Potential effect of climate change on observed fire regimes in the Cordilleran forests of South-Central Interior, British Columbia

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Abstract

Climate change is predicted to result in a warmer and drier climate in many parts of the world, including south-central British Columbia. With a shift in climate, a change in fire regimes is likely to occur. In this study, a statistically significant increase in mean fire size was predicted to occur along with an increase maximum fire size and decrease in the mean fire interval. A change in these fire regime characteristics suggests a climate-change driven shift in fire regimes may occur by the 2020s. The shift in fire regime suggests the proportion of the landscape burning every 50 years or less will increase from 34% to 93% by the 2080s. Change in fire regimes will have direct implications for ecosystem management as the combination of large, flammable fuel types and fire-prone climatic conditions will increase the risk of larger more frequent fires and increase the costs and dangers involved in managing fire-prone forests in the Cordilleran region of south-central British Columbia. The climate change-driven shift in fire regime questions the use of historic fire regime characteristics for determining landscape-level conservation targets within the study area.

Keywords: Fire; Fire regime; Climate Change; Natural Disturbance; Ecosystem management, Ecosystem

Introduction

Local, regional and global changes in temperature and precipitation can influence the occurrence, timing and frequency, duration, extent and intensity of disturbances (Dale et al. 2001). Natural disturbances, particularly fire, interacting with climate change are regarded as major challenges to achieving sustainable forest management (SFM) (Veblen et al. 2003). Fire is one of the primary agents of change in many forest ecosystems in western North America. Fire frequency affects ecosystem structure and composition (Palik et al. 2002), while fire severity influences fire size, which in turn determines landscape patchiness and post-fire ecosystem structure (Flannigan et al. 2003). In addition to being a necessary disturbance agent from an ecological standpoint (Agee 1993), fires have a significant social and economic impact, with governments spending more and more money every fire season to protect forests and homes (Arno and Fiedler 2005). Although the determinants of fire behavior are well understood (Agee 1993), there are significant gaps in the understanding of past and current disturbance regimes (Wong et al. 2003). Fire regimes are characterized by their frequency, extent, cycle, intensity, severity, and seasonality (White and Pickett 1985). Currently, fire regimes are based on their historic or current characteristics (Agee 1993) and do not take into account the potential influence of climate change on fire frequency and severity (Hebda 1998). The growing interaction between climate change and fire regimes is well documented (see Veblen et al. 2003), with climate change predicted to alter fire regimes significantly in the ecosystems of Canada (Wotton et al. 2010). Recent climate change has been linked to an increase in fire season length in the boreal forests of western Canada (Flannigan et al. 2009) while Westerling et al. (2006) found that an increase spring and summer temperatures along with earlier spring snowmelt has caused longer fire seasons and increased fire severity and frequency in the western United States. To address concerns about the impacts of climate change on fire a myriad of studies have been conducted that have focused on the impact of climate change on fire weather (Flannigan and Van Wagner, 1991; Wotton and Flannigan, 1993; Stocks et al., 1998; Flannigan et al., 1998;

Li et al., 2000; Flannigan et al. 2003; Wotton et al., 2003; Flannigan et al. 2009; Krawchuk et al. 2009); area burned (Flannigan et al. 2005; Westerling et al. 2006; Westerling and Bryant 2008; Tymstra et al. 2007; Girardin and Mudelsee, 2008; Krawchuk et al. 2009; Spracklen et al. 2009; Meyn et al. 2010a-b), and on fire frequency (Bergeron et al. 2010; Westerling et al. 2011).

Fire is a driving factor for abrupt ecosystem change (Dale et al. 2001), and identifying how climate change influences fire regimes within ecosystems can inform managers on the need to adapt current management actions to deal with potential changes to fire regimes and fire risk in the future. For adaptation to be successful then an understanding of the spatial and temporal variations of fire regimes is required (Suffling and Perera 2004). To gain this understanding, the complex relationships among fire behavior, climate, topography, vegetation and land use must be considered (Overpeck et al. 1990). The objective of this study is to use spatial modeling to identify the potential impact climate change will have on the behavior and character of observed fire regimes on a heterogeneous landscape in south-central British Columbia (BC) and to discuss the implications this may have for forest management. The majority of climate change-fire impact studies are based on statistical models derived from relationships between area burned and climate variables/ fire weather indices; very few studies have investigated the impact of climate change on fire regimes using spatially explicit fire growth models (see Tymstra et al. 2007). By utilizing spatial fire growth modeling, we aim to provide a more robust assessment of the impacts of climate change on observed fire regimes (Tymstra et al. 2007). The spatial modeling approach allows for the integration of fire spread and behavior with climate, topography, vegetation and existing land use which when combined with observed fire regime characteristics provides the basis for conducting a vulnerability assessment. Such an assessment can provide an understanding of the impact climate change may have on regional fire regimes. The following research question is asked: to what extent will the fire regimes in the Cordilleran forests of south-central

British Columbia shift beyond the characteristics of observed fire regimes due to climate change?

