Expected Effects of Climate Change on Forest Disturbance Regimes in British Columbia

Research Report

Sean R. ***Haughian****, University of New Brunswick; Philip J.* ***Burton*********, Pacific Forestry Centre;*
Steve W. ***Taylor****, Pacific Forestry Centre; Charles L.* ***Curry****, University of Victoria*

** Corresponding Author*

Abstract

In this article we summarize the changes to forest disturbance regimes and forest damage that are projected to emerge under a changing climate in British Columbia (BC). We focus on regionally-specific expectations so that land managers can take pro-active steps to avoid or adapt to future conditions. While some projections are based on extrapolations of recent multi-decadal trends, most are based on global climate models (GCMs) that utilize a range of scenarios for possible atmospheric greenhouse gas emission trajectories over the next century. Regardless of the models or emission scenarios used, it is universally expected that BC will experience warmer air temperatures. Projections for precipitation are more variable, ranging from slight decreases in some regions to substantial increases in others, which have different effects on disturbance projections. Forest fires are expected to be more frequent and more intense in the southern half of the province and in the Taiga Plains, but less important in other portions of the province. Forest insects and fungal pathogens are expected to more fully occupy the current range of their host tree species and expand ranges northward and to higher elevations along with their hosts. More frequent and more detrimental pest outbreaks are expected in some regions when several years of favourable weather align, which is more likely under current and projected climate trends. Wind damage, floods, and landslides can be expected to increase on terrain where they are already a risk factor. For many agents of tree mortality, an expansion or shifting of the seasonal window of activity is expected, but these changes vary among regions within BC. The prediction of future forest disturbance regimes is in its infancy, requiring a much more concerted effort in compiling both empirical and simulated data, but managers may wish to adjust plans accordingly where there is consensus among projections.

KEYWORDS: disturbance ecology; ecoprovinces; forest pathogens; insect outbreaks; tree mortality; wildfire; wind damage

Introduction

Since the early 1990s, researchers have been using projected changes in temperature and precipitation derived from global climate models (GCMs; see Box 1) to explore the potential influence of climate change on disturbance regimes. In general, a warming climate is expected to invoke more active forest fires, insect outbreaks, and

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storm systems (Dale et al. 2001; Volney and Hirsch 2005). Wildfire regimes in boreal ecosystems have been of particular interest due to their dramatic effects on forests and infrastructure (e.g., Trainor et al. 2009), and their potential for positive feedback with global warming (Randerson et al. 2006). The direct and causal relationships between weather, fuel moisture content, ignition probability, and fire behaviour make estimates of climate change impacts on fire danger tractable. Furthermore, historic records of fire occurrence and fire weather allow scientists to develop and test models that translate more directly into economic or social impacts, such as area burned. The widespread perception that significant negative economic and ecological consequences would result from changes in the fire regime has also given such work a relatively high profile (Flannigan et al. 2009). Projected increases in the frequency and intensity of severe weather events as agents of disturbance are of particular interest in regions that are already drought-prone or water-stressed, such as the Okanagan of south-central BC (Cohen and Kulkarni 2001). Despite the potential for severe weather events to directly influence tree growth and survival, few studies have made projections of changes to growth and yield as related to extreme weather, although drought-related tree mortality is now receiving considerable attention (Allen et al. 2010; Birdsey and Pan 2011). Studies projecting changes in the ranges and impacts of forest insect pests are also gaining prevalence (e.g., Dukes et al. 2009; Bentz et al. 2010), but the majority of forest disturbance ecology research, projection efforts, and published literature continue to focus on wildfire.

Box 1: Climate models

The Global Climate Models (GCMs) referred to in the text are the CGCM (Canadian Centre for Climate Modelling and Analysis; Flato et al. 2000), HadCM3 (Hadley Centre, UK; Gordon et al. 2000), and GISS (NASA - Goddard Institute for Space Studies, U.S.A.; Hansen et al. 2002). CRCM is the Canadian Regional Climate Model (Sushama et al. 2010). Results from several versions of each model are available, commonly referenced with the suffix, 1, 2, 3, and so on.

Using GCMs with other available modelling tools to predict future fire regimes has resulted in a number of plausible projections for the circumboreal forest (Fosberg et al. 1996; Stocks et al. 1998; Flannigan et al. 2009), forests of North America (Bergeron et al. 2004; Flannigan et al. 2005a), and other large geographic areas (Soja et al. 2004; Girardin and Mudelsee 2008; Krawchuk et al. 2009); however, projections are less reliable for mountainous terrain and at fine spatial resolutions. Since the majority of BC is mountainous, and most effective management scales are finer than GCM resolution, GCM projections have had limited applicability in BC for much of the last two decades (Bergeron et al. 2004; Flannigan et al. 2005b). To increase the suitability of models for fine-scale projections or mountainous terrain, researchers are beginning to use Regional Climate Model (RCM) projections or combine GCM projections with downscaling tools to incorporate spatial representations of local terrain and vegetation (Sieben et al. 1997; Hamann and Wang 2006; Taylor et al. 2010). These approaches have met with some success, and are steadily improving in consistency and certainty.

Context: large-scale climate variability

As a backdrop to anthropogenic climate change, BC is influenced by coherent, large-scale, natural climate variations that have occurred with some regularity over the last century. The El Niño Southern Oscillation (ENSO) dominates this variability on seasonal to interannual timescales, while the Pacific Decadal Oscillation (PDO) and Pacific North American Pattern (PNA) are dominant on decadal timescales. Each of these "climate modes" is characterized by an index, sustaining positive or negative values over an extended period. For example, the positive phase of ENSO features warmer than usual tropical sea surface temperatures and weak trade winds over a period of 1–3 years, while the reverse is true during the negative phase (La Niña). The PDO has been described as a more persistent (20–30 year) ENSO-like pattern of Pacific climate variability, while the positive phase of the PNA is associated with persistent low pressure in the Gulf of Alaska.

Several studies have examined the effects of these climate modes on western North America. In general, the occurrence of El Niño, and/or positive PDO, and/or positive PNA phases increases the likelihood of a warm and dry winter and spring in BC, while these seasons tend to be anomalously cool and wet in the opposite phases (Redmond and Koch 1991; Stahl et al. 2006; Fleming and Whitfield 2010). In summer and autumn, the correlations are weaker, but certain BC interior locations exhibit an opposite, increased precipitation response to El Niño (Fleming and Whitfield 2010).

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It is important to separate the influence of such cyclical trends from any directional shift in climate. Global Climate Model projections frequently show greater extremes of ENSO and PDO indices in the future (e.g., Lapp et al. 2011), indicating the potential for more severe droughts and fires in some locations, and more precipitation, flooding, and stormy weather at other times and locations. Hence, future forest disturbance regimes in BC need to be considered against this backdrop of ongoing variability, which can ameliorate or exacerbate many of the impacts described below.

Objectives

The primary objective of this paper is to summarize the currently available suite of predictions and projections for future disturbance regimes in BC, specifically over the next 50 to 80 years (i.e., for current forests). Although there have been other literature reviews on this topic in recent years (e.g., Ayres and Lombardero 2000; Flannigan et al. 2005a; Soja et al. 2007), this paper is unique in its regional specificity and inclusion of widely differing types of disturbance. We draw heavily from recent high-resolution projections, while using coarser-scale projections from studies of larger geographic areas when more specific information is unavailable. This information should improve the ability of BC landscape managers to devise regionally-specific but suitably flexible strategies to adapt to a warmer climate, while maintaining the essential values of ecosystem productivity, integrity, and biodiversity.

