogden and Innes 2007, 2008; Rose and Burton 2009
				Use silvicultural systems that maintain genetic, species, and landscape diversity	Williamson et al. 2009; Johnston et al. 2010; Campbell et al. 2009
				Develop corridors for species migration and habitat protection; provide buffer zones for adjustment of reserve boundaries; consider riparian habitats and ecological transitional zones	Williamson et al. 2009; Johnston et al. 2010; Ogden and Innes 2007, 2008; Bernier and Schoene 2009; Johnston et al. 2009; Blate et al. 2009; Heller and Zavaleta 2009; West et al. 2009; Seavy et al. 2009; Vandergast et al. 2008
			Decreased health and viability of forest ecosystems due to cumulative impacts of multiple stressors	Maintain diversity in genes, species, and ecosystem conditions	Whitham et al. 2003, 2006; Ogden and Innes 2007; Seppälä et al. 2009*a*, 2009*b*
				Implement restoration options to recover structural or compositional heterogeneity lost through past management practices	Stanturf and Madsen 2002; Kuuluvainen 2002; Burton and Macdonald 2011
				Protect high evolutionary potential areas, including biodiversity hotspots	Chapin III et al. 2010; Vandergast et al. 2008
			Increased soil erosion due to increased precipitation and melting permafrost	Adopt practices such as maintaining, decommissioning, rehabilitating roads to minimize sediment runoff due to increased precipitation and melting of permafrost	Ogden and Innes 2007, 2008
				Limit harvesting operations to the winter to minimize road construction and soil disturbance	Ogden and Innes 2007, 2008
				Minimize soil disturbance through low impact harvesting activities	Krankina et al. 1997; Ogden and Innes 2007, 2008

Table 5 (*continued*).

Subsystem	Target areas of adaptation	General vulnerability	Detailed vulnerability	Adaptation option	Reference
Human	Reduce stressors	Change in goods and services provided by forest ecosystems	Decrease in forest sinks and increased CO_2 emissions from northern forested ecosystems due to declining forest growth and productivity	Decommission and rehabilitate roads to maximize forest sinks	Ogden and Innes 2007, 2008
				Enhance forest growth and carbon sequestration through forest fertilization	Ogden and Innes 2007, 2008
				Minimize density of permanent road network to maximize forest sinks	Ogden and Innes 2007, 2008
				Minimize risk of the forest ecosystem becoming a net source of carbon	Ogden and Innes 2007, 2008
				Modify thinning practices (timing, intensity) and rotation length to increase growth and turnover of carbon	Ogden and Innes 2007, 2008
			Decreased health and viability of forest ecosystems due to cumulative impacts of multiple stressors	Conduct an assessment of greenhouse gas emissions produced by internal operations	Ogden and Innes 2007, 2008
			Forest fragmentation or forest landbase lost	Allocate forest landbase using a triad approach to landscape zoning; allow high-intensity forestry in productive areas projected to remain relatively stable in climate	Ogden and Innes 2007, 2008; Rose and Burton 2009; McAfee et al. 2010
		Disturbances	Decrease in forest sinks and increased CO_2 emissions from northern forested ecosystems due to increased frequency and severity of forest disturbances	Decrease impact of natural disturbances on carbon stocks by managing fire and forest pests	Ogden and Innes 2007, 2008
				Identify areas where deforestation may be avoided	Ogden and Innes 2007, 2008
				Identify areas where forests have been degraded and can be rehabilitated	Ogden and Innes 2007, 2008
				Minimize soil disturbance through low-impact harvesting activities	Ogden and Innes 2007, 2008
				Practice low-intensity forestry and prevent conversion to plantations	Ogden and Innes 2007, 2008
				Reduce forest degradation and avoid deforestation	Ogden and Innes 2007, 2008
			Increased frequency and severity of forest disturbances	Develop the bioenergy market using wood from disturbed areas	Bernier and Schoene 2009
		Socioeconomic resilience	Dependence on vulnerable goods or services	Develop marketing strategies aimed at recasting wood products as having climate friendly, carbon-sequestering properties	Coalition Bois Québec 2012
			Lack of flexibility	Provide opportunities for forest management activities to be included in carbon trading systems	Ogden and Innes 2007, 2008
	Reduce sensitivity	Change in goods and services provided by forest ecosystems	Alteration of plant and animal distribution	Conduct reciprocal transplant experiments for key species	Cleland et al. 2007
			More and (or) earlier snow melt resulting in changes in the timing of peak flow and volume in streams	Examine the suitability of current road construction standards and stream crossings to ensure they adequately mitigate the potential impacts on fish and potable water of changes in timing and volume of peak flows	Johnston and Williamson 2005; Ogden and Innes 2007, 2008
				Conduct research comparing tree species growth and regeneration at the margins of species ranges	Campbell et al. 2009

Table 5 (*continued*).