Materials and Methods

Study Area

A 145,000 ha landscape located in the North Okanagan region of British Columbia, Canada (49° 52' 6" to 50° 41' 6" North latitude and 119° 14' 6" to 119° 59' 48" West longitude, see Fig. 1) was used as a case study. The landscape is tenured to and managed by Tolko Industries Ltd under the designation Tree Farm License (TFL) 49. TFL 49 has been classified into two different fire regimes, referred to as Natural Disturbance Types (NDT): NDT 3 and NDT4. NDT 3 classified ecosystems are montane forests subjected to frequent stand-initiating events (mean fire interval of 150 years) while NDT 4 classified ecosystems are interior dry belt forests subjected frequent stand-maintaining events (surface fire interval of 4–50 years) and stand-initiating events (crown fire interval of 150–250 years) (Ministry of Forests and B.C. Environment 1995). The TFL 49 landscape has 65.7% of its ecosystems classified as NDT 3 and 34.3% as NDT 4. Interior dry belt forests dominate the low elevation portions of the landscape while the montane forests dominate at higher elevations. The fire regime characteristics for the ecosystems and natural disturbance types for the landscape are provided in Table S1 in the supplemental material1.

TFL 49 comprised of two distinct landscapes and is considered as two separate management blocks by Tolko (Fig. 1). The same approach has been adopted here, with the two landscapes being considered separately. For the sake of clarity, the designations used by Tolko, Block 1 and Block 2 have been used as the landscape names. The analytical results for each block have also been combined to provide an overall summary of the influence of climate change on fire regime for the entire TFL management area.

<Fig. 1>

Modeling

Landscape-level modeling and geographic information systems were used to analyze the response of the following four fire regime characteristics to climate change:

1. mean fire size;
2. maximum fire event;
3. frequency distribution of fire size; and,
4. mean fire interval.

Assessment of the vulnerability of fire regimes to climate change relies on the ability to compare the observed regimes to future regimes for an entire landscape. In this study the fuel and topography sides of the fire behavior triangle (Agee, 1993) were held constant and only climate was altered. The decision to keep fuel types and topography constant was based on the following assumptions:

- elevation, slope, and aspect will remain constant between today and the 2080s;
- fire suppression will continue to be used as a fire management tool and thus maintain the majority of current fuel loads;
- the fuel-loads within and between ecosystems in the study area are highly connected due to fire suppression and will remain highly connected with continued fire suppression (Thompson et al. 1998);
- the regeneration of forest stands after harvesting legally requires the reestablishment of species that have historically persisted on the harvested site and this will remain the policy over the near future; and,
- in the absence of forest management and disturbance, current ecosystem composition would be resistant to change and remain static due to ecosystem inertia. Inertia is a significant mechanism of ecological resistance (Noss 2001).

A fire growth model was used to model fire spread based on user-defined ignition points on a daily resolution with a spatial resolution of 0.25 ha. Fire ignition points were generated from an analysis of lightning and anthropogenic ignition risk and then modeled using the fire growth model (Nitschke and Innes 2008b). Spatial variability was accounted for by including fuel types that represent forest cover and the topography of the landscape. A daily timescale was used to explain temporal variability, and replicated simulations were used to incorporate stochastic variability. The incorporation of these characteristics accounts for and includes the spatial, temporal and stochastic variability identified as important by Suffling and Perera (2004) for modeling fire regimes.

Fire Growth Modeling

The Canadian Wildland Fire Growth Model (CWFGM) Steering Committee's model, Prometheus (Tymstra et al. 2007; 2010), was used to model fire and climate interactions. Prometheus is a stand-alone, process-based, fire growth model developed with the objective of understanding the behavior, propagation, and effects of wildfires on the landscape (Tymstra et al. 2010). The foundation for this model is the Canadian Forest Fire Behavior Prediction (FBP) System (see Hirsch 1996). The Prometheus model incorporates vegetation (fuel types parameterized from Canadian ecosystem-fire behavior studies), topography (slope, aspect and elevation) and weather variables (temperature, precipitation, relative humidity, and wind velocity and direction). For a detailed description of the Prometheus fire growth model see Tymstra et al. (2010).

