Wildfire-mediated vegetation change in boreal forests of Alberta, Canada

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Abstract. Climate-induced vegetation change may be delayed in the absence of disturbance catalysts. However, increases in wildfire activity may accelerate these transitions in many areas, including the western boreal region of Canada. To better understand factors influencing decadal-scale changes in upland boreal forest vegetation, we developed a hybrid modeling approach that constrains projections of climate-driven vegetation change based on topo-edaphic conditions coupled with weather- and fuel-based simulations of future wildfires using Burn-P3, a spatial fire simulation model. We evaluated eighteen scenarios based on all possible combinations of three fuel assumptions (static, fire-mediated, and climate-driven), two fire-regime assumptions (constrained and unconstrained), and three global climate models. We simulated scenarios of fire-mediated change in forest composition over the next century, concluding that, even under conservative assumptions about future fire regimes, wildfire activity could hasten the conversion of approximately half of Alberta’s upland mixedwood and conifer forest to more climatically suited deciduous woodland and grassland by 2100. When fire-regime parameter inputs (number of fire ignitions and duration of burning) were modified based on future fire weather projections, the simulated area burned was almost enough to facilitate a complete transition to climate-predicted vegetation types. However, when fire-regime parameters were held constant at their current values, the rate of increase in fire probability diminished, suggesting a negative feedback by which a short-term increase in less-flammable deciduous forest leads to a long-term reduction in area burned. Our spatially explicit simulations of fire-mediated vegetation change provide managers with scenarios that can be used to plan for a range of alternative landscape conditions.

Key words: boreal forest; Burn-P3; climate change; ecosites; landscape simulation; wildfire.

INTRODUCTION

Global climate change is anticipated to exert biome-scale influences on future vegetation patterns (Hickler et al. 2012, Rehfeldt et al. 2012) and disturbance regimes (Seidl et al. 2017), with profound influences on terrestrial biota. In the western boreal region of North America, there is evidence that recent anthropogenic climate change has resulted in more frequent and extensive moisture deficits (Peng et al. 2011), leading in turn to more frequent and larger fires (Kasischke
soil moisture suggest that area burned could summer temperatures and associated decreases in est region, projected future increases in maximum stone et al. 2010). Across the Canadian boreal for-
wild (Stocks et al. 2002), it is well acknowledged that wild regions (Hogg and Schwarz 1997).

than for seedling establishment in drought-prone mature conifer persistence are less restrictive for extended periods, as the requirements for disturbance, current forest systems may persist for extended periods, as the requirements for mature conifer persistence are less restrictive than for seedling establishment in drought-prone regions (Hogg and Schwarz 1997).

In most parts of the western boreal forest, where wildfires are particularly large and frequent (Stocks et al. 2002), it is well acknowledged that wildfires may trigger vegetation change (Johnstone et al. 2010). Across the Canadian boreal forest region, projected future increases in maximum summer temperatures and associated decreases in soil moisture suggest that area burned could increase by as much as fivefold by the end of the 21st century (Flannigan et al. 2005, Balshi et al. 2009, Boulanger et al. 2014). Consequently, this expected increase in natural disturbance events (i.e., wildfire) will almost certainly accelerate ecosystem shifts, reducing the lag in vegetation responses to climate conditions (Stephens et al. 2013). It should also create a younger forest mosaic, a trend that will be exacerbated by continued timber harvest and other industrial development activities (Schneider et al. 2003, Cyr et al. 2009, Hauer et al. 2010). Ultimately, such changes in forest composition and age structure may be enough to limit populations of some species. Thus, it is critical to understand decadal-scale dynamics of vegetation succession and disturbance in response to climate and land-use change, which are inextricably linked to wildfire dynamics.

Wildfire potential is a function of climate, fuel (flammable vegetation), and ignitions (Parisien et al. 2011a). In the western boreal region, the climate is becoming more fire-conducive, with more extreme fire-weather days already occurring, as well as projected for the future (Tymstra et al. 2007, Wang et al. 2015), thereby extending the length of the fire season (Wotton and Flannigan 1993, Flannigan et al. 2009). This increases the potential for more numerous fire ignitions and longer-burning (thus larger) fires (Wang et al. 2017). Lightning-caused ignitions are already numerous and will likely increase with future weather conditions (Krawchuk et al. 2009, Wotton et al. 2010, Veraverbeke et al. 2017). Fuels, however, may decrease over the next century, as forests become younger (Héon et al. 2014) and more deciduous-dominated (Johnstone et al. 2010) and therefore less-flammable (Cumming 2001, Bernier et al. 2016), providing some degree of eventual fuel limitation (Terrier et al. 2012). The grassland systems that are projected to be most suited to southern boreal climate conditions by the end of the 21st century (Schneider et al. 2009, Mbogga et al. 2010) represent a decrease in flammable biomass relative to forests, although wildfires there may still burn rapidly and cover large areas.