Wildfire

Wherever and whenever forests are expected to experience warmer and drier conditions, the incidence and severity of wildfire will potentially increase; however, the effect of warmer and wetter conditions is less straightforward. This uncertainty stems from indications that a warmer planet will have a moister atmosphere and spawn a greater density of lightning discharges (Price and Rind 1994), the primary cause of large fires in northern forests (Stocks et al. 1998). Much research in Canada has examined the effects of climate change on fuel moisture content, ignition potential, and fire behaviour through the physical and empirical models included in the Canadian Forest Fire Danger Rating System (Stocks et al. 1989). Such projections are typically compared to a base period spanning the 1960s through the 1990s, for which wildfire records are relatively complete (and thus include a fire suppression effect in much of BC) and assume "business as usual" fire management. Unless stated otherwise, projections summarized here use the SRES A2 scenario (see Box 2), which predicts a doubling of pre-industrial atmospheric CO_2 by the 2050s and a tripling by the 2080s. Projection results vary, however, depending on climate models, alternative emissions scenarios, time periods, and the methods used to downscale climate projections to local and daily scales, so this information is specified as needed.

Box 2: Emissions scenarios

Future "storylines" describing global technological and population growth, and projecting associated greenhouse gas (GHG) concentrations. In the A2 scenario, population increases steadily with no substantial mitigation of GHG emissions ("business as usual"). In B2, population grows more slowly, accompanied by the gradual adoption of low- or zero-emitting efficient industrial technologies, resulting in slower growth of GHG concentrations (Nakicenovic et al. 2000).

In northeastern BC, warmer temperatures are expected to result in more frequent and more severe fires by the 2050s and even more so by the 2080s, whereas northwestern BC will likely receive increases in precipitation sufficient to offset the incendiary effects of increased temperatures. Using the first-generation Canadian GCM (CGCM1) and GISS GCM (see Box 1) model outputs, Kadonaga (1997) projected that the Fire Weather Index (FWI; see Box 3) will increase by a mean of 2.8 in the Boreal Plains, 2.6 in the Sub-Boreal Interior, and 3.0 in the Taiga Plains, but only by a mean of 1.0 in Northern Boreal Mountains, for an average increase of 15-60% for northern BC (Kadonaga 1997). Flannigan et al. (2001) projected smaller changes in FWI for the 2050s, with increases of 0-25% across much of western Canada, based on climate projections from the CGCM2 and the Canadian Regional Climate Model (CRCM).

Box 3: Fire Weather Index (FWI)

A numerical rating of potential fire intensity that is derived from sub-indices describing fuel dryness on the basis of cumulative daily weather conditions (including temperature, humidity, and precipitation events), and the potential for fire spread based on temperature and wind (Stocks et al. 1989). The FWI System consists of six components: the Fine Fuel Moisture Code (FFMC), representing surface litter moisture; the Duff Moisture Code (DMC) and Drought Code (DC), representing the moisture content of shallow and deep forest floor organic layers, respectively; and three fire-behaviour indices — the Initial Spread Index (ISI), Buildup Index (BUI), and Fire Weather Index (FWI) — representing the potential for fire spread, the amount of available (dry) fuel, and the resulting estimates for fire intensity, respectively. Long-term average FWI values observed in BC generally vary from 0 to 33, with values of >20 considered high-risk. For more information see http://cwfis.cfs.nrcan.gc.ca

Kotchubajda et al. (2006) examined potential changes to fire regimes with a focus on the Mackenzie Basin, but included projections for most of western Canada. They showed similar results to Kadonaga (1997) and Flannigan et al. (2001), in that the seasonal severity rating (SSR; see Box 4) was predicted to increase by 19-44% across western Canada in the next century, but the latter's projections translated to much higher averages (by approximately 50-150%) and a wider range (<-10% to >200%) of changes for BC. These results also have highlighted the differences between CGCM1-based projections (mean increase of 19% in western Canada, mainly in the far north and along the coast), and Hadley GCM-based projections (mean increase of 44%, mainly in BC and Alberta), but reinforce the expected trajectory of those changes (Kotchubajda et al. 2006).

Box 4: Seasonal Severity Rating (SSR)

Because the FWI is a non-linear index, it is transformed into a Daily Severity Index (DSR) for purposes of monthly (MSR) and seasonal (SSR) averaging. The daily severity ratings are calculated as $0.0272 * FWI^{1.77}$ (Van Wagner and Pickett 1985; Harvey et al. 1986), averaged over individual calendar months for MSR, and from June through August for SSR.

Taylor et al. (2010) examined the implications of climate anomalies projected by the CRCM v4.2 model (Sushama et al. 2010) under the A2 scenario on components of the Canadian FWI System for a number of stations across BC using a stochastic weather simulator. This work also included a model of the relationship between lightning strike frequency and weather, and a downscaling model that incorporated elevation data – both strong advantages for resolution and accuracy over previous projections. This analysis