With Prometheus, the data inputs are developed by the user. The Environmental Systems Research Institute's (ESRI) ArcGIS 9.0 system (ESRI, 2004) was used as the geographic information system to create the fuel and topographic inputs for the Prometheus model from the TFL 49 forest inventory database. Fire ignition points were also defined by geographic location, date, time and duration for each modeled fire. For a detailed description of the methods used to parameterize the fuel, fire ignition and topographic

parameters for the Prometheus model see the methods section in the online supplemental material. Climate inputs used were minimum temperature, maximum temperature, relative humidity, wind speed, wind direction and precipitation. Climate data from two local weather stations (see Fig. 1) were used as the base climate to develop historic and future climate scenarios which incorporate daily climate variation (following Nitschke and Innes, 2008a). For a detailed description of how climate and climate change inputs were developed see the methods section in online supplemental material.

Fire Scenarios and Rules

Each fire simulation was allowed to spread on a daily time step for duration of 14 days. The duration of 14 days was selected to provide a balance between anthropogenic uninhibited fire spread and the reality that fire suppression will occur. The choice of the 14 day fire duration is supported by the average duration of fire spread for 13 fires in the study region that had escaped initial suppression between 2003 and 2006. The average duration of fire spread for these fires was 15.3 days (SD: +/- 6.6 days). In other studies, McKenzie et al. (2006) utilized a fire duration period of eight days to model fire growth and although they underestimated maximum fire size they closely approximated to annual area burned for the observed season they were validating against. Anderson (2002) used a duration period of seven days to model fire growth in the boreal forest of Canada and found this period to reasonably approximate observed fire sizes. The application of a static fire duration period resulted in some fires running out of fuel before the stopping rule was reached and other fires stagnating before the stopping rule was reached due to changes in climatic and/or fuel conditions and/or due to fuel and topographic barriers. The fire duration stopping rule is assumed to stop fire spread but not necessarily extinguish the fire. Fires can burn for many more days, weeks, or months once contained. This form of fire behavior makes some fires prone to eruption when climate conditions are favorable; this is limited to the 14 day fire duration used in this study. McKenzie et al. (2006) identified that these events are hard to predict and also excluded this

mechanism. The use of stopping rules is a serious assumption that has an impact on the results; however, this study is investigating the vulnerability of fire regimes to climate change so the potential biasing of data is removed by the objective of the study. Using this technique to predict versus to understand would require a thorough investigation into the use of these stopping rules; however, as noted the fire duration rules in this study are congruent with observed fire spread in the region and with other fire modeling studies. A total of 8722 simulations were conducted on the TFL 49 landscape.

Analysis of Variance (ANOVA) was used to determine if the mean fire sizes for each climatic period were drawn from different sampling distributions of means (Tabachnick and Fidell 2001). Each climatic time period was considered as an independent treatment. A p-value of 0.10 was used to infer a significant response because the costs associated with making a Type II error were determined to outweigh the costs associated with making a Type I error (McCoy 1996).

Calculating Mean Fire Intervals

To calculate the mean fire interval from the fire simulation modeling a cumulative age distribution for the study area was calculated using a negative exponential equation ($t = \exp(-[t/b])$, where b is the average return interval), with fire return intervals of 50, 150, and 250 years which yields the amount of area expected to burn annually (t) under the average fire return interval (Ministry of Forests and BC Environment 1995). The modelled difference in mean fire size between observed and future scenarios, expressed as a percent modifier (i.e. 0.90 – 1.10), was then used to calculate changes in area burned on an annual basis (t) which in turn was used to solve for ‘ b ’.

Results

Mean Fire Size

The choice of climate change scenarios had a significant impact on mean fire size (MFS). Under each climate change scenario, over each time period, a statistically significant difference ($p \leq 0.1$) was detected in comparison to MFS modeled under current climatic conditions (Table 1). In Block 1, statistically significant differences were found between the mean of the GCM scenarios and the current mean fire size by the 2020s ($n = 1148$; $p \leq 0.005$). In Block 2, statistical differences were found between the mean of the GCM scenarios and the current MFS by the 2020s ($n = 98$; $p \leq 0.036$). The results suggest that a common climatic threshold exists in all scenarios during the 2020s. The mean of all GCM scenarios shows that MFS could increase by 175% by the 2080s in Block 1 and by 411% in Block 2.

Maximum Fire Event

Climate change scenarios increased the size of the maximum fire event in both Block 1 and Block 2 (Table 1). The largest modelled fire event occurred on Block 1 during the 2050s with a maximum fire size of 35,390 ha being modeled. The largest fire size modeled on Block 2 was 7871 ha during the 2080s. The mean of the climate change scenarios showed that an increase in the size of maximum fire events will cause an increase in the proportion of landscape burned from 6% to 15% by 2080s in Block 1 and from 21% to 41% in Block 2. The magnitude of change represented by the scenarios suggests that large fire events affecting 27% of Block 1 and 58% of Block 2 have the potential to occur.

