Forest Ecology and Management 310 (2013) 875–886

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Assessing possible shifts in wildfire regimes under a changing climate in mountainous landscapes

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ARTICLE INFO

Article history:
Received 29 July 2013
Received in revised form 17 September 2013
Accepted 18 September 2013
Available online 15 October 2013

Keywords:
Ecosystem-based management
Extreme drought
Future climate and fire scenarios
Natural disturbance
Wildfire

ABSTRACT

Climate change may affect the probability of extreme events such as wildfires. Although wildfires are some of the most important ecological processes in forest ecosystems, large-scale wildfires are often perceived as an environmental disaster. Since failure to include the dynamic nature of ecosystems in planning will inevitably lead to unexpected outcomes, we need to enhance our ability to cope with future extreme events coupled with climate change. This study presents several future scenarios in three different time periods for Canada's Columbia Montane Cordillera Ecoprovince, which is prone to wildfires. These scenarios predict the probability of occurrence of widespread wildfires based on the hierarchical Bayesian model. The model was based on the relationships between wildfires and the Monthly Drought Code (MDC). The MDC is a generalized monthly version of the Daily Drought Code widely used across Canada by forest fire management agencies for monitoring of wildfire risk. To calculate future MDC values, we relied on different possible future conditions of climate, given by the Global Circulation Models. We found a regime shift in drought intensity with abrupt decreases in lightning-caused wildfire activity around 1940, suggesting that future wildfire risks can be inferred primarily from the summer drought code. For future periods, we found increasing trends in the probabilities of large-scale fires with time in most areas. It should be notable that, by the 2080s, there is a probability of some areas having more than 50% of large-scale wildfires under the "average" climatic conditions in the future, indicating that, even without "extreme" weather conditions, some ecosystems will have a fundamental probability of experiencing catastrophic fires under the condition of average summer. However, the rate of progression toward a fire-prone condition is quite different among the three climate change scenarios and among the region analyzed. Given such scenario-sensitive, spatially-heterogeneous patterns of wildfire probability in response to climate variability, management strategy should be flexible and more localized. By drawing on this knowledge, it may be possible to mitigate climate change impacts both before they arise and once they have occurred. These considerations are critical for maintaining the integrity of systems shaped by large-scale natural disturbances to increase their resilience to the changing climate while protecting human society and infrastructures. Working with alternative scenarios will facilitate our adaptation to climate change in managing fire-prone forest ecosystems.

1. Introduction

Efforts at management and conservation of ecological systems are facing challenges of a global climate change and the need to cope with an accompanying uncertainty (Millar et al., 2007; Lawler et al., 2010). One of the critical components of an understanding of the responses of ecosystems to a changing climate is alterations of the disturbance regimes (Dale et al., 2001; Seidl et al., 2011b). Natural disturbances are currently treated by ecologists not as events bringing destruction, but as fundamental sources of diversity and heterogeneity (Spugel, 1991; Wallington et al., 2005). When natural disturbances are excluded, ecological variability decreases, resulting in homogenization and reduction of ecosystem functioning, degradation of ecosystem services, and loss of biodiversity (Wallington et al., 2005; Mori, 2011b; Pakeman, 2011). On the other hand, most infrequent and large-scale natural disturbances such as wildfires, especially those consuming more than 10,000 ha (Keane et al., 2008), are perceived as disasters to human communities and infrastructure, bringing social and economic devastation (Lindenmayer, 2004; Lindenmayer and Noss, 2006). In addition to such difficulties in evaluating the roles of large-scale natural events, climate instability poses further uncertainty in

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http://dx.doi.org/10.1016/j.foreco.2013.09.036

the management of ecosystems prone to major disturbances (Mori, 2011b; Seidl et al., 2011a). Human-driven climate change may alter the frequency, extent, and severity of major disturbances (Dale et al., 2001); ecosystem conditions in various regions may deviate beyond the historical ranges of variability that land management plans and managers often use as conservation and restoration targets (Millar et al., 2007; Jackson and Hobbs, 2009). Therefore, an urgent reassessment of management strategies is critical to the ability to cope with increased probability of future shifts in disturbance regimes and ecosystem states beyond historical reference conditions.

Among natural disturbances, wildfire is one of the most climate-sensitive events. Numerous studies have indicated that increases in the frequency and the severity of temperature-driven droughts are likely, thus creating more wildfire-prone conditions in many regions (Flannigan et al., 2005, 2009; Gonzalez et al., 2010; Pechony and Shindell, 2010; Mastrandrea et al., 2011; Westerling et al., 2011). In addition to tree mortality, wildfire affects various biological, geochemical, and geophysical characteristics and processes, including carbon dynamics, nutrient cycles, soil properties, seed germination, wildlife habitat, landscape heterogeneity, successional trajectory, community assembly, and biological diversity, among others (Dale et al., 2001; Turner et al., 2003; Noss et al., 2006). Therefore, in the near future, processes and functioning of ecosystems prone to large-scale wildfires may differ vastly from those found in the past. Although climate change is impacting today's ecosystems, other, possibly more serious impacts will emerge decades into the future (Lawler et al., 2010). Jackson and Hobbs (2009) noted that ecological management should aim to conserve and restore historical ecosystems where viable, while simultaneously preparing to steer emerging novel ecosystems to ensure maintenance of ecological goods and services. In the face of uncertainty associated with a rapid climate change, attempts to conserve or restore past conditions will require enormous efforts from managers and could potentially create ecosystems more prone to undesirable changes (Millar et al., 2007; Mori et al., 2013). Therefore, we need to accept that future ecosystems, especially those that may become more vulnerable to widespread wildfires, may be different and unique (Millar et al., 2007; Mori et al., 2013).

