Vulnerability assessment to climate change of three ecosystem-based forest management projects in Quebec

by Héloïse Le Goff[1,2,3] and Yves Bergeron[3]

ABSTRACT

The new forest management stewardship of Quebec acknowledges the importance of integrating climate change consequences into forest management. However, forest professionals do not know how they could take climate change into account into their decision-making. This paper proposes the assessment of climate change vulnerability for three ecosystem-based forest management (EBFM) projects in Quebec: the Tembec project in the Abitibi region, the Triad project in the Mauricie region, and the Laurentian Wildlife Reserve project. The objectives were to identify: i) climate change vulnerabilities affecting forest ecosystems and forest management, ii) adaptation options to decrease these vulnerabilities, and iii) current EBFM practices impeding or facilitating the integration of climate change adaptations in forest management. Several features of EBFM, like promoting ecosystem resilience and using an adaptive management framework, may facilitate the integration of adaptation measures into the current forest management approach. We present climate change adaptation as a piece of the puzzle that would facilitate the achievement of EBFM objectives.

Keywords: adaptation to climate change, sustainable forest management, resilience, adaptive management, case studies

RÉSUMÉ

Le nouveau régime forestier du Québec reconnaît l'importante de considérer les conséquences des changements climatiques en aménagement forestier. Cependant, les professionnels forestiers ne savent pas comment ils pourraient tenir compte des changements climatiques dans leurs décisions. Cet article présente l'évaluation de la vulnérabilité aux changements climatiques de trois projets d'aménagement forestier écosystémique (AFE) au Québec: le projet de Tembec dans la région de l'Abitibi, le projet Triade dans la région de la Mauricie, et le projet de la Réserve faunique des Laurentides. Les objectifs étaient d'identifier i) les vulnérabilités aux changements climatiques des écosystèmes forestiers et de l'aménagement forestier, ii) des options d'adaptation visant à réduire ces vulnérabilités, et iii) les pratiques empêchant ou facilitant l'intégration de l'adaptation aux changements climatiques en aménagement forestier. L'AFE présente plusieurs aspects, comme l'amélioration de la résilience des écosystèmes ou l'utilisation d'une gestion adaptative, qui pourraient faciliter l'intégration de mesures d'adaptation dans notre façon actuelle d'aménager les forêts. Nous présentons l'adaptation aux changements climatiques comme une pièce du casse-tête qui pourrait faciliter l'atteinte d'objectifs d'AFE.

Mots-clé : adaptation aux changements climatiques, aménagement forestier durable, résilience, gestion adaptative, études de cas

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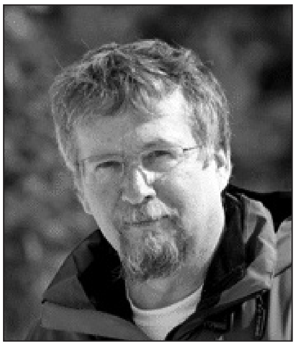

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Introduction

Strategic planning of forest management is based on a window of 150 years in Quebec. We know with certainty that the climate will change over this horizon, although we do not know with certainty what the future climate will be. Current models of timber harvest planning are based on constant climatic conditions so that the projections of forest dynamics and forest productivity are at risk in a changing climate.

While forest professionals and users are facing climate change and its effects on forests and forest management, climate change is still not being explicitly considered during forest management planning (Ogden and Innes 2008). The boreal forest is particularly exposed and sensitive to climate change. Because of their northern latitudes, boreal ecosystems are exposed to

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climate change of larger amplitude (notably larger temperature increase) than ecosystems situated further south (IPCC 2007). Simultaneously, the boreal forest is particularly sensitive to climate change because these impacts affect several biological and ecological processes that are currently limited by climatic conditions including fires, insect epidemics, growth, and distribution areas. Climate changes that will particularly affect boreal forests include increased atmospheric temperatures, an altered precipitation regime (frequency and amplitude of events), an alteration in seasonality (shorter, milder winters and earlier and longer summers, Ouranos 2010), and changes in the frequency and amplitude of extreme meteorological events (e.g., droughts, freeze/thaws, heavy rain; Logan *et al.* 2011). These changes will have a number of important consequences, including: i) an alteration in the frequency and severity of natural disturbances; ii) an increase in the area occupied by early successional species in response to increased disturbances (fire, flooding, insect epidemics); iii) changes in the spatial and temporal occurrences of species (forest composition); iv) modifications in radial tree growth and, thus, on forest productivity; v) latitudinal and altitudinal migrations of species distributions (at locations where edaphic conditions and ecological processes, such as natural disturbances and competition, are favourable); vi) an increased presence in invasive and exotic species; and vii) an alteration in the quantity and quality of faunal habitat and predator–prey relationships (Prato 2008, Huang *et al.* 2010, Ouranos 2010, Logan *et al.* 2011).

These biophysical modifications will surely have consequences on the ecological services offered by forests including the abundance of woody and non-woody forest products, the production of oxygen, regulation of climate, sequestration of carbon, as well as impacting recreational and cultural values and activities (Hassan *et al.* 2005). For these reasons, the Government of Quebec developed an action plan in order to identify and adopt measures to mitigate climate change and stimulate the development of adaptation strategies and measures. The 2006–2012 Climate Change Action Plan (MDDEP 2008) defined a measure specific to the forestry sector. The objective of this measure was to identify vulnerabilities to climate change and to integrate the anticipated effects of climate change in forest management (MDDEP 2008). In addition, the Sustainable Forest Development Act (Gouvernement du Québec 2012), in force since April 2013, equally states the necessity to consider the impacts of climate change in the management of forest resources. The law and the corresponding strategy (MRNF 2010) aim at establishing a new sustainable forest management stewardship primarily based on ecosystem-based forest management (EBFM). This approach focuses on the long-term maintenance of healthy, resilient, forest ecosystems by reducing the differences between natural and managed landscapes (Gauthier *et al.* 2009, MRNF 2010). It requires a good understanding of the natural dynamics of forest ecosystems and an adaptive management framework to quickly integrate new knowledge into our forest management. Consideration of climate change within management planning is essential in this context because it influences natural forest dynamics. The risk of fire, for example, is directly related to the fuel water content, precipitation, relative humidity, air temperature, wind speed, and lightning. We can thus expect changes in the fire regime as a function of climate change and these must therefore be considered within the EBFM context.