Subsystem	Target areas of adaptation	General vulnerability	Detailed vulnerability	Adaptation option	Reference
				Develop experiments (e.g., planting and silvicultural trials) that test management approaches for enhancing resilience or facilitating "ecosystem change" that can be applied at the stand level and over larger landscape areas if successful	Campbell et al. 2009; Burton et al. 2010
				Study changes in ecosystem transition areas	Campbell et al. 2009
				Develop a gene management program to maintain diverse gene pools	Ogden and Innes 2007, 2008
			Decreased forest growth	Focus management on currently productive sites and those likely to remain more productive under future climates, and reduce efforts on poor sites	Johnston et al. 2009
				Include climate variables in growth and yield models to have more specific predictions on the future development of forests	Ogden and Innes 2007, 2008
			Populations or species are no longer suited to site conditions	Bank surplus seed—broader use of non-local seed sources may require the procurement and banking of many different seedlots	Campbell et al. 2009
				Assist population expansion: movement of populations within a species range to improve productivity and health in new climates	Johnston et al. 2009
				Use genomics approaches to generate genetic data and molecular tools for (*i*) identifying forest tree species and populations that are vulnerable to climate change, (*ii*) supporting breeding programs and migration initiatives, and (*iii*) refining models used to predict species distribution and productivity under climate change	Namroud et al. 2008; Pelgas et al. 2011; Prunier et al. 2011
				Adapt silvicultural rules and practices to maintain optimum species–site relationships	Ogden and Innes 2007, 2008
				Review genetic guidelines for reforestation: relax rules governing the movement of seed stocks from one area to another; examine options for modifying seed transfer limits and systems	Ogden and Innes 2007, 2008; Blate et al. 2009
				Design and establish long-term multi-species and (or) seedlot trials to test improved genotypes across a diverse array of climatic and latitudinal environments	Ogden and Innes 2007, 2008; Campbell et al. 2009; Ste-Marie 2011
	Reduce sensitivity	Accessing the resources	Forest closure	Reassess regional fire danger and prepare for reduced harvesting periods	Wotton et al. 2010
			Road access	Prepare for reduced winter harvest	Lemmen et al. 2008; Williamson et al. 2009; Johnston et al. 2010
				Redesign roads and trails to withstand increased rainfall intensity	Blate et al. 2009
				Reassess river and stream peak flows and link them to bridge and road design standards	Ogden and Innes 2007, 2008
				Reassess terrain stability maps in light of changing ground conditions associated with climate change	Ogden and Innes 2007

Table 5 (*continued*).