<Table 1>

Fire Size Frequency Distribution

The statistically significant increases in mean fire size from the current period to the 2080s combined with the increase in maximum fire events resulted in a shift in the

frequency distribution of fire sizes over time (Fig. 2). The fire modeling suggests that there may be a shift in the frequency distribution, with fires less than 1000 ha in size occurring less frequently and fires greater than 1000 ha occurring more often by the 2080s. The change that stands out the most is the increase in fires in the 5000 and 10,000 ha fire size classes compared to the current distribution, and the presence of fires in the 20,000 and 50,000 ha size classes. Under the current climate scenario, no fires were recorded in the latter two categories.

<Fig. 2>

Mean Fire Interval

The mean fire interval for the NDT3 and NDT4 ecosystems under the observed climate scenarios was simulated to be 152 years and 254 years for stand-replacing events, respectively, and 51 years for stand-maintaining events in the NDT 4 ecosystems. Under climate change scenarios the mean fire interval was modeled to decrease to 40 years in the NDT3 ecosystems and 67 and 13 years in the NDT 4 ecosystems for stand-replacing and stand-maintaining fires, respectively by the 2080s . The results for all climate periods are summarized in Table S3. Potential changes in forest age class structure based on changes in fire intervals are illustrated in Figure S3 in the online supplemental material.

Overall Fire Regime

The fire simulation modeling results are compared to the “natural” fire regime for the area in Table 2. There is a noticeable agreement between the “natural” fire regime and the simulated current fire regime. This similarity suggests that the modeled fire regime in the current period represents the historical fire regime.

<Table 2>

Thresholds

The statistical significance of the MFS analysis suggests that a potential climatic threshold will exist that could cause a shift in fire regime. The average change in climatic

conditions that caused the significant increase in are a 1.3°C increase in mean annual temperature and an 8% decline in relative humidity coinciding with a 2.1% increase in precipitation.

Discussion

To emulate natural disturbances forest management must incorporate the frequency, mean patch size, and patch size distribution of the current fire regime (Armstrong 1999). The latter incorporates both maximum and minimum fire sizes. If forest managers are to manage fire-dominated ecological systems by mimicking fire regimes they must not only have an understanding of what their past and current characteristics are but what the future character may be. In this study, climate change altered the observed fire regime characteristics suggesting that future fire regimes will be defined by larger and more frequent fires. Nitschke and Innes (2008a) also found that fire severity was likely to increase on the TFL 49 landscape further adding support to a potential shift to a more intensive fire regime. Interestingly, Nitschke and Innes (2008a) modeled a 95% increase in fire weather severity which based on the relationship found by Flannigan and Van Wagner (1991) could lead to doubling in area burned. In this study mean fire size increased by three to five times, which would point to a larger amount of area burned than expected by the fire weather analysis. In a study using the Prometheus model in the boreal forest of Alberta, Canada, Tymstra et al. (2007) modeled a 12.9 to 29.4 % increase in burned area which was 46 % lower than suggested by Flannigan and Van Wagner (1991); however, Krawchuck et al. (2009) simulated a 1.9 to 2.6 fold increase in area burned in Alberta's boreal forests due to future climate change. The approaches used in each study are quite different which likely explains the divergent findings; however, the three studies found an increase in potential area burned under climate change. This increase in fire size, frequency, and severity beyond the observed range of variation will result in a fire regime shift which could have detrimental impacts for forest ecosystems. Changes in any biotic or abiotic component can alter the stable dynamic equilibrium that exists leading to creation of new ecosystems (Tansley 1935). A climate-driven shift in

the fire regime could therefore impact the dynamic equilibrium that is responsible for the maintenance of ecosystems in their current states. A shift in the fire regime of an ecosystem can also change the rate at which ecological processes occur. A change in ecological processes can lead to changes in species composition and ecological structures. Kimmins (2004) defines the maintenance of these processes as ecological integrity, a shift in an ecosystem's or landscape's fire regime therefore increases the vulnerability of an ecosystem to change by altering the mechanisms that provide integrity.