The transition to a new forest management stewardship provides a good opportunity to explore the possible approaches to integrate adaptation to climate change in forest management in Quebec and to allow forest professionals to cope with both current climate change and future climatic uncertainties. There is an abundant literature on the biophysical impacts of climate change on forest ecosystems and their management, as well as some forest management solutions to address them. However, this information is mostly available in the form of encyclopaedic reports (IPCC 2007, Bourque and Simonet 2008, Lemmen *et al.* 2008) and are conducted at the biome, continental, or provincial spatial scales. They are therefore difficult to integrate into forest planning decisions at the forest management unit scale (Swift 2012) and often require a prior knowledge of climate change and its consequences on forest ecosystems.

The assessment of vulnerability to climate change is an established methodology for providing information in a form that supports policy and decision-making in the context of adaptation to climate change (Williamson *et al.* 2012). Adaptation refers to a variety of responses aimed at reducing adverse impacts or at taking advantage of opportunities created by the novel climatic conditions (Adger *et al.* 2007). Fundamentally, adaptation aims at reducing the vulnerability of a system to the climatic conditions. The vulnerability is the "degree at which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes" (Adger *et al.* 2007). It depends on the nature and magnitude of the climatic change (exposure), the susceptibility of the system to this change (sensibility), the socio-economic characteristic of the system, and the ability of the system to adjust to climate change (adaptive capacity) (Füssel and Klein 2006). Therefore, the adaptive capacity to climate change hinges not only on the scientific and technical knowledge available, but also on the social, economic, and political components associated with the implementation of the different adaptation options (Yohe and Tol 2002).

This paper reports vulnerabilities and adaptations to climate change of three different forest management projects without providing a complete analysis of their respective adaptive capacity. This project aimed at showing the value of this critical information with the goal that it will reach decision-makers involved in forest management and planning. The three EBFM projects examined in light of climate change are: the Tembec project in the Abitibi region, the Triad project in the Mauricie region, and the Laurentian Wildlife Reserve (LWR) project. The objectives of this analysis were to identify:

1. the current and potential vulnerabilities to climate change of forest ecosystems and forest management,
2. the current and potential adaptation options that could contribute to decrease these vulnerabilities identified, and
3. the elements impeding or facilitating the integration of climate change adaptations in forest management.

We first present the three forest management projects that were used as case-studies, and the general approach and functioning of the project. Then, we present the main vulnerabilities and opportunities related to current or future climate change, followed by the proposed adaptation measures. The discussion section deals with the elements facilitating or impeding adaptation to climate change. Finally, we have dedicated a section to lessons learned in light of the implementation and results of the project.

Approach

We have assessed the vulnerability to climate change of three forest management projects based on a literature review on vulnerability of forest management to climate change and discussions with professionals involved in forest management planning. The literature review informed the exchanges with the forest professionals to explore the vulnerabilities particular to each forest management projects examined.

Three case studies

We have chosen three forest EBFM projects to address vulnerability and adaptations to climate change of real forest management cases: the Tembec project in Abitibi, le Triad project, in Mauricie, and the project of the Laurentian Wildlife Reserve (Fig. 1). These choices were based on three main factors.

First, their functioning facilitates the inclusion of new scientific knowledge to better their management strategies. They were developed through a close collaboration between researchers, government managers (*Ministère des Ressources naturelles, Bureau du Forestier en Chef*) and forestry companies (Boulfroy and Lessard 2009).

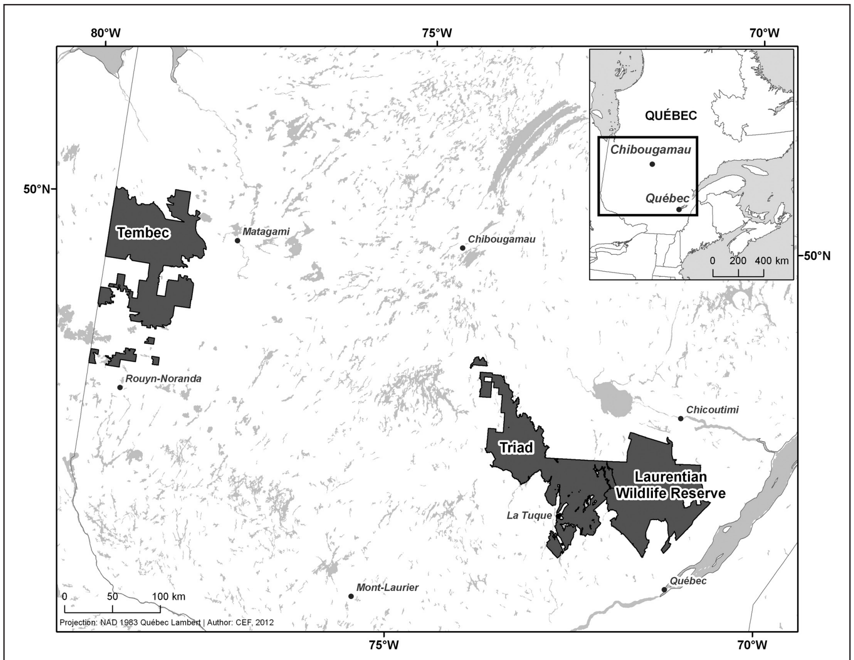

Fig. 1. Locations of the three study regions. Map prepared by Mélanie Desrochers, Centre for Forest Research.

Second, the spatial distribution of the examined areas across Quebec (Fig. 1) allowed us to address a diversity of ecological contexts (features and ecological issues, Table 1), and consequently, to document a wide variety of vulnerabilities and adaptations and opened the discussion to a wide variety of forest professionals. This last aspect has exposed us to a diversity of sensitivity, comprehension and awareness of forest professionals for climate change issues.

Third, the ecological issues currently mobilizing forest professionals are well defined. The forest regions studied have been considerably modified by forest management (Gauthier *et al.* 2009, Boulfroy and Lessard 2009). Several elements, including the proportion of old forests and stand composition and structure, are currently outside their bounds of natural variability (Cyr *et al.* 2009). It is generally accepted that significant modifications to stands can have strong impacts on biodiversity and the various natural processes of forest ecosystems (Hunter 1993, Burton *et al.* 1999, Landres *et al.* 1999, Messier and Kneeshaw 1999, Gauthier *et al.* 2009).