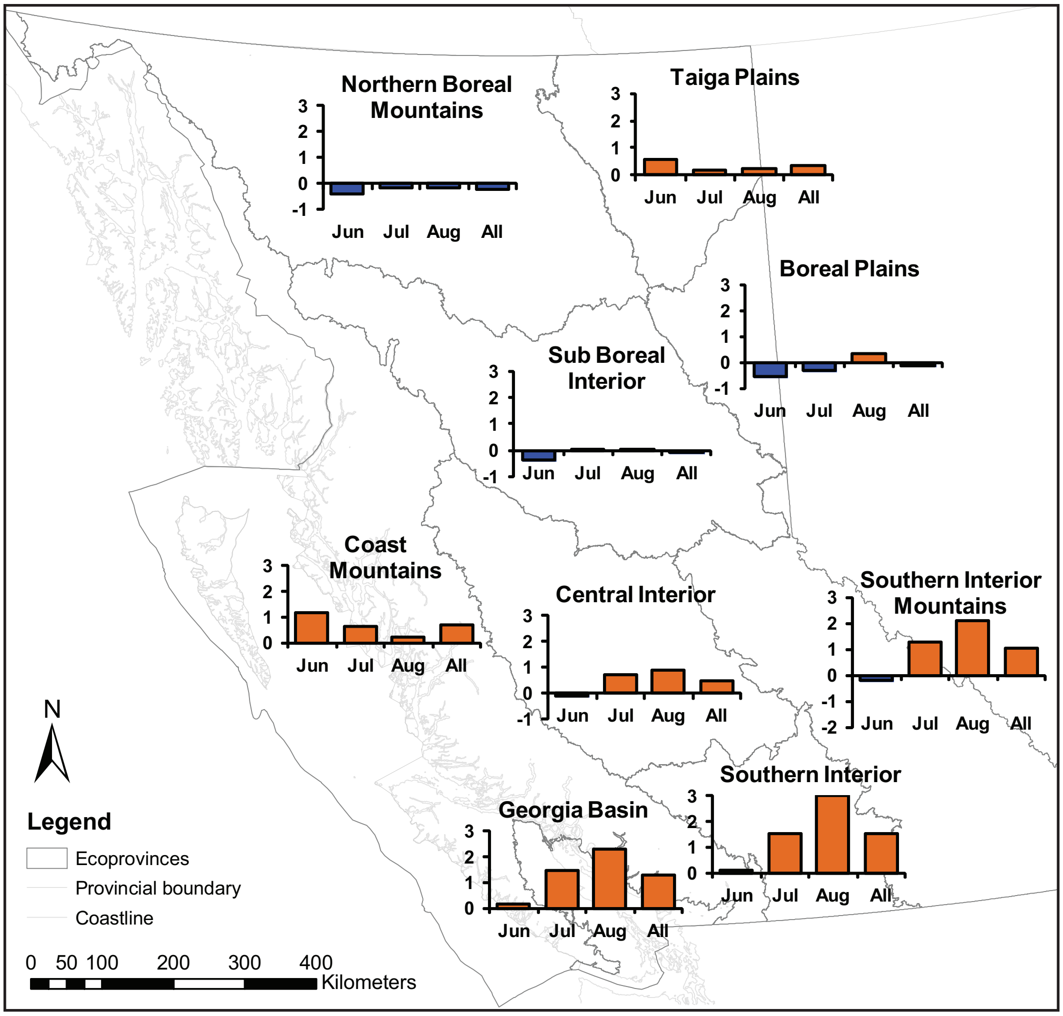

FIGURE 1. Projected changes (approximating the 2080s under the A2 scenario) for British Columbia from current monthly (MSR for June, July, August) and seasonal mean severity ratings (SSR, "all") by ecoprovince. Change is expressed as absolute change in MSR; baseline MSR values range from 0 to 12, with higher values in the south and lower values in northern and coastal areas. Data are summarized and extended from Taylor et al. (2010).

incorporates increases in mean monthly summer temperatures of 3–4°C, and from slight decreases to 50% increases in summer precipitation across BC (Rodenhius et al. 2009). Contrary to several previously cited reports, Taylor et al. (2010) suggest that much of northern BC would experience little change in FWI and fire severity over the next century (Figure 1). Nevertheless, their results concur with previous reports that SSR is expected to consistently increase throughout the southern half of BC, albeit with a smaller magnitude of change (by 10–20%, Figure 1; Taylor et al. 2010). In coastal regions, projected increases in MSR were high in both absolute (0.7–1.3) and relative (30–60% higher than historical) terms. In some cases, expected increases in precipitation appear to counteract the effect of increasing temperatures by increasing the moisture content of slow-drying forest floors. Thus, some fire weather elements influenced by forest floor moisture content (DMC, DC, BUI, FWI, DSR; see Box 3 and 4) were projected to decrease in northern BC, particularly in June; however, indices reflecting the moisture content of rapidly drying surface fuels (FFMC, ISI), which are important to ignition and fire spread, may increase under a warmer wetter regime.

The southern interior of BC is expected to experience the most significant increases in fire indices (Figure 1). Using an ensemble projection (mean of 3 GCM and scenario combinations), Nitschke and Innes (2008a) found that warming by 4°C (expected by the 2080s) would increase fire size (from a mean of 7,961 ha to 19,076 ha), increase fire severity (by 40% in spring, 95% in summer, and 30% in fall), increase fire season length (and consequently fire frequency, by 30%), increase the risk of crown-fire ignition and severe fire behaviour (by 4% to 7%), and decrease the extent of fire-free areas (-39%). Due to the regional specificity of their study and the incorporation of vegetation dynamics, fire behaviour, ensemble modelling, and multiple disturbance types, this work currently constitutes the most comprehensive projection of fire regimes for the southern interior of BC (Nitschke and Innes 2008a; 2008b).

For the rest of BC, broad-scale projections suggest that fire season length will continue to increase as the climate warms, particularly in the spring, with increases ranging from 30 to 52 days (Wotton and Flannigan 1993; Kochtubajda et al. 2006). Indeed, the fire season is already starting earlier in much of the western United States, with trends less pronounced for BC (Westerling et al. 2006).

The annual area burned (AAB) is another important indicator of wildfire regime, and changes in AAB may not necessarily correspond to changes in fire indices, such as FWI or SSR. For example, in the Yukon, SSR is projected to remain similar over the next 50 years, while AAB increases by 20% because of increased fire season length (McCoy and Burn 2005). In contrast, Meyn et al. (2010) found correlations between seasonal drought measures and AAB in BC ranging from r = 0.20 in the Bunch Grass biogeoclimatic zone to r = 0.73 in the Interior Cedar Hemlock zone. These findings suggest that while drier fuels may lead to an increase in the area burned, the correspondence between AAB and other fire or drought indices will vary with forest type.

Using the Hadley GCM3 projections, Flannigan et al. (2005b) examined how AAB would change (for the time period 2080–2099) by ecozone across the Canadian boreal forest. They suggested that AAB would increase by 50% to 300% from the historic baseline conditions over the next 100 years; the largest increases (200%–300%) are projected for the Boreal Cordillera and Boreal Plains ecozones, followed by the Montane Cordillera (100%–200%), and the Taiga Plains (50%–100%; Flannigan et al. 2005b). When these projections were repeated with the CGCM1, strong agreement was observed with the Hadley GCM results in the Boreal Cordillera and Taiga Plains ecozones, but much smaller changes (0 to 25%

increase) in AAB were inferred for the Boreal Plains, while projections for the Montane Cordillera were inconclusive because of high topographic variability. Similarly modest increases in AAB were predicted by Tymstra et al. (2007) in the Boreal Plains eco-region, using the CRCM in conjunction with fire behaviour simulations.

It is noteworthy that Flannigan et al. (2005b) saw fit to include a precipitation correction of -2.0 to -1.5 mm/day in the climate projections from both models at four weather stations in eastern Canada, due to the overestimation of current precipitation levels by these models. To our knowledge, only Kochtubajda et al. (2006) and Krawchuk et al. (2009) have applied such corrections to projections for western Canada, but comparisons between the observed and predicted precipitation levels under current CO_2 conditions are uncommon. Until the uncertainty associated with precipitation projections (Rodenhuis et al. 2009) has been satisfactorily addressed by models, precipitation correction factors should be considered when modelling future fire regimes.

For the boreal forest of western Canada and Alaska, Balshi et al. (2009) projected that AAB would double by the 2050s, and reach over five times the historical AAB by the 2080s (based on the A2 scenario in the CGCM2). In addition, they projected a decrease in the fire return interval of 40% under the same scenario by the 2080s (Balshi et al. 2009). Even under the alternative SRES B2 scenario (see Box 2) of less greenhouse gas production, fire return intervals are projected to decrease by 35% and AAB is projected to increase by 250% (Balshi et al. 2009). This supports earlier work incorporating much of the circumboreal forest (Fosberg et al. 1996; Stocks et al. 1998).

The increased number of natural, that is, lightning-caused (Price and Rind 1994), and anthropogenic (Wotton et al. 2003) fire ignitions, coupled with projected increases in overall area burned, could lead to increases in the number of escaped fires and the cost of fire suppression programs. For example, Wotton et al. (2005) projected that escaped fires would increase in frequency by as much as 80% by the 2090s in Ontario, and suppression costs would rise by 54% (excluding inflation). More work is needed, however, to examine the impact of potential changes in numbers of fires and fire behaviour on the dynamics of the fire management system, as there is some evidence that small changes in initial attack effectiveness can have substantial impacts on annual area burned (Arienti et al. 2006).