The complete and continual shift in the fire regime suggests that the entire emulation paradigm would have to be continually adjusted over the next 70 years to match the climate-driven changes to the fire regime variables. Miller and Urban (1999) identified that fire regimes are limited by one of two mechanisms: fuel or climate. Fuel-limited fire regimes occur where climate conditions are always right for fire ignition and spread but the absence/ presence of fuels dictates the event. In climate-limited fire regimes, fuels are always present but the climatic conditions required for successful fire ignition and spread are limiting. Fuel-limited systems usually undergo frequent, stand-maintaining fires while climate-limited systems undergo infrequent, stand-replacing fires (Miller and Urban 1999). Based on these coarse classifications, the NDT 4 ecosystem and NDT 3 ecosystems found on the study area could be considered a fuel-limited and climate-limited fire regime respectively. Under the current fire regime, 34% of the landscape can be considered fuel-driven; by the 2080s this increases to 93%. The transition of a large portion of the landscape from climate- to fuel-driven systems may result in two very different impacts. In climate-limited areas, climate change may lead to large, severe fires as the existing NDT3 forests are affected by stand replacing fires which will require these forests to regenerate and accumulate biomass until enough fuel is present to sustain stand-replacing fires or fires occur more frequently as fuel becomes available, which are of lower intensity, but still reduce fire-sensitive species and promote fire-tolerant species (Bartlein et al.1997).

The shift in fire regime on the TFL 49 landscape will likely enhance the habitat for species that have coevolved in systems with frequent fire regimes. For example, Agee (1993) identified *Pseudotsuga menziesii*, *Pinus ponderosa* and *Larix occidentalis* as species that are adapted to frequent fire regimes. On the other hand, species that are susceptible to frequent fires may be significantly reduced. For example, *Abies lasiocarpa*, *Picea engelmannii*, and *P. glauca x engelmannii* are regarded as species with low tolerance to fire and are generally absent from areas with frequent fires (Agee 1993). Nitschke and Innes (2008b) modeled the response of these species on the study area and found that *Abies lasiocarpa*, *Picea engelmannii*, and *P. glauca x engelmannii* may suffer climatic range contractions in their regeneration niche by over 90% while *Pseudotsuga menziesii*, *Pinus ponderosa* and *Larix occidentalis* may expand into these ecosystems as climate warms. The increase of fire-tolerant species into the NDT3 forests could potentially lead to reductions in fire severity and size and gradually transition a stand-replacing fire regime to a stand maintaining regime. To what exact degree the landscape will be fuel- or climate-driven will therefore become dependent on the vegetation dynamics, species productivity and climate that will define these ecosystems in the future. The dynamics between fire regimes and changing vegetation will impact future fire regimes and this was not considered in this study; however, if the interaction between climate, topography and fuels remains the same, then by the 2080s the majority of the landscape will be climatically vulnerable to a more frequent, severe fire regime. The exclusion of vegetation changes may lower the confidence of the long-term fire regime changes identified; however, the changes identified over the next 10 to 50 years are much more credible as the existing vegetation communities and the landscape-scale will take time to transition from one group of species to another due to the inertia that exists within ecosystems (Noss 2001). The shift to a more severe and frequent fire regime needs to be considered as a significant climate change impact however as fire can overcome the

ecological inertia of a system and place the system into a reorganisation stage that will provide opportunities for change within ecosystems (Gunderson et al. 2002).

How can potential changes in fire regime be managed? Should the landscape be maintained in a static state? Historically and presently, the notion of constancy has been the foundation for managing landscapes (Gunderson et al. 2002). The suppression of fires is an example of maintaining ecosystems in a static state. Fire suppression has created ecosystems with highly connected fuel loads that cause fires to be larger and hotter than historically observed (Thompson et al. 1998). The forests of south-central British Columbia are a mix of montane and interior dry-belt forests. Like many of the interior dry-belt forests of western North America they have also been altered by fire suppression, resulting in an increase in both hazardous fuel loads and fire severity (Arno and Fiedler 2005). Even in the montane forest types where fire suppression has had little impact, future changes in climate will likely interact with high fuel loads and higher fire severity (Westerling et al. 2006). A number of options exist. Fire-prone forests could be actively restored through fuel management to restore their natural resilience to frequent fires (Arno and Fiedler 2005). Surface fires could be used as a management tool to maintain fire-susceptible habitat features in conservation areas (Fulé et al. 2005). A “Fire-Smart” management regime could be used to reduce the risk posed by wildfires (Hirsch et al. 2001), which in turn could maintain integrity. Using our understanding of future fire regime vulnerability to guide emulation strategies will require dynamic and flexible management approaches that adapt actions as fire regime shifts with climate. Ignoring fire regime vulnerability will increase the risk to maintaining one of the foundations of sustainable forest management; functioning ecosystems.