Table 1. Main ecological features and ecological issues of the tree case studies (see location in Fig. 1)

Project	Area (km^2)	Bioclimatic domain	Natural process dominant the forest dynamics	Ecological issues (Boulfroy and Lessard 2009)
Tembec	10826	Black spruce–moss forest	Fire regime Paludification	Spatial distribution of natural and anthropogenic disturbances with open forests Conservation strategy for woodland caribou Deficit old forests in the south Maintain or ameliorate the productivity of paludified stands
Laurentian Wildlife Reserve	7860	Balsam fir–paper birch forest	Insect epidemics	Loss of mature and old forest dominance Depletion of mature and old forest Scarcity of dead wood Loss in the integrity of the wooded buffer zones adjacent to wetland Uniformization of horizontal and vertical stand structures
Triad	8590	Southern maple–yellow birch forest Central balsam fir-yellow birch forest Northern black spruce-moss forest	Fire regime Insect epidemics	Reduction in mature and old forests along with their biological functions Decrease in certain conifer species abundance Decrease in conifer dominant mixed stands Simplification of internal stand structure

Maintenance of biodiversity and ecological processes is crucial in order to ensure the resilience of forest stands (Drever *et al.* 2006, Gauthier *et al.* 2009). This resilience allows ecosystems faced with disturbances to maintain their functions and structure (Brand and Jax 2007). The uniformization of stand structure and composition and the loss of old forests associated with forest management reduces forest resilience (Landres *et al.* 1999, Gauthier *et al.* 2009). This situation may lead to forests more vulnerable to climate change (Leduc *et al.* 2004).

The ecological issues (Table 1) were used to demonstrate how climate change and its consequences on forest ecosystems can impede forestry professionals from attaining certain management objectives. Then the other vulnerabilities to climate change identified in the literature review were discussed to determine their relevance according to the concerned forest professionals. These discussions aimed at identifying the main vulnerabilities to climate change for which adaptation measures should be determined. Here again, we used the literature to inventory the potential adaptation measures that could contribute to reducing the identified vulnerabilities.

Vulnerability assessment

Our vulnerability assessment approach was derived from a draft of the framework presented by Williamson et al. (2012). We have proceeded with the five following steps (Fig. 2):

1. Describe the vegetation, natural dynamics, climate, management approaches, and ecological issues that characterize the region.
2. Identify the elements associated with the forest ecosystems and forestry operations that are currently vulnerable to climate change and for which adaptations have been implemented.
3. Characterizing the future climates of the study area regions with the aid of a variety of regional climate models.
4. Anticipate vulnerabilities associated with climate change projections that concern natural dynamics and forestry operations;
5. Propose actions that could be implemented in order to limit the negative effects of climate change and take advantage of opportunities related to climate change (e.g., increased tree growth).

Future climate

Future climate was simulated using different climate models. These models are numeric representations of the climate system based on the equations that govern the physical processes of the components of the climate (Logan *et al.* 2011). These tools allow modelling a complex set of processes responsible for climate change. Climate trends anticipated around 2050 for the three examined territories were quantified using the 10th, 50th (median) and 90th percentiles calculated using eight simulations of different regional climate models. The range separating 10th and 90th percentiles of projected changes illustrates the uncertainty associated with climate change projections. Larger differences denotes larger disagreement between the different climate simulations. In this case, the values are considered less reliable.

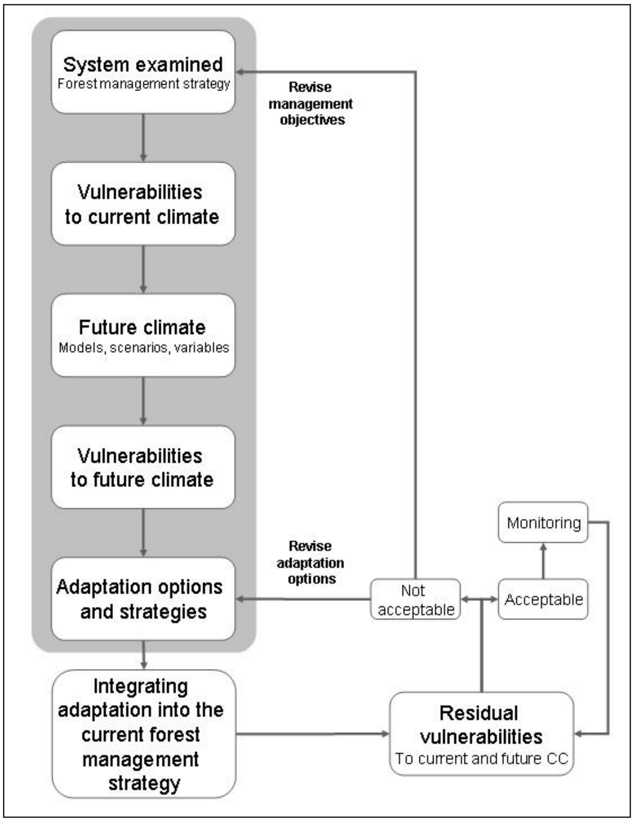

Fig. 2. Climate change vulnerably and adaptation measures assessment framework. The results presented in this paper are related to the steps indicated in the grey box.

Consultation committees

We consulted a committee for each of the projects examined. For the Tembec project, there was a pre-existing committee responsible for implementing the EBFM strategy, while for the Triad and LWR projects, we worked with *ad hoc* committees. The consultations with the committees (Table 2) had three objectives: i) to evaluate the perception of regional partners towards climate change amongst their other concerns; ii) to raise awareness of the consequences of climate change on their professional practice; and iii) to determine the vulnerabilities of climate change in their respective regions. In the context of this paper, only the last aspect is presented.

We used ecological issues to demonstrate the implications of climate change on management objectives that are currently requiring considerable efforts to be achieved. This allowed us to popularize the concept of vulnerability to climate change and initiate the vulnerability assessment for each of the examined management projects.

Table 2. Composition of the committees consulted for the three pilot projects according to their member affiliation. LWR: Laurentian Wildlife Reserve

Pilot project	Industry	Ministère des Ressources naturelles	Universities	Natural Resources Canada	Municipalities
Tembec	7	7	2	–	–
LWR		7	4	1	–
Triad	3	1	3	–	1

Results

Future regional climate

The climate conditions anticipated around 2050 for the three territories examined are presented in Table 3. Overall in Quebec, the annual median temperature would increase by 2.7°C to 2.9°C. The increase would be larger in winter (3.2°C to 3.6°C) and for northern territories (the area of the Tembec project in the context of the current study). Models display more uncertainties for the predicted values of precipitations. They anticipate an increase in the annual median precipitation (97 mm to 100 mm), more important in spring (34 mm to 36.5 mm) and for the area of the Triad project. Equally predicted is an increase in the number of days with freeze–thaw events (5.2 to 5.7 days) and the number of growing degree days (381 to 387 degree days).