In addition to developing options for the strategic and flexible deployment of fire response personnel and equipment, many land management agencies and stakeholders are already undertaking pro-active fuel reduction activities (especially around forest communities and infrastructure) in anticipation of the growing risks of uncontrolled forest fires (Graham et al. 2004; Stephens and Ruth 2005). These activities are often bundled under the terms "FireSmart" forest management, interface management, or community protection (e.g., Hirsch et al. 2001; see http://www.srd.alberta.ca/Wildfire/FireSmart/ and http://bcwildfire.ca/Prevention/firesmart.htm). Further research and planning are needed to examine the effectiveness of these treatments, the roles of changing fire season length and ignition sources, and how suppression and mitigation costs can be expected to change over time.

Forest insects

Research projecting future insect disturbance regimes in BC is less common than projections of fires, and is typically more qualitative. The potential impact of insect disturbance on forests and timber production is great; it is estimated that forest insects annually cause 1.3 to 3 times the damage of forest fires to timber volumes across Canada (Volney and Fleming 2000), and can affect ten times as much area (CCFM 2011). At a recent workshop, experts compiled a ranked list of significant forest pests in British Columbia, including both insects and pathogens (Abbott et al. 2008). Those pests thought to be potentially most significant, either in terms of the damage they may do or in terms of the general lack of information available on population dynamics, were ranked as the highest priority for research and modelling. The top ranking insect pests for all of British Columbia are considered to be (Abbott et al. 2008):

- Douglas-fir bark beetle, *Dendroctonus pseudotsugae* Hopkins (Coleoptera: Curculionidae, Scolytinae),
- Western balsam bark beetle, *Dryocoetes confusus* Swaine (Coleoptera: Curculionidae, Scolytinae),
- Western spruce budworm, *Choristoneura occidentalis* Freeman (Lepidoptera: Tortricidae),
- Spruce beetle, *Dendroctonus rufipennis* Kirby (Coleoptera: Curculionidae, Scolytinae),
- Mountain pine beetle, *Dendroctonus ponderosae* Hopkins (Coleoptera: Curculionidae, Scolytinae),
- Loopers – including western hemlock looper, *Lambdina fiscellaria lugubrosa* Hulst (Lepidoptera: Geometridae),
- Two-year cycle budworm, *Choristoneura biennis* Freeman (Lepidoptera: Tortricidae),
- White pine terminal weevil, *Pissodes strobi* Peck (Coleoptera: Curculionidae),
- Western blackheaded budworm, *Acleris gloverana* Walsingham (Lepidoptera: Tortricidae),
- Gypsy moth, *Lymantria dispar* Linnaeus (Lepidoptera: Lymantriidae),
- Douglas-fir tussock moth, *Orgyia pseudotsugata* McDunnough (Lepidoptera: Lymantriidae), and
- Warren's root-collar weevil, *Hylobius warreni* Wood (Coleoptera: Curculionidae).

Eleven of these twelve forest pests are native to BC, and have probably been part of BC forest disturbance regimes since forests recolonized the landscape after the last ice age. The only exception is the gypsy moth, a Eurasian species that first appeared in BC in 1978 (Nealis 2009).

A warmer, drier climate is widely expected to favour increased growth rates, survival, and fecundity among many insect pest species due to the direct effects of temperature and moisture on development and survival of over-wintering life-stages or early larval instars (Fleming and Volney 1995; Logan et al. 2003; Hlásny and Turcani 2009; Bentz et al. 2010). However, such predictions have not always taken into account limitations imposed by other physiologically relevant thresholds such as minimum temperatures required for dispersal (Safranyik 1978), potential negative interactions with nutritional quality (e.g., an increased ratio of C to N in plant tissues) or stress of the host plants (Fleming and Volney 1995; Hogg 2001; Bentz et al. 2010), maladaptive seasonality resulting in over-winter mortality (Bentz et al. 2010), or insect predator and parasitoid population responses (Fleming and Volney 1995; Fleming and Candau 1998; Bentz et al. 2010). Some forest insect pests may display complex and compensatory responses to climate change; for example, western hemlock looper outbreaks are positively related to drought conditions in southern coastal forests of BC, and may therefore increase in frequency or severity in response to a warming climate (McCloskey et al. 2009). Yet, the outbreak duration will likely remain unchanged, as population collapses appear to result from increased egg parasitism or disease outbreaks after two to four years, even under conditions favourable for the looper (McCloskey et al. 2009).

Despite the relatively low explanatory power of climatic variables, Gray (2008) was able to extrapolate some effects of global warming on eastern spruce budworm (*Choristoneura fumiferana* Clem.), as projected by CGCM3 in the B1 (low-emissions) scenario: by the 2080s, outbreak duration could increase by a mean of 6 years and outbreak severity (the level of defoliation) by a mean of 15%. At the same time, however, outbreak consistency (variance in outbreak severity across the study area) is expected to decrease by 60%, meaning that forest damage will be less predictable (Gray 2008). Although the eastern spruce budworm is only prevalent in the Taiga Plains and Boreal Plains ecoprovinces of northeastern BC, several other budworm species are found throughout much of the province and may exhibit similar responses to climate change (Volney and Fleming 2007). Outbreaks of the related western spruce budworm, which primarily affect Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), are positively associated with warm air and sea temperatures (Thomson and Benton 2007), which will become more frequent as the climate warms. It has been suggested that western spruce budworm outbreaks in the Southern Interior appear to be followed by a reduced incidence of forest fire (Lynch and Moorcroft 2008), in contrast to landscape-level trends in area burned after spruce budworm outbreaks in Ontario (Fleming et al. 2002).

White pine terminal weevil infests young spruce (*Picea* spp.) trees in BC, often causing irregular apical growth such as forking, but will not develop at temperatures less than 7.2ºC. Sieben et al. (1997) exploited this temperature sensitivity to predict future white pine weevil hazard in the Mackenzie River basin, including portions of northeastern British Columbia, using the GISS climate model with an elevation correction. They found that within the next 50 years, white pine terminal weevil would likely expand its range to include “all areas that presently contain white spruce” (Sieben et al. 1997, p.173).

The forest tent caterpillar (*Malacosoma disstria* Hübner; Lepidoptera: Lasiocampidae) is the main defoliator of trembling aspen (*Populus tremuloides* Michx.) throughout much of the southern boreal forest and aspen parkland of western Canada. This species, in conjunction with recurrent growing season drought, has been responsible for large dieback events in the Prairie Provinces in recent years (Hogg et al. 2002). Hogg (2001) projected that most of the current aspen parkland and even some of the southern boreal forest may consequently be converted into grassland by the middle of the 21st century. Aspen-dominated forests in BC may be similarly susceptible to increased defoliator activity as temperatures increase over the next century, despite an apparently greater sensitivity to the amount of suitable host (i.e., trembling aspen) found within each biogeoclimatic unit than to any specific climatic attribute of those units (Otvos et al. 2010). This is because the Sub-Boreal Spruce and Boreal White and Black Spruce biogeoclimatic zones throughout central and northeastern BC, which have the highest proportion and greatest total coverage of aspen, as well as the highest historical losses to forest tent caterpillar (Otvos et al. 2010), are also projected to have some of the greatest increases in temperature. As a result, northern boreal regions currently dominated by black spruce (*Picea mariana* (Mill.) B.S.P.) and underlain by permafrost, may become more suitable to hardwoods as the permafrost melts (Chapin et al. 2010) and may experience coinciding shifts in disturbance regimes from fire or conifer pests to hardwood-associated pests, such as the forest tent caterpillar. Consideration of such “second order” impacts (i.e., those that may arise after a change in the distribution of host species) is beyond the scope of this paper, but is required to fully envision the forests of the following century.