Subsystem	Target areas of adaptation	General vulnerability	Detailed vulnerability	Adaptation option	Reference
				Avoid constructing roads in landslide-prone terrain where increased precipitation and melting of permafrost may increase hazard of slope failure	Ogden and Innes 2007, 2008
		Disturbances	Increased frequency and severity of forest disturbances	Include climate change considerations when planning, constructing, or replacing infrastructure	Blate et al. 2009; Williamson et al. 2009; Johnston et al. 2010
				Include disturbances in management rules and forest management plans; develop an enhanced capacity for risk management; apply ecosystem management approaches	Gauthier et al. 2009*b*; Campbell et al. 2009; Kolström et al. 2011; Ogden and Innes 2007, 2008; Bernier and Schoene 2009
				Develop fire-smart landscapes around communities; develop strategies at the wildland–urban interface	Hirsch et al. 2001
				At the operational level, plan logging, salvage logging and environmental protection with disturbance-triggered contingencies in mind	Lindenmayer et al. 2008; Williamson et al. 2009; Johnston et al. 2010; Ogden and Innes 2007, 2008; Le Goff et al. 2005
				At the operational level, plan logging, salvage logging and environmental protection with contingency	Lindenmayer et al. 2008
				Breed for pest resistance and a wider tolerance to a range of climate stresses and extremes in specific genotypes	Ogden and Innes 2007, 2008
				Protect higher value areas from fire through fire-smart techniques	Ogden and Innes 2007, 2008
				Adjust harvest schedules to harvest stands most vulnerable to insect outbreaks	Ogden and Innes 2007, 2008; Johnston et al. 2009
				Reduce disease losses through sanitation cuts that remove infected trees	Ogden and Innes 2007, 2008; Johnston et al. 2009
				Develop technology to use altered wood quality and tree species composition, modify wood processing technology	Ogden and Innes 2007, 2008; Williamson et al. 2009; Johnston et al. 2009, 2009
				Account for disturbance losses at all stages of planning	Savage et al. 2010; Raulier et al. 2013
				Prepare for variable timber supply	Williamson et al. 2009; Johnston et al. 2010
				Plan landscapes to minimize the spread of insects and diseases	Williamson et al. 2009; Johnston et al. 2010; Bernier and Schoene 2009
				Increase the proportion of salvage logging as part of overall sustainable harvest levels	Williamson et al. 2009; Johnston et al. 2010; Ogden and Innes 2007, 2008
				Shorten the rotation length to decrease the period of stand vulnerability to disturbances and facilitate change to more suitable species	Williamson et al. 2009; Johnston et al. 2010; Ogden and Innes 2007, 2008; Johnston et al. 2009
		Species invasion	Invasions by non-native species	Enhance the early detection and response strategy associated with non-native invasive species	Blate et al. 2009
				Adopt policies to ensure that disruption of ecosystems by non-native species is avoided to maintain integrity	Ogden and Innes 2007
	Enhance adaptive capacity	Socioeconomic resilience	Lack of awareness or poor access to information	Development of forest management plans that reduce vulnerability of forests and forest-dependent communities to climate change	Ogden and Innes 2007, 2008
				Establish objectives for the future forest under climate change	Ogden and Innes 2007, 2008

Table 5 (*continued*).

Subsystem	Target areas of adaptation	General vulnerability	Detailed vulnerability	Adaptation option	Reference
				Make choices about the preferred tree species composition for the future	Ogden and Innes 2007, 2008
				Increase awareness about the potential impact of climate change and encourage proactive actions, e.g., climate change impacts on the fire regime and proactive actions in regard to fuel management and community protection	Ogden and Innes 2007, 2008
				Establish stronger relationships between scientific researchers and management to help identify resilience thresholds for key species and ecosystem processes, determine which thresholds will be exceeded, prioritize projects with a high probability of success, and identify species and vegetation structures tolerant of increased disturbances	Blate et al. 2009; Littell et al. 2012
				Enhance awareness and understanding of climate change in the forest sector: communications, debate, education	Chapin III et al. 2006; Williamson et al. 2009; Lemprière et al. 2008; Johnston et al. 2010
				Enhance dialogue amongst stakeholder groups to establish priorities for action on climate change adaptation in the forest sector	Chapin III et al. 2006, 2010; Ogden and Innes 2007, 2008
				Support research on climate change, climate impacts, and climate change adaptations and increase resources for basic climate change impacts and adaptation science	Ogden and Innes 2007, 2008; Bernier and Schoene 2009
				Increase technical understanding by developing educational material for employees and stakeholders	Blate et al. 2009
				Combine ecosystem process models with spatial landscape models; link ecosystem process models to spatially explicit landscape models	Campbell et al. 2009
				Delineate bioclimatic envelopes and project changes	Campbell et al. 2009
				Develop process-based models of species range shifts and ecosystem changes	Campbell et al. 2009
				Historical information from extreme climate effects may provide some information about cumulative responses to climate conditions outside the bounds of recent history	Campbell et al. 2009
				Encourage societal adaptation	Ogden and Innes 2007, 2008
				Enhance capacity to undertake integrated assessments of system vulnerabilities at various scales	Ogden and Innes 2007, 2008
				Review forest policies, forest planning, forest management approaches, and society's institutions to assess our ability to achieve social objectives under climate change	Ogden and Innes 2007, 2008
				Support knowledge exchange, technology transfer, capacity building, and information sharing on climate change; maintain or improve capacity for communications and networking	Ogden and Innes 2007, 2008; Bernier and Schoene 2009

Table 5 (*continued*).