Vulnerabilities and opportunities for forest management in the face of climate change

Table 4 lists the vulnerabilities and opportunities identified from a literature review and discussions with the committees. The principal vulnerabilities and opportunities for the three projects are briefly described in the following paragraphs. We first present the biophysical vulnerabilities and opportunities, then we present a few that are linked to socio-economic aspects.

Tree growth

The response of tree growth to climate change is a function of the given species and the latitude at which it is growing. Paper birch (*Betula papyrifera* Marsh.) above 49°N, trembling aspen (*Populus tremuloides* Michx.) between 53°N and 54°N, and black spruce (*Picea mariana* [Mill.] BSP) and jack pine (*Pinus banksiana* Lamb.) above 47°N may benefit from an increase in winter and spring temperatures and respond with increased growth rates (Huang *et al.* 2010). The relationship between temperature and tree growth suggests that an increase in temperatures would favour growth by, amongst other factors, lengthening the growth season (20 to 27 days by 2050 according to the model used; Logan *et al.* 2011). An increase in growth due to more favourable climate conditions can only occur if edaphic conditions (soil nutrients and water content) and the species physiological plasticity allow it. These uncertainties mean that this aspect may represent a vulnerability (if growth decreases) or an opportunity (if growth increases) for forest management.

Migration of climate niches for the principal tree species

In the literature, potential changes in the distribution ranges of species due to climate change are considered either as a vulnerability (if a commercial species is not favoured by anticipated climate change) or an opportunity (if the species is favoured). Berteaux *et al.* (2010) predicted a northward shift of isotherms, ranging from 240 km for the 5°C isotherm to 650 km for the -5°C isotherm, from their current positions by 2071 to 2100 in Quebec. McKenney *et al.* (2007) suggested a displacements of favourable climate conditions more than 700 km, corresponding with an average decrease by 12% for the distribution areas of 130 species in North America. However, the models used to predict these climate envelops shifts considered neither the other environmental requirements of the species (edaphic conditions) nor the ecological processes that might interfere with the climate (such as competition). For these reasons, these results should not be interpreted in terms of a migration of species, but instead in terms of the displacement of climate favourable for their presence. Given the uncertainty associated with the capacity of any given species to occupy a territory that was previously unfavourable (e.g., dispersion, installation, competition), it is preferable to interpret the results of these studies inside the limits of the current range of species (Catherine Périé, Ministère des Ressources naturelles et de la Faune, personal communication, 2012).

Generally, it is predicted that the anticipated changes in climate conditions over the next few decades will favour deciduous species over coniferous species. Climate conditions should remain favourable for the main species present in the Tembec and Triad regions. However, these conditions may become more or less favourable to certain species less abundant in these regions. While future climate conditions may be advantageous for red pine (*Pinus resinosa* Ait.), yellow birch (*Betula alleghaniensis* Britt.), black ash (*Fraxinus nigra* Marsh.), white pine (*Pinus strobus* L.), red maple (*Acer rubrum* L.) and bigtooth aspen (*Populus grandidentata* Michx.), for the Tembec region, it might favour white Ash (*Fraxinus americana* L.), ironwood (*Ostrya virginiana* [Mill.] K. Koch), and American basswood (*Tilia americana* L.), for the Triad region. In the LWR, future climate conditions may be unfavourable for larch (*Larix laricina* [Du Roi] Koch.) and jack pine while be advantageous for eastern hemlock (*Tsuga canadensis* [L.] Carr.), butternut (*Juglans cinerea* L.), American

Table 3. Principal changes in the median of different climate variables anticipated in 2050 in comparison to 1971–2000 (Logan *et al.* 2011) for the regions of the three forest management projects. Values are indicated as following: median (10th percentile; 90th percentile). A large range between the 10th and the 90th percentiles of the values denotes inconsistencies between the different climate models used to calculate the median value (values are thus less reliable). The seasonal values are shown when they differ from annual values.

Climate variables	Laurentian Wildlife Reserve	Triad	Tembec
Mean temperature (°C)	2.7 (2.0; 3.2) Winter : 3.2 (2.5; 4.7)	2.7 (2.0; 3.3) Winter : 3.2 (2.4; 5.0)	2.9 (2.1; 3.3) Winter : 3.6 (2.6; 5.4)
Total precipitation (mm)	99 (44; 184) Spring : 35,3 (-5.8; 58.6) Autumn: 25.8 (1.5; 61.1)	100 (51; 172) Spring : 36.5 (-11; 58)	97 (47; 156) Spring : 34 (-7; 63) Autumn: 30 (11; 50)
Number of days with winter freeze–thaw events	5.7 (2.5; 9.25)	5.5 (2.7; 8.65)	5.2 (2.5; 9.2)
Number of growing degree days	384 (290; 59)	387 (285; 473)	381 (295; 454)

Table 4. Principal climate change vulnerabilities of the three examined management strategies as a function of their origin and source of identification (committee of regional partners, literature review, resource person responsible for assessing the vulnerabilities). The members of the three committees identified vulnerabilities/opportunities observed in their own professional experience, some of which were cited in the literature. The aspect documented by the resource person is linked to the specific context of Quebec's new forest management stewardship. The first part of the table displays biophysical vulnerabilities/opportunities and the second part socio-economic vulnerabilities/opportunities. V: vulnerability; O: opportunity.

	Tembec			Triad			Laurentian Wildlife Reserve		
	Committee	Literature	Resource person	Committee	Literature	Resource person	Committee	Literature	Resource person
Tree growth	V,O	V,O	–	V,O	V,O	–	V,O	V,O	–
Migration of climatic niches	V,O	V,O	–	V,O	V,O	–	V,O	V,O	–
Early budbreak	–	–	–	–	V	–	–	–	–
Fire activity	V,O	V,O	–	V	V	–	–	–	–
Insect outbreaks	–	–	–	–	V	–	V	V	–
Windthrow	–	–	–	–	V	–	–	–	–
Extreme events (precipitation, droughts) and winter freeze-thaws	V	V	–	V	V	–	–	V	V
Paludification	V,O	V,O	–	–	–	–	–	–	–
Increase in watercourse temperatures (Salmonids)	–	–	–	V	V	–	–	–	–
Forest certification	V	–	–	–	–	–	–	–	–
New forest management stewardship	–	–	V,O	–	–	V,O	–	–	V,O
User diversity	–	–	V,O	–	–	V,O	–	–	V,O
Pilot project functioning	–	–	O	–	–	O	–	–	O
Logging history	–	–	V	–	–	V	–	–	V
Regionalization of decision-making	–	–	O	–	–	O	–	–	O

beech (*Fagus grandifolia* Ehrh.), white pine, and red pine (Périé *et al.* 2014). Similar to tree growth, the migration of climatic niches is associated with numerous uncertainties. For this reason, this aspect may represent both a vulnerability and opportunity for forest management depending on the location and tree species considered.