One of the most dramatic manifestations of climate change in BC is the recent outbreak of mountain pine beetle that began in the late 1990s. Fire history, fire suppression, and preferential timber harvesting practices are thought to be responsible for the lodgepole pine (*Pinus contorta* var. *latifolia* Engelm) age-class structure that contributed to the severity of the outbreak (Taylor and Carroll 2004, Burton 2010), while the unprecedented spatial extent and synchrony of this outbreak are related to an increase in the amount of climatically suitable habitat (Berg et al. 2006; Carroll et al. 2006). Because the climatic changes that contributed to this outbreak are expected to become more pronounced over the next 50–100 years, most of BC is projected to become climatically favourable to the mountain pine beetle, creating newly suitable beetle habitat in the Boreal Plains, Taiga Plains, and Sub-Boreal Interior ecoprovinces, as well as throughout much of the Southern Interior and Coast Forest Regions (Carroll et al. 2006; Bentz et al.

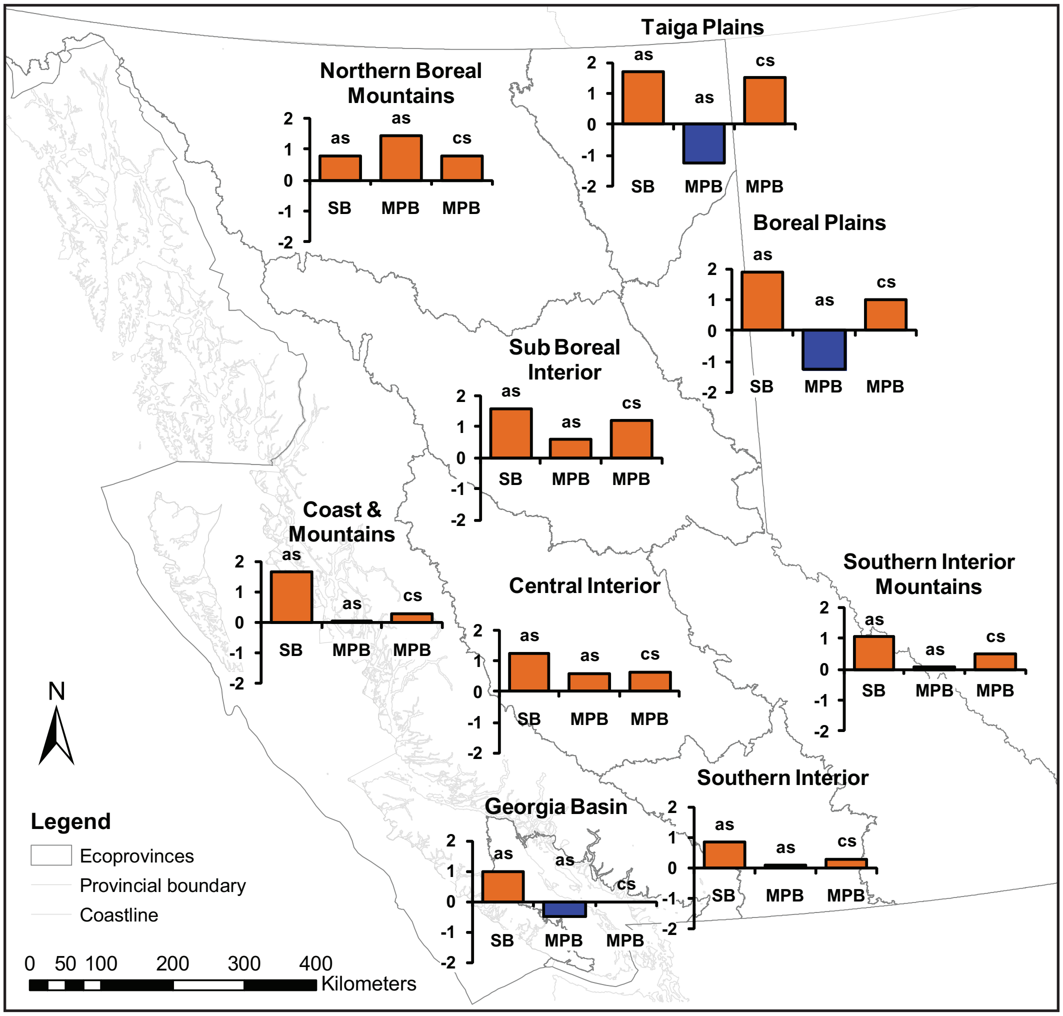

FIGURE 2. Projected changes in bark beetle outbreaks in British Columbia by ecoprovince. The y-axes are indices of projected changes in the probability of beetle adaptive seasonality (as) or cold survival (cs), with a maximum theoretical value of five corresponding to a change from a probability of zero to a probability of one. Values were converted to the numerical scale (0-5) from the six colour-codes (violet, blue, green, yellow, orange, and red) presented in Figures 1 and 3 of Bentz et al. (2010), such that a change of 1.0 is equal to a full shift from one colour to another (approximately equal to a change of 0.17 in probability). Changes are from historical (1961-1990) to projected future (2071-2100) outbreak probabilities, SB = spruce beetle, MPB = mountain pine beetle.

2010; Safranyik et al. 2010) (see Figure 2). These changes in climatic favourability are due to the combination of stabilized or slightly increased adaptive seasonality (i.e., synchronization of the beetle life cycle with local climate such that a generation is completed in one year) and increased likelihood of overwinter survival (Safranyik et al. 2010); however, these changes may not translate linearly into changes in beetle outbreak severity or frequency. Much of the Northern Boreal Mountains should remain free of mountain pine beetle over the next 20–30 years, because the projected changes will be insufficient to overcome the current climatic barriers until after that time (Safranyik et al. 2010). These projections do not address the potential impact of host tree defences, which will be poorly developed where there is no history of recurrent mountain pine beetle outbreaks (Cudmore et al. 2010), or of changes to age structure and stand continuity across regions. Just as FWI indicates the risk of a fire becoming severe if it is established, rather than the actual area burned, adaptive seasonality and cold survival probabilities should be regarded as estimates of the risk of beetle outbreaks becoming severe if they start.

Other *Dendroctonus* species may similarly show increasing outbreak severity and extent throughout BC as the climate warms (Ayres and Lombardaro 2000; Berg et al. 2006; Abbott et al. 2008; Bentz et al. 2010). In the last decade, spruce beetle has undergone rapid population growth and expansion into previously marginal habitat in the Yukon and Alaska (Berg et al. 2006). The spruce beetle typically takes two years to complete its life cycle across much of its range, but can develop in one year (a process known as univoltinism) when conditions are good, thereby facilitating much more rapid population growth. The probability of spruce beetle univoltinism is projected to increase moderately in southern and northeastern BC by the 2050s. By the 2080s, the probability of univoltinism and outbreak occurrence is projected to be substantially higher than observed today in the Coast and Mountains, Southern Interior, Central Interior, Boreal Plains, and Taiga Plains ecoprovinces (Bentz et al. 2010) (see Figure 2).