In order to capture both the direct effect of climate and the facultative effect of wildfire on vegetation change, dynamic models are needed to address short-term (i.e., decadal scale) vegetation trajectories. Spatially explicit landscape simulation models are numerous and well developed for many regions and systems (see Keane et al. 2004 for a review), but they have limited potential to predict outside the range of initial conditions. Disturbance-mediated ecosystem shifts are therefore not well developed due to the large spatial extents required to encompass the magnitude of expected climate change (but see Boulanger et al. 2016b). Dynamic global vegetation models capture broad-scale ecosystem shifts but are coarse in resolution and lacking in spatial and thematic detail. Furthermore, their potential to project climate-change responses is similarly constrained by the range of baseline conditions used for parameterization (Williams and Abatzoglou 2016).
Given the challenges associated with strictly dynamic models, hybrid approaches may be best suited—or at least most practically implemented—for broad-scale ecological inference in a climate-change context (Cushman et al. 2006, Gustafson 2013, Williams and Abatzoglou 2016). We developed such a hybrid approach for northern Alberta, Canada, by simulating scenarios of future fire behavior as a catalyst for climate-driven vegetation change. We thereby incorporated critical ecosystem processes, as well as empirically derived relationships, over broad climatic gradients. To develop these fire-mediated scenarios, we simultaneously took advantage of a wealth of systematically surveyed vegetation ecosite data (Boutin et al. 2009) and recent methodological developments in the simulation of future fire weather (Wang et al. 2015, 2016) and duration (Wang et al. 2014, 2017). Our focus was on upland vegetation, due in part to the additional complexities associated with wetland hydrologic feedbacks (Waddington et al. 2015), and the additional lags expected in these systems (Camill and Clark 2000), especially where permafrost degradation results in additional organic matter deposition (Vitt et al. 2000).

Our overarching objective was to identify decadal-scale effects of climate change on upland boreal forest vegetation, considering (1) topographic constraints to vegetation change, that is, soil moisture/nutrient conditions; and (2) changes in wildfire activity (as measured by simulated burn probability at a 500-m pixel level). Using a scenario evaluation framework and three complementary global climate models (GCM), we addressed the following set of specific questions for northern Alberta:

1. How will burn probability change over the 21st century as fire weather, fire-regime parameters, and fuels (vegetation types) change?
2. How much of the variability in future burn probability can be attributed to fire weather (as represented by different GCMs) vs. fire-regime parameters vs. fuels?
3. What are the combined projected impacts of climate change and wildfire on upland vegetation composition under different fire weather and fire-regime scenarios?
4. How do fire-mediated scenarios of change in upland vegetation differ from direct climate-change projections?

To address these questions, we evaluated eighteen scenarios based on all possible combinations of three fuel assumptions (static, fire-mediated, and climate-driven), two fire-regime assumptions (constrained and unconstrained, in terms of (1) the number of fires and (2) the duration of each), and three GCMs. Although our understanding of potential future fire-regime characteristics such as fire size and frequency is increasing, studies have mainly focused on changes in weather and climate; how these elements will co-vary as a function of vegetation change and other factors is largely unknown. Our goal was to bracket the possible range of outcomes while also exploring the influence of different assumptions about the future.

**Methods**

**Study area**

Our study area was the boreal forest region within the province of Alberta, Canada, with a total area of 438,063 km$^2$, ranging from $\sim$55° N to 60° N latitude at the border with the Northwest Territories (Fig. 1). Specifically, we focused our inference on Alberta’s boreal natural regions (boreal forest and Canadian Shield), as well as the lower portion of the foothills natural region (Natural Regions Committee 2006).

Boreal Alberta is characterized by a strongly continental climate. The average annual moisture balance is slightly positive (Hogg 1994), and fire is the predominant natural disturbance. Geologically, the boreal region of Alberta primarily consists of the boreal plain, an area of deep marine sediments, and a small section of the Canadian Shield (eroded Precambrian rock) in the northeastern corner of the province. Upland forests are composed primarily of aspen (Populus tremuloides) and white spruce (Picea glauca) in various mixtures, with a tendency for the former to dominate on warmer, more exposed sites, and the latter on colder and more sheltered sites. Extensive forested wetlands are also found, where black spruce (Picea mariana) and eastern larch (Larix laricina) dominate on cold, poor wetland soils. Forests on the granitic expanse of the western Canadian Shield are composed mostly of black spruce and jack pine (Pinus banksiana). Foothills forests contain primarily lodgepole pine (Pinus contorta), white spruce, and aspen.
Alberta's wildfire regime is characterized by large, stand-renewing fires primarily initiated by lightning strikes, and a fairly long season, starting early April and ending late September (Tymstra et al. 2005). Most fire activity occurs in the boreal region, particularly in the northern part of the province, with less activity in the foothills region (Tymstra et al. 2005). The region contains little urban/rural development (<2%), and agricultural activities are climate-limited, covering 10.6% of the boreal region and 3.0% of the foothills region (Schieck et al. 2014). In terms of total area, forestry and energy sector footprints are estimated to cover just 2.7% and 1.7%, respectively, of the boreal region (including the Canadian Shield portion), and 16.9% and 2.5%, respectively, of the foothills region (Schieck et al. 2014). However, the industrial land-use footprint is quite extensive, consisting of a combination of timber harvest blocks; oil, gas, and bitumen wells; mines; and a network of linear features that includes pipelines, seismic lines, powerlines, and variety of other roads and trails (Schneider et al. 2003). Fire activity is generally suppressed within the immediate vicinity of human disturbance, but may also be enhanced by the permeation of human infrastructure and activities in remote regions (Robinne et al. 2016).