Early budbreak of sugar maple

The production of maple syrup has decreased over the last 20 years due to unfavourable climatic conditions (Duchesne *et al.* 2009). This decrease is expected to continue and reach from 15% to 22% between 2050 and 2090 in comparison to the levels of 1985 to 2006. However, it is possible that the expected loss may be smaller or completely compensated if sugar maple (*Acer saccharum* Marsh.) is able to adapt to an earlier period of production (by two to three weeks between 2050 and 2090, Duchesne *et al.* 2009). Sugar maple seems to have already reacted to the recent climate change since its budbreak is now occurring several days earlier as compared to over the last hundred years (Bernier and Houle 2005). However, this earlier budbreak could lead to an increase in frost damage if the frequency of freeze–thaw events increases in winter. The flow of sap that is used for maple syrup production is also dependent on warm days accompanied by nights where temperatures are below freezing. A rapid transition to warmer periods is therefore a reason for concern.

Fire activity

Changes in fire activity under the influence of climate change have been identified as vulnerabilities within the Tembec and Triad projects. However, it does not represent an area of concern for the LWR management project since fire activity has little influence on the dynamics of its forests. In the context of the Tembec project, an increase in fire activity could be considered as an opportunity to improve the productivity of paludified stands. Indeed, an increase in fire severity could improve the productivity where tree growth is limited by the thickness of the soil organic layer. However, most of the studies anticipating the impact of climate change on fire activity model the annual area burned and not the severity (burnt soil depth) at the stand scale. Climate change may increase fire frequency in several of Quebec's forested regions (Bergeron *et al.* 2006, 2010) by increasing drought, lengthening the fire season (Wotton and Flannigan 1993) and increasing lightning activity (Price and Rind 1994). The anticipated increase in precipitation during the fire season (+4% in summer by 2050, +10% by 2100; Logan *et al.* 2011) may moderate the effects of the rise in temperatures on fire frequency. In the Tembec project region, a lengthening of the fire cycle that corresponds with a decrease in fire frequency has been observed over the last 300 years and is due primarily climatic factors (Carcaillet *et al.* 2001, Lefort *et al.* 2003) but this could be reversed in the future and the fire cycle anticipated for 2100 could approach the shorter fire cycles reported in the past (Bergeron *et al.* 2010, Girardin *et al.* 2012). According to Le Goff *et al.* (2009), fire frequency should increase for several regions of eastern Canada with anticipated climate change, but will not exceed historical values. However, these trends are difficult to predict at the scale of the forest management unit. The effects of increasing drought on fire frequency could be limited by a change to less fire-prone vegetation type (Terrier *et al.* 2012). This effect might be observed only in the medium term (around 2050) due to slow migration of tree species under the influence of climate change.

Insect epidemics

The sectors currently affected by the spruce budworm (*Choristoneura fumiferana* [Clem.]) in Quebec are located at higher latitudes than the sectors affected by previous infestations (Régnière *et al.* 2012). Meanwhile, British Columbia is struggling with mountain pine beetle (*Dendroctonus ponderosae* [Hopk.]) epidemics of unprecedented magnitude. Increased droughts along with warmer summers and winters, possibly associated with climate change, have contributed to the scale of these epidemics (Carroll *et al.* 2004 in Williamson *et al.* 2009, Berg *et al.* 2006, Soja *et al.* 2007). These examples illustrate the fact that climate change can increase the frequency and severity of forest insect epidemics (Logan *et al.* 2003, Lemprière *et al.* 2008, Williamson *et al.* 2009). Insect epidemic dynamics are complex and it is difficult to precisely determine the impacts that climate changes may bring. Indeed, the climate can affect all kinds of interactions at all trophic levels, making any prediction in relation to climate change highly speculative (Dukes *et al.* 2009). Forest professionals that were consulted considered there was too little information on the influence of climate on the population dynamics of forest insect in Quebec to properly document this type of vulnerability at the scale for examined territories (Triad and LWR projects). After these discussions occurred, Régnière *et al.* (2012) published predictions of the distribution of the spruce budworm using climate simulations from the Canadian Regional Climate Model, thus well suited for the territories examined in this project. Their simulations for the 2041 to 2070 period suggest that areas of the Tembec and Triad projects would become less favourable to spruce budworm epidemics while the insect would stay a threat for the LWR territory.

Windthrow

The risk of windthrow is greatest on thin or waterlogged soils and is more common for species with shallow roots or low-density wood (Whitney 1961, Mitchell 1995, Auclair *et al.* 1996, Clinton and Baker 2000, Ruel 2000, Ruel *et al.* 2001). The time of occurrence of windstorms likely plays a role in the tree mortality rate. If wind events occur during the springtime when soils are waterlogged, more severe damage may result (Peltola *et al.* 1999). Our comprehension of the effects of climate change on windthrow frequency is limited. However, the anticipated increase in extreme precipitation events suggests that an increase in wind damage is likely, although the risk may be different from one territory to another depending on the soil type and tree species. In general, this factor is mentioned in the literature, but was not considered as a significant risk by the forest professionals that were consulted in this project. For example, Panferov *et al.* (2009) have anticipated an increase in windthrow for Norway spruce (*Picea abies* [L.] Karst.) and Scots pine (*Pinus sylvestris* L.) in Germany over the 21st century under climate change. Climate models also predict an increase in the frequency of storms and tornados that suggest an increase windthrow (Overpeck *et al.* 1990).

Extreme weather events

Changes in the frequency and quantity of sudden increases in water flow have been observed over the last 10 years in the Triad region, leading to the installation of culverts of large diameter. Forest professionals in the Triad project fear further increases in water flows, particularly if extreme precipitation events occur on successive days during periods of high flow in early spring. Simulations of extreme precipitation events by the Canadian Regional Climate Model suggest that flow frequency may increase by 2100 (Barbara Casati, Ouranos, personal communication, 2011). The shortened winter season and subsequent period when the soil is frozen, the increase in January and February freeze–thaws, the decrease in soil frost depth, and the increase in winter soil moisture may all affect tree harvesting and wood transport (Venäläinen *et al.* 2001). In summer, the trafficability of roads may be limited due to dust clouds raised by the passage of trucks. For example, droughts in the summer of 2010 required more frequent watering of roads to reduce dust clouds (Sylvy Lepage, Ville de La Tuque, personal communication, 2010). While the LWR committee did not mention the vulnerability of forestry operations to climate change, it is certainly a problem existing in the region. This may be explained by the fact that no specialists in forestry operations were involved in the committee.