The European gypsy moth is more geographically limited than other insect pests in BC, and it has not reached outbreak status due largely to active detection and control programs (Nealis 2009). Control programs have been successful because females do not fly, making local eradication an effective method to control regional populations (Nealis 2009). Nevertheless, given its sensitivity to climatic parameters, and the large amount of broadleaf tree cover available in both urban and rural habitats, gypsy moth populations could become well established throughout lower elevations of the Coast and Southern Interior Forest Regions if control programs do not expand to include habitat expected to become suitable over the next 50 years (Régnière and Nealis 2002; Régnière et al. 2009).

Forest pathogens

Like pest insects, outbreak characteristics of many forest pathogens (bacteria, viruses, fungi, or vascular parasites that infect trees) are sensitive to climatic conditions. In BC, pathogens of significance include several root-rot fungi, foliar diseases, rusts, and dwarf mistletoes, many of which infect pine (*Pinus* spp.), spruce, or Douglas-fir exclusively (Ayres and Lombardero 2000; Abbott et al. 2008). Some root rots, blights, and rusts are expected to expand where climate becomes warmer and wetter, while diseases caused by those same organisms may decline or remain unchanged in severity where conditions become drier (Sturrock et al. 2011). In contrast, those pathogens that are primarily opportunistic and rely on poor host vigour may display greater virulence in areas where host trees become stressed by drought. Forest pathogens in general are expected to show increased frequency or duration of infection as the climate warms (Boland et al. 2004;

Woods et al. 2010; Sturrock et al. 2011). Although models of future pathogen prevalence or infection rates have not been developed or fully exercised for BC, two well established climate-pathogen relationships are illustrative.

The coincidence of *Dothistroma septosporum* (Dorog.) Morelet (pine needle blight) outbreaks in northwestern BC with high-rainfall summers may serve as a future climate analogue. Projected increases in both precipitation and temperature over the next 80 years could allow this moisture- and warmth-loving fungus to expand its ranges to include much of BC's Northern Interior, and expand its host preferences to include mature as well as young lodgepole pine. The key climatic parameter for *Dothistroma* expansion in west-central BC appears to be high humidity under relatively warm conditions, with the frequency of three-day rainfall events when daily mean temperatures are greater than 16 °C being predictive of stimulated spore germination and host infection (Woods et al. 2005). Even-aged lodgepole pine plantations are especially vulnerable to a wide range of foliar diseases and stem rusts that are expected to expand over the coming decades (Woods et al. 2010; Sturrock et al. 2011).

Cronartium ribicola (J.C. Fisch.) is an introduced pathogen that causes white pine blister rust. It infects all five-needle pine species in the province (*Pinus monticola* Dougl. ex D. Don, *P. flexilis* James, and *P. albicaulis* Engelm.), but its most devastating impacts (observed and predicted) are on the whitebark pine (*P. albicaulis*). Whitebark pine is declining throughout BC and is considered a species of special concern by the provincial government (Zeglen 2002; BC Conservation Data Centre 2011). Whitebark pine is limited to the southern half of BC at high elevations, and is a keystone species; it facilitates the colonization of alpine environments by forest vegetation (i.e., by upward treeline advancement), and can be an important food for animals such as Clark's nutcracker (*Nucifraga columbiana* Wilson) and grizzly bears (*Ursus arctos* L.; Tomback and Resler 2007). White pine blister rust spore dispersal requires at least two days of 100% humidity under cool conditions (0–20°C), so its importance may decrease in the Southern Interior of BC if there are fewer humid days in spring and early summer, or expand in northwestern BC as conditions allow (Sturrock et al. 2011). White pine blister rust appears to be more prevalent at the treeline, and kills whitebark pine directly, thereby inhibiting the ability of subalpine forests to expand into higher elevations as the climate warms (Tomback and Resler 2007). Whitebark pine trees weakened by blister rust or summer drought are also more susceptible to mountain pine beetle attack (Campbell and Antos 2000). Intervention programs, such as screening for more resistant genotypes and the use of facilitated migration, will likely play an important role in conserving whitebark pine under future climates.

Abiotic disturbances

In some ways, extreme weather and the crossing of climatic thresholds (e.g., Raffa et al. 2008) are most dramatically manifested through the ways they interact with other disturbances, such as the interaction between drought and fire, or between warm winters and insect outbreaks. Explicitly addressing these interactions is beyond the scope of this review; instead, we address some direct effects expected from changes in the frequency or intensity of wind storms, drought, flooding, and landslides, and suggest that understanding these interactions become a priority for future research.

Wind

Analysis of several GCM projections under likely climate scenarios has suggested no change (Zhang and Wang 1997; Kharin and Zwiers 2000; Lambert and Fyfe 2006), slight decreases

(Bengtsson et al. 2006; Wang et al. 2009), or slight increases (e.g., Abeysirigunawardena et al. 2009) in mean wind speed across most of BC. Historical data indicate that the total number of storm events and the number of intense storm events are negatively correlated (Lambert and Fyfe 2006). There is broad consensus that GCMs underestimate the overall number and intensity of storms (Sinclair and Watterson 1999; Wang et al. 2009) and may overestimate the number of very intense storm events (Lambert and Fyfe 2006). Nonetheless, a number of projections indicate a decrease in the occurrence of light storms and an increase in the frequency of intense storms (Lambert 1995; McDonald 2011), with more intense storms especially noted for Haida Gwaii, the North Coast, and the Alaska Panhandle (Gastineau and Soden 2009; McDonald 2011). Storm tracks are variously projected to remain approximately the same (Lambert 1995) or to shift northward and intensify (Salathé 2006), whereas storm density is projected to decrease west of the Rocky Mountains and increase in the northwest (McDonald 2011).

Curry (2008) analyzed results from the CRCM v4.2 (Sushama et al. 2010) under the SRES A2 scenario to make refined regional projections for BC wind climatology into the 2060s. Of particular interest are the projections for changes in 90th percentile surface