Insights on future wildfire regimes have been provided mainly at broader spatial scales such as intercontinental comparisons, nation-level trends, and spatially-heterogeneous responses (Flannigan et al., 2005; Gonzalez et al., 2010; Pechony and Shindell, 2010; Moritz et al., 2012; de Groot et al., 2013). However, much of the information about climate change impacts is too broad to fully inform the managers of specific ecosystems (Lawler et al., 2010). Furthermore, actual data, projections, and possibilities for specific local areas are generally not available. Thus, a new approach needs to be incorporated into the future management options, one that addresses local responses of ecosystems to climate change and simultaneously compensates for limitations of local data. Here, we aim to develop such a model to evaluate the future probability of large-scale wildfires and a possible wildfire regime shift in a mountainous ecoprovince in southwestern Canada. The model is based on the hierarchical Bayesian approach and is applied to show future scenarios of wildfire vulnerability at the more localized scale within the study ecoprovince. Based on these scenarios, we discuss flexible approaches to cope with inherent variability and uncertainty under the changing climate.

2. Methods

2.1. Study area

The national ecological framework for Canada has hierarchical levels (ecozone, ecoprovince, ecoregion, and ecodistrict) as ecological management units (Marshall et al., 1999). These levels were deemed most suitable for reporting on national issues and regional issues of national significance concerning the environment and sustainability of resources. Ecodistricts are the smallest of the management units, and are characterized by distinctive assemblages of landform, relief, surficial geologic material, soil, water bodies, vegetation, and land uses. Ecodistrict size is a function of regional variability of these defining attributes.

In this study, a total of 24 ecodistricts constituting the Columbia Montane Cordillera Ecoprovince in western Canada were included to determine drought-wildfire relationships (Fig. 1). The studied ecoprovince is one of the four subdivisions of the Montane Cordillera Ecozone, which is the most diverse of Canada's 15 terrestrial ecozones, exhibiting some of the driest, wettest, coldest, and hottest conditions anywhere in Canada (Wiken, 1986). The ecosystems in this region are heterogeneous, ranging from alpine tundra and dense conifer forests to dry sagebrush and grasslands. Much of the region is rugged and mountainous. Each ecodistrict in the ecoprovince has different land-cover characteristics (Table 1), indicating that working at the ecodistrict level will yield more appropriate perspectives on ecosystem-wildfire relationships than that at the higher hierarchical levels.

2.2. Wildfire data

The Canadian National Fire Database (CNFDB; http://cwfis.cfs.nrcan.gc.ca/) is a collection of wildfire data, which include year, date, location, perimeters, cause (human or lighting), and data source (provided by Canadian fire management agencies of provinces, territories, and Parks Canada) of fires of all sizes. In this study, all the data available for lightning-caused fire up to 2009 in the Columbia Montane Cordillera Ecoprovince were obtained from the CNFDB. The CNFDB had partial fire data for 2010 at the time of data access (March 2011); these were excluded from analyses as incomplete. The database includes information on past human-caused fires; however, it is difficult to predict their occurrences in the future, as human-caused fires are expected to largely depend on societal behavior. Although several recent studies have projected future possibilities of human-induced wildfire activity (e.g., Liu et al., 2012), we therefore focused only on natural wildfire regime, which is tightly associated with the changing climate. The ecoprovince straddles British Columbia (BC) and Alberta (AB) and the time period of the CNFDB data differs between the two provinces (from 1917 in BC and from 1931 in Alberta). However, the larger portion of the study ecoprovince is within BC so we assumed that the lack of data for AB did not significantly affect the results. In interpreting our results from analyses of temporal changes in wildfire activity, we addressed the lack of early data in some ecodistricts located in AB.

2.3. The drought code

Currently, forest fire management agencies in Canada (Lawson and Armitage, 2008) and other countries (de Groot et al., 2007) use the Fire Weather Index (FWI) System to assess wildfire risks. FWI relies on three indices, i.e., Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC), and Drought Code (DC) (Lawson and Armitage, 2008). Among them, the DC is an index of the net change in evapotranspiration and precipitation on cumulative moisture depletion in organic soils. The DC is practical for estimating the danger and risk of fire; it has a slower response time (62 days at 15 °C and 44 days at 30 °C), less day to day variability than the other two codes, and is more in tune with the blocking high pressure systems associated with large wildfires that determine wildfire regimes (Johnson and Wowchuk, 1993; Macias Fauria and Johnson, 2006). However, the DC relies on daily weather data,