Conclusion

Predicted changes in climate over the next 70 years may result in a shift in the fire regime on the TFL 49 landscape beyond the observed range of variation. A shift in the fire regime will mean that a greater proportion of the landscape will be increasingly subject to

a fire regime characterized by larger, more frequent fires. The uncertainty and risks associated with the shift in a fire regime need to be incorporated into an adaptive management approach driven by climatic indicators based on system thresholds. This study has identified that a significant change in fire regimes may occur; of course, there is too much uncertainty with climate change modeling to say that this will happen as modeled but it can be suggested that a shift in climate variables, by the magnitudes identified, will begin to trigger a shift to new fire regimes. This change would increase the risk of current ecosystems to climate change. The loss of ecosystem integrity at the landscape-level will have severe repercussions on the ability to achieve all SFM objectives on the TFL 49 landscape. Managers who decide to emulate natural disturbance should incorporate the risk of a climate change-driven shift in fire regime. The change in the spatial/ temporal characteristics of the fire regime will cause management to either emulate the new regime or continue to mimic the past. If the decision is the latter than the risk of reducing ecological integrity is increased by the increasing fragility of managing for a constant state.

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References

- Agee JK (1993) *Fire Ecology of Pacific Northwest Forests*. Island Press, USA
- Anderson KR (2002) Fire growth modelling at multiple scales. In Viegas DX (ed) *Forest Fire Research & Wildland Fire Safety: Proceedings of IV International Conference on Forest Fire Research 2002 Wildland Fire Safety Summit*, Luso, Coimbra, Portugal 18-23 November 2002. Millpress: Rotterdam, pp 1–6
- Armstrong GW (1999) A stochastic characterisation of the natural disturbance regime of the boreal mixedwood forest with implications for sustainable forest management. *Canadian Journal of Forest Research* 29: 424–433
- Arno SE, Fiedler CE (2005) *Mimicking Nature's Fire: Restoring Fire-Prone Forests in the West*. Island Press, Washington
- Bartlein PJ, Whitlock C, Shafer SL (1997) Future climate in the Yellowstone National Park Region and its potential impact on vegetation. *Conservation Biology* 11: 782–792
- Bergeron Y, Cyr D, Girardin MP, Carcaillet C (2010) Will climate change drive 21st century burn rates in Canadian boreal forest outside of its natural variability: collating global climate model experiments with sedimentary charcoal data. *International Journal of Wildland Fire* 19: 1127–1139
- Dale VH, Joyce LA, McNulty S, Neilson RP, Ayres MP, Flannigan MD, Hanson PJ, Irland LC, Lugo AE, Peterson CJ, Simberloff D, Swanson FJ, Stocks BJ, Wotton BM (2001) Climate change and forest disturbances. *Bioscience* 51: 723–734
- Davis LS, Johnson KN, Bettinger P, Howard TE (2001) *Forest Management: To Sustain Ecological, Economic, and Social Values*. Waveland Press, Long Grove
- Environmental Systems Research Institute (2004) *ESRI ArcGIS 9.0*. Environmental Systems Research Institute Ltd, USA
- Flannigan MD, Van Wagner CE (1991) Climate change and wildfire in Canada. *Canadian Journal of Forest Research* 21: 66–72
- Flannigan MD, Krawchuk MA, de Groot WJ, Wotton BM, Gowman LM (2009) Implications of changing climate for global wildland fire. *International Journal of Wildland Fire* 18: 483–507
- Flannigan MD, Logan KA, Amiro BD, Skinner WR, Stocks BJ (2005) Future area burned in Canada. *Climate change* 72: 1–16
- Flannigan M, Stocks B, Weber M (2003) Fire regimes and climate change in Canadian forests. In Veblen TT, Baker WL, Montenegro G, Swetnam TW (eds) *Fire and Climate change in Temperate Ecosystems of the Western Americas*. Springer, New York, pp 97–117
- Flannigan MD, Bergeron Y, Engelmark O, Wotton BM (1998) Future wildfire in circumboreal forests in relation to global warming. *Journal of Vegetation Science* 9: 469–476
- Fulé PZ, Villanueva-Díaz J, Ramos-Gómez M (2005) Fire regime in a conservation reserve in Chihuahua, Mexico. *Canadian Journal of Forest Research* 35: 320–330