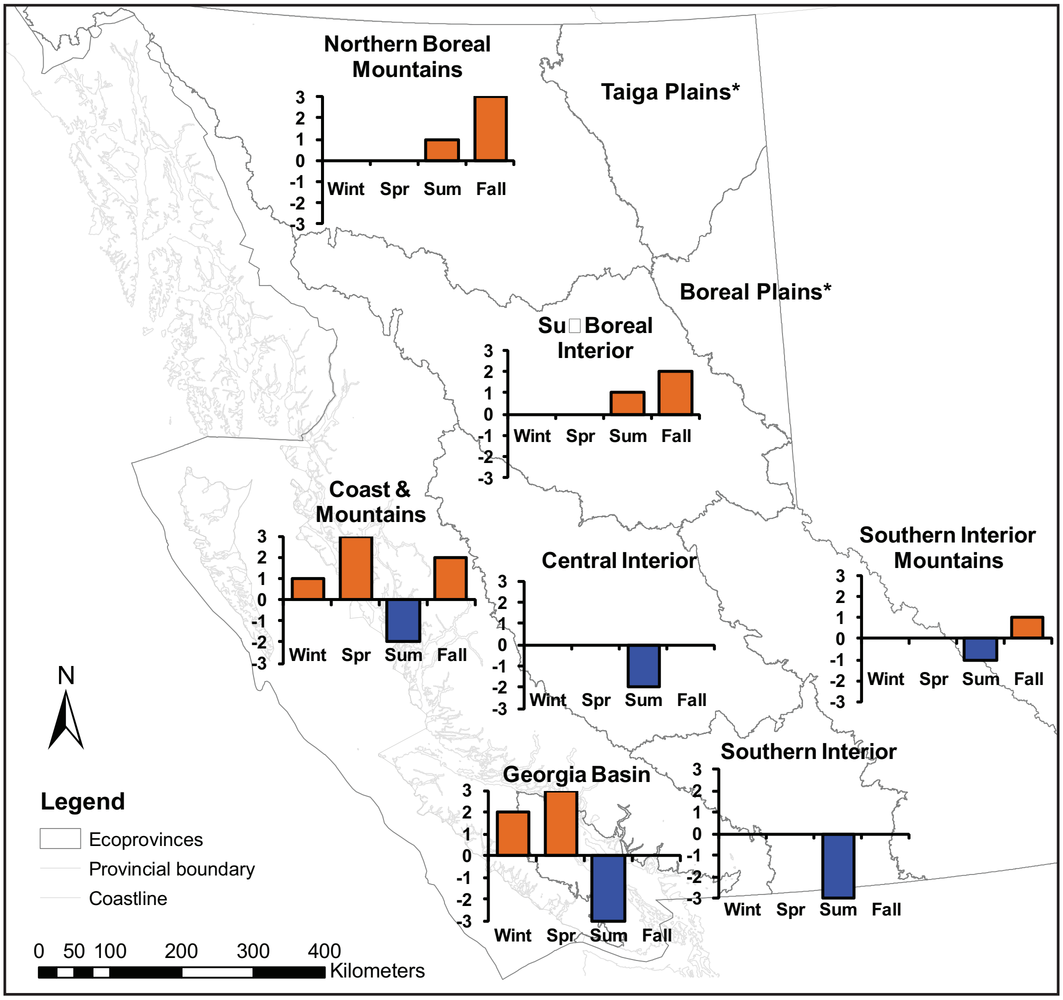

FIGURE 3. Projected changes in high wind speeds (90th percentiles) from the 1981-2000 period to the 2051-2070 period under the A2 scenario, summarized for BC ecoprovinces by season. Change from the current climate is expressed in the following categories: 3 = large increase in mean high-wind speeds (6.1 to 14%); 2 = moderate increase (2.1 to 6%); 1 = slight increase (1 to 2%); 0 = no change (-1 to 1% difference); -1 = slight decrease (-1 to -2%); -2 = moderate decrease (-2.1 to -6%); and -3 = large decrease (6.1 to 14%); asterisks, *, indicate that differences from the historical period were not statistically significant. Data are summarized and extended from Curry (2008).

winds (i.e., the intense winds that could be expected to cause forest damage), for which some general seasonal trends and regional differences are presented in Figure 3. Wind events of this sort are expected to increase in frequency during autumn across northwestern BC, winter on the South Coast, and spring along the entire coast. Small increases in extreme winds are projected for the Sub-Boreal Interior and Southern Interior Mountains in autumn, while the less mountainous terrain of northeastern BC and the Central and Southern Interior is generally projected to experience insignificant changes in wind climate, except for a pronounced decrease in the frequency of extreme summer winds across the southern half of the province (Figure 3).

Although not as well studied, wind behaviour is also tied to prevailing climate modes. The Pacific storm track is affected by ENSO, shifting towards the equator in El Niño years and bringing fewer land-falling storms to coastal BC (Chang et al. 2002). This relationship is further supported by observations that strong El Niño events coincide with weak wind years over the western Canadian interior (St. George and Wolfe 2009), and that extreme high wind events at the Vancouver airport are more frequent during La Niña phases (Abeysirigunawardena et al. 2009). Forest damage from severe windthrow events may increase in frequency as the climate warms, but like precipitation, predicting future changes in wind speed, direction and storm events is highly sensitive to the choice of model and CO2 emissions scenario (Beniston et al. 2007). Although air movement is a core function modelled by GCMs, average wind speed says little about forest damage, which primarily occurs during extreme cyclonic events with wind speeds in excess of 100 km/hr (Peterson 2000).

The relative stability of storm tracks projected under future climates, combined with the importance of topography and soil conditions in determining the extent of wind damage to forests (Mitchell 1998), suggests that areas of BC that are currently prone to wind damage will continue to be vulnerable. Coastal forests are likely to be at the greatest risk from an increased severity or frequency of windthrow events, since wind is currently a primary disturbance agent in these forests (Wong et al. 2003). The Central and Southern Interior of BC may also be at risk of increased windthrow because of a projected increase in the frequency of tornados (Price and Rind 1994; Etkin 1995), and forests in the far north may be more vulnerable due to earlier thawing (and destabilizing) of soils in spring. Several studies have projected from slightly decreased to significantly increased windthrow in northern Europe due to global warming, but the windthrow risks there appear to be more closely related to terrain, stand management practices, and species composition than to any expected changes in climate (Blennow et al. 2010; Peltola et al. 2010).

Flooding and Drought

Stream systems can be classified according to the relative importance of different water sources (i.e., runoff, glacial melt, etc.). This practice has assisted researchers and planners in characterizing current and future flood risks for different watersheds and can be extended to riparian forest ecosystems. Rodenhuis et al. (2009) suggest that, throughout much of southern BC over the next four decades, many glacier- or snow-fed streams will become hybrid streams (i.e., with roughly equal dependence on precipitation runoff and melt-water), while hybrid streams will become more pluvial (fed directly by precipitation runoff). Glacier- and snow-fed stream systems tend to have peak flow from May to August, whereas in the Coast and Mountains and Georgia Basin ecoprovinces, pluvial streams systems have peak flow (and greater short-term variability) in the winter (Déry et al. 2009). Increasing temperatures may lead to earlier spring and summer peak flows and increase winter flood risk for much of BC (Leung and Qian 2003; Whitfield et al. 2003; Pietroniro et al. 2006; Rodenhuis et al. 2009); however, there is substantial variation in the current long-term trend of streamflow among watersheds. For example, the annual flow of the Fraser River Basin has steadily declined over the last 30 years, while flow in the Columbia River Basin has increased (Rodenhuis et al. 2009). Changes in flood frequency are projected to show similar variability. For example, flood frequency in the Upper Campbell River watershed is expected to increase by over 40%, while it is projected to decrease in the Illecillewaet River by about the same amount by the 2080s (Loukas et al. 2002; 2004). A number of detailed basin-specific projections are available at http://pacificclimate.org/news/2011/final-reports-published-pcic-hydrologic-projects.

Along with changes to the streamflow regimes, several models predict changes in the seasonal distribution of precipitation, which similarly varies among regions of the province. Northwestern and coastal areas are expected to experience substantial increases in precipitation throughout the year, while southern and central areas will receive more in winter and less in summer (Pike et al. 2008a; Rodenhuis et al. 2009). In northeastern BC, the increase in temperature will likely maintain the current equilibrium between evapotranspiration and precipitation, such that little change in overall moisture levels will occur (Toth et al. 2006). Many areas will experience accelerated snow melt and higher stream levels in winter (Pike et al. 2010). Conversely, much of southern BC can be expected to experience increasing frequency or duration of summer drought events, where drought stress is already greater than for other areas in the province (Cohen and Kulkarni 2001; Pike et al. 2008b; Rodenhuis et al. 2009). Increasing aridity may decrease the dominance of spruce, fir (*Abies* spp.), western redcedar (*Thuja plicata* Donn ex D. Don.), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and even lodgepole pine (Coops and Waring 2011), and favour more drought-tolerant ponderosa pine (*Pinus ponderosa* C. Lawson), aspen, and Douglas-fir (Hogg and Bernier 2005; Hamann and Wang 2006; Nitschke and Innes 2008a). In extreme cases, this persistent drought will cause parkland and savannah (dominated by aspen, Douglas-fir, or ponderosa pine) to be replaced with scrub or grassland (Hogg and Hurdle 1995; Allen and Brashears 1998; Hogg 2001; Hogg and Bernier 2005).