Paludification

In Quebec, paludification is a phenomenon specific to forests situated in the Clay Belt. Paludification refers to the development of a thick layer of organic matter comprised primarily of mosses that accumulates over the mineral soil (Fenton *et al.* 2005). The development of this organic matter layer affects trees by impeding drainage and reducing soil fertility and tree growth (Simard *et al.* 2007). The lengthening of the fire cycle in the forests of the Clay Belt (Bergeron *et al.* 2006) along with anticipated climate change suggests that the proportion of paludified stands will continue to increase (Weber and Flannigan 1997, Ali *et al.* 2009), potentially at a lower level due to higher decomposition and increasing fire frequency and severity (Lafleur *et al.* 2013). It would thus remain a major concern in the Tembec project area (Drobyshev *et al.* 2010).

Forest certification

The impacts of climate change are not yet reflected in the standards of forest certification (Forest Stewardship Council, Sustainable Forest Initiative and Canadian Standards Association). As currently formulated, forest certification standards may limit the integration of climate change adaptations in forest management planning due to their preoccupation with preindustrial conditions that necessarily prevailed under climatic conditions different than those anticipated in the future. However, if climate change was considered, the objectives of the forest certification standards would be strengthened, as a consideration of climate change in forest management is recognized as being an important condition for ensuring sustainable forest management (Spittlehouse and Stewart 2003).

New forest management stewardship

Although the Sustainable Forest Development Act (Government of Quebec 2010) and the corresponding strategy (MRNF 2010) mention climate change as a subject of importance, the practical implementation and integration of these issues in current forestry management still remains theoretical. The principal limitations to including climate change issues identified by discussions with forest professionals are linked to: i) the implementation of the new forest management stewardship and EBFM principles that is already using a lot of resources; ii) the difficulty for professionals who make decisions regarding forest management to access information concerning climate change (there is a lack of resource personnel to facilitate this integration); and iii) climate change is not a priority.

Regionalization of decision-making powers

The implementation of integrated and regional management could favour adaptation strategies. The vulnerabilities associated with climate change, along with management objectives and socio-economic contexts, may be different from one region to the other. Management at the local level may therefore allow the best identification of adaptation options to be chosen as a function of local conditions and issues. Even if it is not obligatory to consider climate change in planning, the local integrated land and resource management panels (*tables de gestion intégrée des ressources et du territoire*) are priviledged strutures to educate forest management professionals and users and to integrate adaptations to the issues that are discussed.

These vulnerabilities and opportunities associated with climate change were identified in collaboration with the consulted forest professionals. We then conducted a literature review in relation to identify adaptation measures and approaches to decrease these vulnerabilities or to take advantage of the potential opportunities.

Proposed adaptation measures

Few adaptation measures have been integrated into the management of natural resources in recent years due to the uncertainty associated with future climate predictions (Lawler *et al.* 2010). However, several documents offer adaptation strategies as well as adaptation measures. Adaptation strategies include, for example, targeted monitoring, the development of adaptation policies and improving the capacity to control natural disturbances control (Millar *et al.* 2007; USCCSP 2008; Lindner *et al.* 2008, 2010; Eastaugh *et al.* 2009; Swanston and Janowiak 2012). Some authors propose adaptation measures to reduce specific vulnerabilities at tactical and operational levels (Millar *et al.* 2007; Ogden and Innes 2007a, 2008, 2009; Prato 2008; Swanston and Janowiak 2012). Table 5 presents the strategies and adaptation measures that could contribute to reduce vulnerabilities presented in the previous section.

Some of these adaptations are already in use (natural regeneration, promote growth through silviculture), while other adaptation measures should be implemented (e.g., replant using mixed species, Fire-Smart forest management). For the latter, we must first assess their feasibility and compatibility with all management objectives of the territory considered. In the next section, we discuss the factors that facilitate or slow adaptation to climate change.

Discussion

To our knowledge, this study is the first to examine the vulnerabilities to climate change of three forest management strategies simultaneously. This approach allowed us to assess a wide range of vulnerabilities. While a large number of studies exist concerning the impacts of climate change on forest ecosystems and forestry management, very few of them have been disseminated to people involved in forest management planning (Ogden and Innes 2007a,b; 2008; 2009). This project provided a unique opportunity to communicate relevant information concerning climate change to professionals involved in forest management planning in Quebec.

From ecological issues to vulnerabilities to climate change

The ecological issues previously identified for each forest management project are similar to those identified by other authors for Quebec (Varady-Szabo *et al.* 2008, Lecomte *et al.* 2010). Only Lecomte *et al.* (2010) have linked ecological issues specifically to climate change and its impact on forest management in Abitibi-Témiscamingue;

- an increase in the productivity of forests on sites where water and nitrogen are not limiting factors,
- an increase in the decomposition rate of soil organic matter and consequently in the fertility of soils in the majority of forests,
- a reduction in snow cover that could lead to hydric stress for conifers in winter and spring,
- soil nutrient depletion following an increase in freeze–thaw episodes,
- an earlier budbreak that could leave trees more vulnerable to spring frosts,
- a northward migration of climatic niches,
- an increase in the fire frequency,
- an increase in the duration of spruce budworm epidemics along with a reduction in their intensity,
- a lengthening of the growing season along with warmer, drier conditions that could favour the development of forest tent caterpillar moths (*Malacosoma disstria* Hubn.).