- Girardin MP, Mudelsee M (2008) Past and future changes in Canadian boreal wildfire activity. *Ecological Applications* 18: 391–406
- Gunderson LH, Holling CS, Pritchard Jr L., Peterson GD (2002) Resilience of large-scale resource systems. In Gunderson, LH, Pritchard Jr L (eds) *Resilience and Behaviour of Large-Scale Systems*. Island Press, Washington, pp 3–20
- Hebda R (1998) Atmospheric change, forests and biodiversity. *Environmental Monitoring and Assessment* 49: 195–212
- Hirsch KG (1996) Canadian Forest Fire Behavior Prediction (FBP) System: users's guide. Natural Resources Canada Special Report 7. Government of Canada
- Hirsch K, Kafla V, Tymstra C, McAlpine R, Hawkes B, Stegehuis H, Quintilio S, Gauthier S, Peck K (2001) Fire-smart forest management: a pragmatic approach to sustainable forest management in fire-dominated ecosystems. *The Forestry Chronicle* 77: 357–363
- Kimmins JP (2004) *Forest Ecology: A Foundation for Sustainable Forest Management and Environmental Ethics in Forestry*, 3rd Ed. Prentice Hall, New Jersey
- Krawchuk MA, Cumming SG, Flannigan MD (2009) Predicted changes in fire weather increases lightning fire initiation and future area burned in the mixedwood boreal forest. *Climatic Change* 92: 83–97
- Li C, Flannigan MD, Corns IGW (2000) Influence of potential climate change on forest landscape dynamics of west-central Alberta. *Canadian Journal of Forest Research* 30: 1905–1912
- McCoy ED (1996) Advocacy as part of conservation biology. *Conservation Biology* 10: 919–920
- McKenzie D, O'Neill SM, Larkin NK, Norheim RA (2006) Integrating models to predict regional haze from wildland fire. *Ecological Modelling* 199: 278–88
- Meyn A, Taylor SW, Flannigan MD, Thonicke K, Cramer W (2010a). Relationship between fire, climate oscillations, and drought in British Columbia, Canada, 1920–2000. *Global Change Biology* 16: 977–989.
- Meyn A, Schmidtlein S, Taylor SW, Girardin MP, Thonicke K, Cramer W (2010b). Spatial variation in wildfire and summer drought in British Columbia, Canada, 1920–2000. *International Journal of Wildland Fire* 19: 272–283.
- Miller C, Urban DL (1999) A model of surface fire, climate and forest pattern in the Sierra Nevada, California. *Ecological Modelling* 114: 113–135.
- Ministry of Forests, BC Environment (1995) *Biodiversity guidebook: Forest practices code of British Columbia*. ISBN 0–7726–2619–7, Province of British Columbia
- Nitschke CR, Innes JL (2008a) Climate change and fire potential in south-central British Columbia, Canada. *Global Change Biology* 14: 841–855
- Nitschke CR, Innes JL (2008b) Integrating climate change into forest management in South-Central British Columbia: an assessment of landscape vulnerability and

development of a climate-smart framework. *Forest Ecology and Management* 256: 313–327

Noss RF (2001) Beyond Kyoto: Forest Management in a Time of Rapid Climate Change. *Conservation Biology* 15: 578–590

Overpeck JT, Rind D, Goldberg R (1990) Climate-induced changes in forest disturbance and vegetation. *Nature* 343: 51–53

Palik BJ, Mitchell RJ, Hiers JK (2002) Modeling silviculture after natural disturbance to sustain biodiversity in the longleaf pine (*Pinus palustris*) ecosystem: balancing complexity and implementation. *Forest Ecology and Management* 155: 347–356

Spracklen DV, Mickley LJ, Logan JA, Hudman RC, Yevich R, Flannigan MD, Westerling AL (2009) Impacts of climate change from 2000 to 2050 on wildfire activity and carbonaceous aerosol concentrations in the western United States. *Journal of Geophysical Research* 114: D20301

Suffling R, Perera AH (2004) Characterizing natural disturbance regimes: concepts and approaches. In Perera AH, Buse LJ, Weber MG(eds) *Emulating Natural Forest Landscape Disturbances: Concepts and Applications*. Columbia University Press, New York, pp 43–54

Stocks BJ, Fosberg MA, Lynham TJ, Mearns L, Wotton BM, Yang Q, Lin J-Z, Lawrence K, Hartley GR, Mason JA, McKenney DW (1998) Climate change and forest fire potential in Russian and Canadian Boreal forests. *Climate change* 38: 1–13

Tabachnick BG, Fidell LS (2001) *Using Multivariate Statistics* 4th edn. Allyn and Bacon, Boston

Tansley AG (1935) The use and abuse of vegetational concepts and terms. *Ecology* 16: 284–307.