Subsystem	Target areas of adaptation	General vulnerability	Detailed vulnerability	Adaptation option	Reference
				Incorporate new knowledge about the future climate and forest management plans and policies	Ogden and Innes 2007, 2008; Johnston et al. 2009
				Include climate variables in growth and yield models and incorporate climate change effects into long-term timber supply analysis and forest management plans	Williamson et al. 2009; Johnston et al. 2010; Ogden and Innes 2007, 2008
				Expand conservation education programs to include climate change	Williamson et al. 2009; Lemprière et al. 2008; Johnston et al. 2010
				Agree on standardized climate scenarios for analysis	Williamson et al. 2009; Lemprière et al. 2008; Johnston et al. 2010
				Foster learning and innovation and conduct research to determine when and where to implement adaptive responses	Chapin III et al. 2006, 2010; Ogden and Innes 2007, 2008; Gray 2005; Brown 2009
				Anticipate variability and change and conduct vulnerability assessments at a regional scale	Ogden and Innes 2007, 2008
			Lack of flexibility	Engage the public in a dialogue on values and management under a changing climate	Williamson et al. 2009; Johnston et al. 2010
				Remove barriers and develop incentives to adapt to climate change; encourage local and community-based adaptation planning, informed by local knowledge and empowered with more local control	Ogden and Innes 2007, 2008; Burton et al. 2010
				Provide incentives and remove barriers to enhancing carbon sinks and reducing greenhouse gas emissions	Chapin III et al. 2006; Ogden and Innes 2007, 2008
				Involve the public in an assessment of forest management adaptation options	Ogden and Innes 2007, 2008
				Provide long-term tenures to encourage long-term considerations within short-term decisions	Ogden and Innes 2007, 2008
				Incorporate climate change into land-use plans and consider the possibility of land-use changes at specific locales (forest to agriculture and vice versa)	Williamson et al. 2009; Johnston et al. 2010
				Prepare for increases in wildfire activity	Williamson et al. 2009; Johnston et al. 2010; Bernier and Schoene 2009
				Redesign and (or) implement society's institutions that facilitate cost-effective and economically efficient adaptation and provide forest managers with the tools necessary to achieve forest management objectives	Williamson et al. 2009; Johnston et al. 2010
			Increased uncertainty	Incorporate long-term climate change into wildland fire planning	Blate et al. 2009
				Develop flexible forest management policies, plans, and practices that are capable of responding to changes	Ogden and Innes 2007, 2008; Bernier and Schoene 2009; Seppälä 2009; Burton et al. 2010
				Practice adaptive management: rigorously combine management, research, monitoring, and means of changing practices so that credible information is gained and management activities are modified by experience; include risk assessment practices	Chapin III et al. 2010; Ogden and Innes 2007, 2008; Bernier and Schoene 2009

Table 5 (*concluded*).

Subsystem	Target areas of adaptation	General vulnerability	Detailed vulnerability	Adaptation option	Reference
				Study population responses to climate change with a focus on growth, reproductive processes, recruitment rates, mortality, and demography, particularly for ecologically significant (keystone and dominant) species and economically important species	Campbell et al. 2009
				Monitor changes in hydrologic regimes, such as shifts in seasonal precipitation patterns (i.e., rain vs. snow) and changes in precipitation intensity, in relation to their impact on ecosystems, vegetation, and tree growth	Campbell et al. 2009
				Monitor changes in key processes (e.g., nutrient and hydrological cycles) for vulnerable ecosystems, and measure their effects on vegetation	Campbell et al. 2009
				Adopt risk assessment and adaptive management principles	McAfee et al. 2010; Locatelli et al. 2010
				Measure, monitor, and report on indicators of climate change and sustainable forest management to determine the state of the forest and identify when critical thresholds are reached	Ogden and Innes 2007, 2008
				Develop flexible forest management plans and policies that are capable of responding to changes	Ogden and Innes 2007, 2008; Bernier and Schoene 2009
				Evaluate the adequacy of existing environmental and biological monitoring networks for tracking the impacts of climate change on forest ecosystems, identify inadequacies and gaps in these networks, and identify options to address them	Ogden and Innes 2007, 2008; Bernier and Schoene 2009
				Modify objectives for sustainable forest management, including reduction of expectations and the means we use to achieve them	Williamson et al. 2009; Johnston et al. 2010; Burton et al. 2010
				Monitor to determine when and what changes are occurring	Williamson et al. 2009; Johnston et al. 2010
			Dependence on vulnerable goods or services	Evaluate recreational impact on ecosystems under a changing climate	Blate et al. 2009
				Expand recreational opportunities across all four seasons	Blate et al. 2009
				Adopt a holistic management approach such as ecosystem management that balances timber and non-timber goods and services	Ogden and Innes 2007
				Diversify economy (forest, regional)	Chapin III et al. 2006; Ogden and Innes 2007, 2008
				Diversify society's portfolio of forest assets	Williamson et al. 2009; Johnston et al. 2010