As currently defined, the ecological issues of the three EBFM projects are not explicitly related to climate change. For example, the decrease in the proportion of old forests due to forest

Table 5. Examples of climate change adaptation measures that address the identified vulnerabilities. LWR: Laurentian Wildlife Reserve

Vulnerability	Adaptation option	Examples
Increase in fire activity	Include fire risk in forest timber supply estimates Use Smart-Fire landscape management Functional zoning (conservation zones, intensive, and extensive development zones)	The operation/functional zone used in the Triad project can serve to finely map the priorities concerning fire suppression (Le Goff *et al.* 2005)
Changes in tree growth	Promote natural regeneration Replant using a mix of species in order to maximise the chances of success under new climatic conditions Replicate the natural regeneration composition if it is insufficient Monitor growth Implement silvicultural practices that favour growth (thinning, partial cuts) Use thinning and selective cutting to remove trees that are suppressed, damaged, or of poor quality Adapt silvicultural practices and principles to maintain optimum species-site association Evaluate the improvement of genotypes over the long-term in a variety of climatic and environmental conditions	When planting, use seeds or seedlings with the genotype best adapted to the anticipated future climatic conditions (Parker *et al.* 2000, Spittlehouse and Stewart 2003, Millar *et al.* 2007, Williamson *et al.* 2009). This may mean genotypes obtained from sites further south in the case of the Triad project, whose region covers a large latitudinal gradient, or from sites at lower altitudes for the case of the LWR
Paludification	Prepare terrain through drainage, scarification, or prescribed burns Summer logging	In the northern part of the Tembec project region, the presence of *Sphagnum sp.* limits tree growth. If future climate conditions do not naturally control *Sphagnum spp.* through decreased moisture or increased fires then silvicultural efforts should be undertaken to reduce the organic layer and improve productivity
Reduction in trafficability of logging roads and terrain	Change tire pressure according to road and logging terrain trafficability	Increases in spring precipitation may affect the trafficability of logging roads and terrain. Various technical solutions have been devised to reduce the bogging down of machinery and fuel consumption
Migration of species	Assist the migration of species and genotypes Diversify genotypes in order to increase the adaptive capacity of species to climate change Conduct provenance tests over large latitudinal gradients Change laws restricting the use of seeds from outside the planting zone Reconfigure conservation zones and intensive and extensive managements zones to facilitate the latitudinal and altitudinal migration of species	See "Changes in tree growth"
Insect outbreaks	Plant genotypes resistant to epidemics, disease, and drought Monitor population to acquire knowledge	The distribution of several defoliating insects may extend northwards. In particular the distribution range of spruce budworm will also be affected by the change of climate (Régnière *et al.* 2012). The hemlock woolly adelgid (Skinner *et al.* 2003, Evans and Gregoire 2007) may affect hemlock populations on the Triad region.
Extreme precipitation	Increase culvert sizes	Culverts should be replaced with larger diameter culverts in some parts of the Triad region in order to address the increased frequency of extreme springtime precipitation events.
User diversity	Raise awareness Education Knowledge transfer Knowledge exchange	The LWR region is used for forestry, resorts, outdoor recreation, hunting, fishing, etc. Two First Nation communities also occupy part of the region. The interests of these diverse users must converge to avoid antagonistic actions.

Table 5. Examples of climate change adaptation measures that address the identified vulnerabilities. LWR: Laurentian Wildlife Reserve (continued)

Vulnerability	Adaptation option	Examples
Forest certification, Forest management stewardship	Assess the flexibility of legal frameworks and regulations to integrate issues related to climate change Formulate long-term supply contracts Flexible policies and management plans Adaptive management	Climate change impacts are still not being considered in forest certification standards (Forest Stewardship Council, Sustainable Forest Initiative et Canadian Standards Association). The standards, as currently formulated, can limit the integration of climate change adaptations in forest management.
Regionalization of decision-making	Raise awareness in stakeholders in order to ensure that the question of climate change is considered as a major issue and seriously discussed Integrate climate change experts into local integrated land and resource management panel to aid in decision-making related to climate change Develop tools to guide the local integrated land and resource management panel Ensure that forest managers send a clear message to regional stakeholders concerning the need to adapt to climate change and take it into consideration when planning. Adaptation options should also be conveyed	The meetings with the committees showed us that identifying the vulnerabilities and the impacts associated with climate change on forest stands is a complex task, even for experts. Integrating climates change adaptations into management plans is therefore not easy. There is also the risk that stakeholders may not feel concerned by climate change issues which may lead them to believe that it is not an important issue for them. It is therefore important to facilitate the transfer of knowledge from the local integrated land and resource management panel.
Lack of tools for identifying and reducing climate change vulnerabilities	Develop a climate change vulnerability assessment for natural and human systems and develop means to achieve it Estimate the uncertainties associated with climate projections and their potential consequences Improve access to climate change expertise Foster innovation and research to determine when and where to implement adaptation measures Hire professionals with expertise in climate change adaptation	Promote "no regret" adaptation options, i.e., robust adaptation measures that reduce climate change vulnerabilities and improve the system regardless of the predicted scenarios (Ogden and Innes 2007, Lempert and Collins 2007, Johnston *et al.* 2010).

harvesting may be exacerbated by an increase in fire activity related to climate change. On the other hand, the potential increase in burned area may compensate for the lack of recruitment of certain types of dead wood in managed forests. The anticipated migration of climate niches may act in combination with the increased presence of exotic and invasive species to change the composition of forests already modified by forest management. Thus, while the ecological issues are not explicitly related to climate change, climate change does exacerbate or offset some of the effects that management practices have on the composition and distribution of forest stands. For this reason, identifying and taking into account climate change and their consequences would help us to achieve EBFM objectives more easily.

Three elements facilitating the integration of adaptation in forest management

Given the novelty of the concept of climate change adaptation for the forest sector and the context of transition to a new forest management stewardship in Quebec, it is necessary to use the features of current forest management that facilitate the integration of climate change adaptations. Three elements make it possible to integrate adaptation to climate change in EBFM: the objective of maintaining resilience of managed forest ecosystems, a framework for knowledge exchange with forest professionals, and an adaptive management approach.

Resilient forest ecosystems have a better chance to maintain themselves and their ecological services in the context of climate change (Dale *et al.* 2001, Spittlehouse and Stewart 2003). Just as EBFM is based on the best available knowledge of forest ecosystems, climate change adaptation must be based on the best available knowledge of climate change and its influence on forests. Thus, the process for determining adaptations to climate change could greatly benefit from the tools that allowed EBFM to develop, namely the knowledge exchange between forestry professionals and scientists and a management approach facilitating the inclusion of new knowledge (adaptive management). Furthermore, our experiences show that the current forest management framework addresses some climate change vulnerabilities such as the increase in the frequency of spring floods in the Triad project. Thus, there are already several approaches, already in use, that would aid in the implementation of climate change adaptations into forest management.