Thompson ID, Flannigan MD, Wotton BM, Suffling R (1998) The effects of climate change on landscape diversity: an example in Ontario forests. *Environmental Monitoring and Assessment* 49: 213–233

Tymstra C, Bryce RW, Wotton BM, Taylor SW, Armitage OB (2010) Development and structure of Prometheus: the Canadian wildland fire growth simulation model. Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, AB. Information Report NOR-X-417

Tymstra C, Armitage OB, Logan K (2007) Impact of climate change on area burned in Alberta's boreal forest. *International Journal of Wildland Fire* 16: 153–160

Veblen TT, Baker WL, Montenegro G, Swetnam TW (Eds) (2003) *Fire and Climate change in Temperate Ecosystems of the Western Americas*. Springer, New York

Westerling AL, Bryant (2008) Climate change and wildfire in California. *Climatic Change* 87: S231–S249

Westerling AL, Turner MG, Smithwick EH, Romme WH, Ryan MG (2011) Continued warming could transform Greater Yellowstone fire regimes by mid-21st century. *Proceedings of the National Academy of Science* 108: 13165–13170

Westerling AL, Hadalgo HG, Cayan DR, Swetnam TW (2006) Warming and earlier spring increase in Western U.S. forest fire activity. *Science* 313: 940–943

White PS, Pickett STA (1985) Natural disturbance and patch dynamics: an introduction. In Pickett STA, White PS (eds) *The Ecology of Natural Disturbance and Patch Dynamics*. Academic Press, Orlando, pp3–13

Wong C, Dorner B, Sandmann H (2003) Estimating historical variability of natural disturbances in British Columbia. *Land Management Handbook* 53. Government of British Columbia

Wotton BM, Flannigan MD, Nock CA (2010) Forest fire occurrence and climate change in Canada. *International Journal of Wildland Fire* 19: 253–271.

Wotton BM, Martell DL, Logan KA (2003) Climate change and people caused forest fire occurrence in Ontario. *Climatic Change* 60: 275–295.

Wotton BM, Flannigan MD (1993) Length of the fire season in a changing climate. *The Forestry Chronicle* 69: 187–192.

List of Tables and Figures

Table 1. Change in mean and maximum fire size (ha) under predicted climate change

Table 2. TFL 49 fire regime comparison, observed vs. observed simulated vs. climate change

Fig. 1. Tree Farm License 49 Landscape in the North Okanagan region of British Columbia, Canada (▲^{Location} indicates locations of weather stations used in the study: SA = Salmon Arm, FIN = Fintry). The Tree Farm License 49 landscape is classified by lightning risk rating and location of human- and lightning-caused ignitions.

Fig. 2. Change in fire size frequency distribution for the TFL 49 landscape under predicted climate change

Table 1. Change in mean and maximum fire size (ha) under predicted climate change

Scenario	Block 1: Mean Fire Size (ha)				Block 2: Mean Fire Size (ha)			
	Observed	2020s	2050s	2080s	Observed	2020s	2050s	2080s
Current	679.5	X	X	X	197.5	X	X	X
CGCM2	X	980.0*	1011.0**	1267.6***	X	332.9*	370.9*	583.8*
HADCM3	X	1151.2***	2391.3***	3449.8***	X	468.1*	1337.9**	2048.6**
Mean	X	1065.6***	1701.2***	2358.7***	X	400.5*	854.4**	1361.2**

Scenario	Block 1: Maximum Fire Size (ha)				Block 2: Maximum Fire Size (ha)			
	Observed	2025	2055	2085	Observed	2025	2055	2085
Current	7961	X	X	X	2882	X	X	X
CGCM2	X	11305	10505	16024	X	3186	3614	5272
HADCM3	X	12762	35390	27836	X	4167	6318	7871
Mean	X	12033.5	22947.5	21930	X	3676.5	4966	6571.5

Levels of significance: (+) 0.10, (*) 0.05, (**) 0.01, and (***) 0.001

Table 2. TFL 49 fire regime comparison, observed vs. observed simulated vs. climate change

Time Period	MFI Stand Replacing (yrs)	MFI Stand Maintaining (yrs)	Min Fire Size (ha)	MFS (ha)	Max Fire Size (ha)
Observed ^I	184	50	0.1	650	6528
Simulated ^{II}	187	51	0.25 ^{III}	641	7555
2020s ^{II}	115	31	0.25 ^{III}	975*	10638
2050s ^{II}	70	19	0.25 ^{III}	1426*	17855
2080s ^{II}	49	13	0.25 ^{III}	1861*	19076

I: from Table 1 (weighted average calculated for MFI)

II: weighted averages for TFL 49 calculated from fire simulation modeling

III: minimum fire size recorded equals one raster cell (resolution of 0.25 ha)

*: statistically significant ($\alpha \leq 0.05$)

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