Campbell et al. 2009; Table 5). The maintenance of diversity in genes, species, and ecosystem conditions (one of the Canadian SFM criteria) allows for a variety of responses to occur under changing environmental conditions, therefore increasing the capacity of the forest ecosystem to take advantage of new conditions (Whitham et al. 2003, 2006; Ogden and Innes 2007; Seppälä et al. 2009*a*, 2009*b*).

The maintenance of heterogeneity at the stand and landscape scales (i.e., the diversity of habitats) is key to maintaining biodiversity (Ogden and Innes 2007; Bernier and Schoene 2009; Gauthier et al. 2009*a*; Williamson et al. 2009; Johnston et al. 2010), which is itself a determining factor of the adaptive capacity of ecosystems. Silvicultural practices to recover structural or compositional heterogeneity lost through past management practices can also be implemented (Stanturf and Madsen 2002; Kuuluvainen 2002; Burton and Macdonald 2011). Minimizing fragmentation among habitats (Ogden and Innes 2007; West et al. 2009) by maintaining migration corridors and landscape connectivity at the regional scale enables genes and species to access new environments as conditions change (Ogden and Innes 2007; Bernier and Schoene 2009; Blate et al. 2009; Heller and Zavaleta 2009; Johnston et al. 2009, 2010; West et al. 2009; Williamson et al. 2009; Andrew et al. 2014). Riparian zones might be of particular importance to this end. As topographic and ecological transition zones, they can serve as coherent transport corridors that link aquatic and terrestrial ecosystems (Seavy et al. 2009; Vandergast et al. 2008).

Conservation plans can also be designed to accommodate future changes (Andrew et al. 2014). In fact, it is possible to locate and protect climate refugia (Ogden and Innes 2007; Rose and Burton 2009) and areas of high diversity. Protection can focus on undisturbed landscapes (Ogden and Innes 2007) or zones with high evolutionary potential across multiple taxa (Vandergast et al. 2008), such as hybrid zones (Swenson and Howard 2005), where new combinations of alleles and genotypes can be favoured under changing environmental conditions (Rieseberg et al. 2003). Hybrid zones are known for a number of boreal tree species—e.g., species complexes of Sitka–Engelmann–white spruce (Sutton et al. 1991; Bennuah et al. 2004), lodgepole–jack pine (Wheeler and Guries 1987), and black–red spruce (Perron and Bousquet 1997)—and can be defined as important conservation zones.

The expected increase in disturbances throughout the Canadian boreal forest (Volney and Hirsch 2005; Burton et al. 2010) may increase the potential for regeneration failure. The post-disturbance stage, whether following natural or human disturbances, is therefore a crucial period during which actions can facilitate forest adaptation in preparation for future conditions. Options to facilitate adaptation and maximize opportunities include assisted species or provenance migration (Millar et al. 2007; O'Neill et al. 2008; Pedlar et al. 2011; Ste-Marie 2011), as well as the creation of species or provenance mixtures to spread the risk and increase the probability of capturing growth opportunities (Campbell et al. 2009).