New measures to develop the capacity to adapt to climate change

The predicted climate changes are unprecedented in the history of forest management in Canada. It is therefore necessary to implement measures that specifically reduce the identified vulnerabilities. Several strategies could contribute to improve the adaptive capacity of forest management projects examined. The first is to implement adaptation options to climate change that allow forest management objectives to be achieved regardless of future climate. For example, by diversifying the species and genotypes planted after harvesting, it is possible to maintain current harvest levels while diminishing the risk of creating forests that are ill-adapted to future climate conditions. In addition, Lawler *et al.* (2010) have proposed implementation of adaptation measures within a limited resource context as a function of the certainty level associated with future biophysical impacts. We could also look to prioritize adaptation measures based on their projected efficacy. In the scope of this project, neither the adaptation measures proposed in the literature nor the approaches used to prioritize their implementation were discussed with regional partners. This should be the next step of the project. Forest professionals should evaluate the compatibility of the adaptation measures proposed with the current management practices and strategies.

The applicability of EBFM in the context of climate change

EBFM is based on our understanding of forest dynamics and ecological definitions of what makes a landscape "natural". Our definition of natural landscapes is based on the natural variability of historical forest conditions documented in scientific studies. Due to the fact that the historical conditions of forests existed under historical climate conditions, the EBFM is considered by some researchers to be inappropriate when considering climate change as future climatic conditions will be different from the historical conditions (see Millar *et al.* 2007). These authors suggested that drawing on past climactic conditions to manage forests could lead to the creation of forest ecosystems that are ill-adapted to deal with future climate.

However, using the historical range of variability is still considered to be the most viable short-term approach due to its low level of uncertainty (Keane *et al.* 2009) and remains one of the best methods to understand and predict the impacts of climate change on forest ecosystems (Landres *et al.* 1999). For the EBFM to be effective in the context of climate change, it must compare existing conditions with both historical reference conditions (retrospective approach) and with conditions linked to future climatic scenarios (prospective approach) (Gärtner *et al.* 2008).

Towards Better Integration of Climate Change Adaptations in Forest Management

We summarize here the principal lessons learned in this project in order to improve the climate change vulnerability assessment process, the identification of adaptation measures, and the integration of these measures into current forest management.

Facilitating the exchange of knowledge on climate change adaptations

Given the complexity and novelty of climate change for professionals involved in forest planning, the first issue is one of communication and extension. The support of regional partners varied and strongly depended on their awareness and understanding of climate change and its consequences on their professional practices. It is necessary to deploy specific resources in order to promote constructive exchanges on climate change and forest planning. For example, while presenting this project to regional partners, we were introduced as resource personnel providing relevant information concerning climate change (pictures of future conditions) that were easy to understand (how to interpret future conditions). In addition, a key element to successful collaboration is valuing the personal and professional experiences of the partners and concerning climate change (Swift 2012). A good starting point to identify the vulnerabilities to climate change is to review the experiences of climate change of forest professionals over the last 10 years (Ogden and Innes 2008). When partners understand the relationships between climate change variability and their professional tasks, vulnerabilities to future climate in simulations of future conditions can be addressed. It is necessary to engage a specialist in climate change adaptations to accompany the committee during their evaluation process (to present future climatic conditions, to conduct specialized literature review, to contacts experts for specific questions, etc.).

Building on regional partners' concerns

Since climate change is not a priority, we have chosen ecological issues and their corresponding management objectives to initiate the vulnerability assessment process and to demonstrate how adaptation to climate change could facilitate the work of forest professionals. The most tangible link is the one between extreme events (droughts or precipitation, exceptional and prolonged thaws) that concern logging operations and require a change in operational planning and tactics. This aspect clearly demonstrates that climate change is not only a new isolated concern, but rather a piece of the puzzle that could facilitate the achievement of management objectives.

Conducting an analysis of ecological, social, and economic issues

Within the scope of this project, social issues (e.g., First Nations ancestral rights, diversification of forest values) and economic issues (e.g., increased supply costs, global competition) were not addressed. However, several of the identified vulnerabilities touch on these aspects and should be objects of further research in order to provide a complete picture of the adaptive capacity of forestry management to climate change in Quebec. For example, the number and interests of forest stakeholders and users implied in a forest management project may greatly facilitate or impede the integration of adaptation to climate change. When land users come from diverse backgrounds, forest management needs and concerns are consequently varied and may at some times be contradictory. Thus, the management objectives for some groups may align contrary to the management options required for climate change adaptation. However, users can attest to the impacts of recent climate change on their land uses and propose concrete adaptation measures.

Evaluating the initial adaptive capacity of the examined management strategy

The forest has always adapted to environmental changes (including climate) (Prescott 2012), but always in response to these changes. Today we have new tools (e.g., predictive models, risk management approaches) that allow us to develop adaptation strategies that occur before the expected impacts. This project documented some already-implemented adaptation strategies. By using spontaneous adaptation measures and practices that are already in place, we can facilitate the integration of adaptations to climate change into forest management and demonstrate that we are not starting from scratch, but instead capitalizing on and adapting already existing practices. The next step is to conduct an analysis that specifically considers climate change alongside regular planning activities.

Acting in the context of uncertainties

According to Manning (2003), the question of uncertainty arises as soon as climate change is mentioned. However, the science of climate change is not facing more uncertainty than any other scientific domain. For example, genetics, the epidemiology of new diseases, and the distribution of food all pose significant challenges to decision-makers who must deal with incomplete knowledge. The uncertainties surrounding key factors should be described whenever possible in order to allow users to make informed decisions concerning the results. A good example to illustrate the difficulty of taking into account risks and uncertainties associated with climate change is the influence of forest fires on forest productivity and timber estimates. Because timber estimates are based on deterministic models, they are ill-adapted to take into account probabilities and risks like those associated with forest fires. Yet, Raulier *et al.* (2013) have demonstrated that the integration of fire risk into forest productivity estimates could allow decision-maker to choose the level of risk they are ready to face in the context of forest management. One approach for working in the context of incertitude advocates the use of an adaptive management framework, i.e., a framework that explicitly includes the iterative inclusion of new information as soon as it develops. This management framework is inseparable from EBFM as our understanding of natural system dynamics is constantly developing. This common point between EBFM and climate change will contribute to the integration of adaptation within the current forest management framework.

Conclusions

EBFM and adaptation to climate change have in common their regional dimension and the necessity of using an adaptive management approach. EBFM aims the development of ecosystem resilience to environmental changes including those of climate. In return, adaptation aims to take into account climate change in decision-making and could improve our capacity to achieve sustainable forest management objectives. This project clearly demonstrates that climate change is not an isolated issue for forest professionals but rather a piece of the puzzle that could facilitate the implementation of ecosystem-based forest management.

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