Mass movements

Not all of BC is expected to become hotter and drier. West-central BC is already experiencing a trend of increasing summer precipitation (Woods et al. 2005), and parts of northern and coastal BC are projected to receive 6%–26% more annual precipitation by the 2080s. This increased precipitation may lead to increased forest productivity, but may also compromise slope stability and increase the frequency of landslides (Wieczorek and Glade 2005; Geertsema et al. 2006; Rondenhuis et al. 2009; Pike et al. 2010). Indeed, a 10% increase in precipitation, as is projected to occur by the 2080s in the Georgia Basin, would result in a 165% increase in the frequency of slope instability events (M. Miles and Associates Ltd. 2001).

The relative importance of different causes of slope failure will vary among regions. In northern areas, a reduction in the area underlain by permafrost would be a primary contributor to slope failure, whereas high alpine areas may have greater incidence of rockslides from a reduction in glacial buttressing (Davies et al. 2001; Geertsema et al. 2006). The increased incidence of droughts and forest fires is expected to reduce the erosion-protecting and water-transpiring cover of hillslopes, resulting in elevated levels of soil movement and associated sediment loss and debris flows in the BC Southern Interior

(Pierce et al. 2004). Conversely, projections for 40%–60% increases in storm-mediated precipitation on the South Coast and 100%–150% increases in the northern Cariboo Mountains (Salathé 2006) suggest increased incidence of mass movements in those regions. Although landslides and debris flows tend to be more limited in spatial extent than other types of disturbance, they often have greater capacity to damage infrastructure, such as roads and pipelines, because most infrastructure is located within and parallel to valley bottoms (Geertsema et al. 2006). As with forest damage from windthrow, the main factors determining the likelihood of mass movement are topography and soils; this suggests that, while some risks are elevated, the bulk of the province's "low risk" or "no risk" terrain will remain so.

Conclusions

British Columbia is a large province, with forest-climate combinations that vary over short distances and drive multi-agent regimes of natural disturbance. It is no surprise that future trends in climate and sequences of weather events favourable to various agents of tree mortality are difficult to project with any confidence. Existing regional differences in topography and forest type will still drive new disturbance regimes as storm behaviour, vegetation, fire incidence and spread, insect populations, and forest pathogens adjust to changing conditions.

Existing regional differences in topography and forest type will still drive new disturbance regimes as storm behaviour, vegetation, fire incidence and spread, insect populations, and forest pathogens adjust to changing conditions.

Our understanding and prediction of even current forest disturbance regimes is elementary and disparate among disturbance types, making projections into the future under a warmer climate extremely difficult. The mechanisms by which various abiotic and biotic disturbances exhibit any consistent behaviour within a region, and how such behaviour is constrained or directed by climate is understood at only a general level. Ideally, an understanding and prediction of disturbance regimes should be based on a comprehension of disturbance processes and mechanisms (Johnson and Miyanishsi 2007). Specialists in many separate disciplines have identified the work required to understand individual agents of disturbance, but that understanding is often restricted to a particular location or climatic regime. Most of the projections reported above assume more or less constant forest types, yet we know that fires depend on fuels, and insects depend on host tree distributions, so the next generation of disturbance regime prediction will require a consideration of how the composition, structure, and productivity of forest vegetation will change directly with the climate as well.

Although the magnitude of regionally specific changes may be difficult to predict, several trends are becoming clear for BC. The northeastern and southern parts of the province will become much hotter and drier over the next century, indicating the potential for an increased frequency and severity of wildfires, droughts, and insect outbreaks. Western parts of the province will become wetter and warmer, suggesting increased incidence of some fungal tree pathogens, with the potential for more flooding and slope failures. Despite uncertainties and the need for further research, land managers and communities across BC would do well to identify those forest types and locations with the highest risk of disruption, and to consider the potential for new (as well as existing) agents of forest mortality. Enhanced projections of changes to the climate, the forest, and disturbance regimes are needed. Much more must be done in order to understand disturbance trends and interactions, which requires that disturbance events must be tracked, that the relevant information must be compiled in long-term and broad-scale data sets, and that the relationship of disturbances to climatic drivers must be thoroughly analyzed.

Where risks are increasing and forests are stressed, managers should avoid plans that are too tightly dependent on historical disturbance patterns and other assumptions. Using more diverse seed sources or species mixes when planting, altering rotation times, and facilitating species migration will likely play important roles in adapting to altered climates over the next century. But perhaps most importantly, a time of change and uncertainty calls for a greater emphasis on risk analysis than on optimizing productivity, with conscious efforts to manage for flexibility and resilience (Campbell et al. 2009; Burton 2010).

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Author information

Sean R. Haughian – Ph.D. Student, University of New Brunswick, Saint John, NB. Email: seanh@unb.ca

Philip J. Burton – Manager of Northern Projects, Pacific Forestry Centre, Canadian Forest Service, 3333 University Way, Prince George, BC V2N 4Z9. Email: pburton@NRCan.gc.ca

Steve W. Taylor – Research Scientist, Pacific Forestry Centre, Canadian Forest Service, 506 W. Burnside Road, Victoria, BC. V8Z 1M5. Email: staylor@NRCan.gc.ca

Charles L. Curry – Research Associate, University of Victoria, Victoria, BC. Email: cc@uvic.ca

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Test Your Knowledge

How well can you recall the main messages in the preceding article? Test your knowledge by answering the following questions.

Expected Effects of Climate Change on Forest Disturbance Regimes in British Columbia

1. What does CGCM stand for?
   a) Carbon Gas Climate Model
   b) Canadian Global Climate Model
   c) Canadian Greenhouse Carbon Model
   d) Clearly Great Canadian Model

2. Which factor is expected to be the largest contributor to projected increases in area burned over the next 80 years?
   a) Increased number of lightning strikes due to stormy weather
   b) Increased fuel buildup on the ground
   c) Increased fire season length
   d) Increased frequency/duration of weather with severe fire hazard

3. The Taiga Plains and Boreal Plains ecoregions are projected to show increased mountain pine beetle cold survival – why might this not translate into increased outbreak size or frequency?
   a) Because effective control programs have been implemented
   b) Because the annual area burned is projected to increase
   c) Because beetle adaptive seasonality is projected to slightly decrease
   d) Because the beetles cannot use jack pine (Pinus banksiana) as a host

4. Parts of BC may experience a slight increase in wind disturbance events, but differ in terms of the mechanisms. What changes may lead to increased windthrow in coastal, northern, and interior parts of the province, respectively?
   a) Increased frequency of high-speed winds, reduced permafrost, and increased frequency of tornados
   b) Increased saturation of soils, increased rainfall, and increased drought
   c) Increased saturation of soils, increased permafrost, and reduced root growth rates
   d) Increased frequency of high-speed winds, increased beaver activity, and increased tornado frequency

ANSWERS: 1=b; 2=c; 3=c; 4=a