5.4. Reducing stressors on the human subsystem

The capacity to maintain the flow of services from forests to society and, more broadly, to use these services to maintain and enhance the well-being of society is dependent on factors that extend well beyond climate. Understanding these agents of change and the broader social and institutional contexts within which forest management takes place can be of considerable benefit in terms of helping the forest management system develop ways to adapt to climate change. The boreal forest management system in Canada is currently under pressure from multiple stressors, including structural changes in global markets, globalization, technological change, and changes in societal values. Using market forces through certification or marketing to maintain or increase demand for forest products obtained from sustainably managed forests is an adaptation option that enables the capture of opportunities and the reduction of economic impacts on industry. An example is the development of marketing strategies promoting renewable wood products, which have climate friendly, carbon-sequestering properties that help reduce climatic stressors (e.g., see the Coalition Bois Québec 2012, http://www.coalitionbois.org/en; Lempière et al. 2013). Expanding markets for bioenergy and bioproducts may also provide an additional revenue stream for forest management (Table 5).

Although deforestation rates are very low in Canada's forests (Kurz et al. 2013), loss of productive forest landbase to competing land uses (agriculture, mining, oil and gas exploration and extraction, water reservoirs, utility corridors, protected areas, and urban expansion) can be important stressors on the human subsystem of the forest management system at the local level. The adoption of an integrative land-use planning framework, already in place in many provinces, provides a framework within which climate change considerations can inform decision-making. As an example, a functional zoning strategy where activities with different management objectives are distributed in different areas of the landscape (Ogden and Innes 2007) enables efficient planning for the different services desired by society from the forest. Developed mainly in forestry, the triad approach can be taken as an example in which the management unit is divided into three different zones where conservation, intensive timber production, and extensive management are applied (Rose and Burton 2009; McAfee et al. 2010). In a climate change adaptation context, a combination of functional zoning and identification of climate refugia could be used to identify sites that will remain productive under future climate conditions and focus field-level investments on adaptation actions in these areas (Rose and Burton 2009).

5.5. Reducing sensitivity of the human subsystem

A number of adaptation options already exist that could reduce the sensitivity and direct impacts of climate change on the human subsystem of the forest management system of Canada's boreal forests (Table 5). First and foremost, incorporation of climate change considerations into all aspects of forest management policy and decision-making should be undertaken (Blate et al. 2009; Johnston et al. 2010).

At the strategic level, reduced sensitivity could be achieved through better planning for risk, for example, by accounting for disturbance losses (Savage et al. 2010; Raulier et al. 2013), moving towards shorter rotation lengths (Johnston and Williamson 2005), or accommodating flexible long-term targets and periodically revisiting the SFM criteria and indicators (Tables 5 and S1[2]). Application of an ecosystem management approach that incorporates risk into planning for the maintenance of diversity in age-class structure, composition, and connectivity of boreal forest landscapes could help reduce sensitivity (Gauthier et al. 2009*b*; Campbell et al. 2009; Kolström et al. 2011). Application of a fire-smart management approach (Hirsch et al. 2001) in the immediate vicinity of forest communities may reduce exposure of these communities to wildfires (see the "partners in protection initiative" at https://www.firesmartcanada.ca/).

At the operational level, contingency planning could lead to an efficient redirection of harvesting activities to salvage logging while maintaining planned levels of environmental protection and habitat provisioning (Lindenmayer et al. 2008). In terms of forest access, roads could be designed to sustain more extreme storm events. Plans for reduced winter harvest and hauling, adoption of high-flotation tires, or building of more permanent roads could reduce vulnerabilities to shorter winters and permafrost degradation (Lemmen et al. 2008; Williamson et al. 2009; Ogden and Innes 2008).

5.6. Enhancing the adaptive capacity of the human subsystem

As identified in the previous sections, current organizational structures may not be equipped to deal with the impacts of climate change. The creation, fostering, and maintenance of an adaptation and innovation culture within forest management organizations would enhance the capacity of forest managers to adapt (Van Damme 2008). Greater inter-institutional exchanges and networking have also been found to promote adaptation capacity in the Ontario forest sector (Brown 2009). Enabling more nimble organizational structures in which adaptation decisions can be taken at the appropriate level (national, regional, local) may also provide more flexibility in the identification of vulnerabilities and timely implementation of appropriate actions (Ogden and Innes 2007; Bernier and Schoene 2009; Burton et al. 2010). Improved projections of future timber supply would also support sound investment decisions in forest industry processing capacity and forest management investment (Table 5).

Enhancement of internal awareness and understanding of climate change in the forest sector is also a major category of adaptation actions. Awareness-building, communication, debate, and education within the Canadian forest sector is on-going and will enhance the response to climate change (Williamson et al. 2009; Lemprière et al. 2008; Johnston et al. 2010). As an example of internal capacity building, science–management partnerships have been established in some US national forests specifically for the identification of forest management adaptation options (Littell et al. 2012). Some of the case studies reported by Johnston and Edwards (2013) have also initiated such partnerships.

Changes in the overall forest management context must be an integral part of the adaptation framework. Rules, laws, regulations, and other such formal arrangements such as certification frameworks can limit the capacity of forest managers to test and deploy adaptation actions. Laws and regulations often impose long-term forest management goals irrespective of climate change, or constrain short-term responses to climate-driven events. Revising such barriers to adaptation is an important step towards mainstreaming climate change into forest management practices (Williamson et al. 2012*a*).

In general, with increasing uncertainty as to future ecosystem processes, the best approach would be to embrace adaptive management through which forecasts, goals, and progress are re-evaluated periodically against the evolving reality and adjustments are made to planning and expectations (Ogden and Innes 2007; Bernier and Schoene 2009). The implementation of an adaptive management framework would require the maintenance or enhancement of monitoring capacity targeted at pertinent indicators.

6. A "road map" to climate change adaptation

In the previous sections, we have identified vulnerabilities and related adaptation actions for the forest sector. However, adaptation is first and foremost a context-dependent exercise and the mix of actions could be better identified and implemented by the entities that need to adapt. We, therefore, offer a three-step "adaptation road map" that provides a general framework for any exercise in adaptation, irrespective of circumstances. The three steps are the identification of the contextual vulnerabilities, the selection of adaptation actions, and the implementation of an adaptive management framework, including a strong monitoring component.

The first step in adapting to climate change is to identify the vulnerabilities of the system of interest to current climate, scope out potential vulnerabilities to climate change, and determine what gaps in adaptive capacity need to be resolved to alleviate such vulnerabilities. Vulnerability assessment involves exploring exposure and sensitivity to climate and climate change to understand possible impacts that a community or organization might face and examining the capacity that exists or may be needed in the future to adapt to these impacts (i.e., adaptive capacity; see Williamson et al. 2012*a*). By identifying sources of vulnerability, adaptation options that reduce exposure and sensitivity and increase adaptive capacity can be identified.

As a second step, adaptation actions should be chosen as a function of current and future climate conditions and related vulnerabilities. Unfortunately, climate projections include a large and often irreducible amount of uncertainty (Dessai et al. 2009). Scenarios can be used to explore possible futures and test the feasibility of adaptation strategies (Glick et al. 2011). When faced with uncertainty, however, one strategy is to select robust, no-regret adaptation actions that may be suboptimal relative to any particular scenario, but robust across a range of scenarios (Lempert et al. 2003; Crowe and Parker 2008; Ogden and Innes 2009; Lawler et al. 2010). Another strategy is to implement a portfolio of adaptation options (Oliver 1995; Hobbs et al. 2006, 2010; Spittlehouse and Stewart 2003; Millar et al. 2007). This approach acknowledges at the start that some adaptation actions within the portfolio will fail because of unforeseen events or inexact predictions (Locatelli et al. 2008). In addition to making forest management more adaptable to climate change, portfolio diversification may also be used to address conflicts by taking into account the multiple values of the different stakeholders (Sarr and Puettmann 2008).

The third step is the implementation of an adaptive management framework within which adaptation actions can be deployed. Adaptive management is a strategic approach for managing under uncertainty and has been identified as a way to deal with climate change in forest management (Tompkins and Adger 2004; Millar et al. 2007; Locatelli et al. 2010; Gray 2012). Adaptive management is centered on a feedback loop of design, implementation, assessment, and adjustment, thus creating an iterative process for decision-making aimed at reducing the unknowns and uncertainties. In this type of framework, goals are periodically evaluated against trends via feedback from monitoring. Adjustments are then made to decrease the gap between observed and desired conditions, modify goals through changes in planning, or do both. Monitoring provides the information necessary to track changes in the biophysical and human subsystems of the management system and assess the success or failure of the adaptation options being implemented.

This "road map" to climate change adaptation presents a broad, high-level approach to adapting forest management to climate change. In practice, assessing vulnerability of forest management systems can be a complex task that is highly context-specific to the biophysical and human subsystems being assessed. A number of recently published guides provide structured approaches that forest resource professionals can follow to identify vulnerabilities and adaptations relevant to the ecosystems and forest management systems within which they work (Gleeson et al. 2011; Glick et al. 2011; Peterson et al. 2011; Swanston and Janowiak 2012; Edwards et al., In press). These guides follow similar approaches for assessing impacts and vulnerabilities but vary in scale and scope of application.

Peterson et al. (2011) and Swanston and Janowiak (2012) focused on adapting United States National Forests to climate change and Glick et al. (2011) provided an excellent plain language guide to understanding vulnerability, uncertainty, and scenarios within a context of species and habitat conservation. Gleeson et al. (2011) focused on impacts and vulnerability of Ontario ecosystems, and Edwards et al. (In press) focused specifically on sustainable forest management systems and is the only guide to explicitly include assessment of the human subsystem. These guides offer a number of common suggestions for adapting forest management systems to climate change through the use of impact and vulnerability assessment, and many of these recommendations are consistent with findings from a synthesis of forestry adaptation projects in

Canada (Johnston and Edwards 2013). Besides the three steps presented previously, these guides also stress the importance of several elements for successful adaptation: (1) the integration of vulnerability assessment and adaptation planning within existing decision-making frameworks (e.g., part of the forest management planning process); (2) the creation and fostering of active partnerships between forest resource professionals, scientists, and other stakeholders (i.e., science–management partnerships) to incorporate expert, local practitioner, and stakeholder knowledge into adaptation planning; and (3) the use of climate and forest impact scenarios as an approach to dealing with an uncertain future in selecting the adaptation options.

7. Highlights and conclusions

In this review, we have offered a broad analysis of climate change vulnerability and related adaptation needs and approaches for boreal biophysical and human subsystems of the forest management system. In terms of adapting to future changes, we have identified some major gaps, notably in information on expected impacts at the appropriate spatial and temporal scales, assessments of adaptation options, and adaptive capacity. Our analysis also recognized that adaptation needs vary with institutions and contexts and most adaptation is done in reaction to events, with only some planned actions to deal with an uncertain future.

Ideally, moving adaptation towards a planned mode could help ensure greater resilience of the forest management system in a way that will help maintain ecosystem services and provide stability to communities. Such an endeavour is hampered by uncertain forecasts of impacts to come, especially at local scales. Decision makers within any institution, therefore, have to find their own way through sometimes conflicting information and face the prospect of planning with and for uncertainty. Although challenging, the shortcomings highlighted earlier in the paper bound the adaptation choices and in essence simplify the task of decision makers, much like a bumpy road forces drivers to slow down, giving them more time to read the signs. It points to the importance of integrating uncertainty into forest management planning and operations, while possibly lowering expected returns or at least expecting fluctuating forest yields in exchange for system stability.

With these broad uncertainties as to future ecosystem processes, monitoring is crucial. The implementation of an effective monitoring system for adaptive forest management implies identifying vulnerabilities, putting in place systems to acquire information in an experimental set-up, at the appropriate spatial and temporal scales, and committing to maintaining such a system over the long term. Because it informs multiple decision-making processes within the forest management system, monitoring is also a no-regret adaptation action.

One of the major vulnerabilities identified for the Canadian managed boreal forest is the increase in disturbance frequency and severity. These disturbances will affect the amount and quality of timber supply as well as the wealth and health of communities living and working in the forest. Disturbances (natural and human) also offer forest managers a window of opportunity to prepare stands for future forest conditions through a range of silvicultural practices, and therefore represent target areas for forest-based adaptation actions. Monitoring of regenerating areas, especially if they are formerly mature-forest plots, would also provide early warning of change.

Adapting the forest management system of the Canadian boreal zone to climate change is required, as climate change will affect forests and forest ecosystems for the foreseeable future. However, adaptation should generate multiple benefits by adding intelligence to the system and enabling responses to multiple sources of stress in addition to climate change. Different levels of government and institutions have already started to move down this road. With this type of planning and foresight, the boreal forests of Canada and the associated forest management sector should, therefore, be able to maintain their role as generators of services and well-being for Canadians.

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