Vegetation model and simulation overview

To assess potential future patterns of vegetation change and wildfire activity, we developed new 500-m resolution vegetation layers to use as fuel inputs to fire simulations under various scenarios. These were achieved by modeling vegetation as a function of geology, terrain, and climate in a two-stage process using a random forest (Breiman 2001) machine-learning algorithm, with performance assessed according to out-of-bag (OOB) classification accuracy (Appendix S1). Future potential vegetation distributions were projected as a function of future climates, assuming that current topo-edaphic characteristics (i.e., geology, topography, and resulting soil moisture and nutrient conditions) would remain constant over the 90-yr study period. We held wetlands constant and focused our analysis on upland forests, where vegetation transitions are more dynamic than in wetland systems (Schneider et al. 2016). Specifically, we first constructed models relating current ecosite type (defined as soil moisture and nutrient class) to geology, terrain, and climate. We then modeled vegetation as a function of ecosite type, terrain, and climate within our boreal study area, and projected future potential, hereafter “climate-driven,” vegetation based on future climate variables, holding ecosite type and terrain variables constant (Fig. 2a). Climate variables were based on historical normals (1961–1990) and climate projections for three future time periods: 2011–2040, 2041–2070, and 2071–2100. Global climate models with available future fire weather projections (Wang et al. 2017) were from the Coupled Model Intercomparison Project, Phase 5 (CMIP5, Taylor et al. 2012); CanESM2 (Chylek et al. 2011), CESM1-CAM5 (Hurrell et al. 2013), and HadGEM2-ES (Jones et al. 2011). We used representative concentration pathway 8.5, to capture the conditions that are to be expected without dramatic reductions in greenhouse gas emissions or technological fixes (Fuss et al. 2014).

Assuming that vegetation can only reach its future projected climatic potential if catalyzed by wildfire or other disturbance (Schneider et al.
strained, in terms of the number of regime assumptions (constrained and unconstrained, in terms of the number of fires and the duration of fire spread conditions; Table 1; Appendix S2: Table S1). Simulations were conducted using Burn-P3 (P3 = probability, prediction, and planning; Parisien et al. 2005), a spatially explicit fire model that simulates the ignition and growth of individual fires on the landscape using the Prometheus fire growth engine (Tymstra et al. 2010). The Prometheus model calculates fire growth based on fuels and terrain according to the Canadian Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992) and fire spread mechanisms (Richards 1995). Burn-P3 uses Prometheus to simulate individual fires deterministically for one fire year, and this process is repeated for a large number of iterations using variable ignitions and weather. We used Burn-P3 outputs of simulated fires to update burned areas based on climate-projected potential future vegetation for three 30-yr periods from 2011 to 2100 (Fig. 2b). In order to evaluate the importance of future vegetation for burn probability, we also simulated fires for the same time periods with static and climate-driven fuel scenarios, where baseline and future climate-predicted vegetation, respectively, were used as inputs to Burn-P3 (Table 1; Appendix S2: Table S1).

Fire simulation—general parameters

Each Burn-P3 model iteration represents one realization of parameters for one year. Within this period, two seasons were defined to stratify the temporal variability in fire ignition and spread: spring (April 15–May 24) and summer (May 25–Sept 15). The start date of the spring season and the end date of the summer season correspond, on average, to the earliest and latest dates at which fires ≥200 ha occur. The start date of the summer season corresponds to green-up of broadleaf trees. The fire seasons were determined through summary explorations of weather and, in particular, of the distributions of fire numbers and area burned throughout the year. Percent grass curing (dry dead grass) was estimated to be 70% for the spring season and 55% for the summer season. For both seasons, we assumed spatially random ignitions within each fire zone and 4 h of potential fire growth per day.

Due to the large extent of our study area, and the variation in fire regimes it contains, we stratified it following the fire zone delineation of Boulanger et al. (2012). Three distinct fire zones were contained in our study area: the northern Great Slave Lake zone (highest fire frequency), the Southern Prairies zones (intermediate), and the Southern Cordillera zone (lower fire frequency; Fig. 1). To allow fires to begin outside the study area and thus avoid edge effects, we calculated a 30-km buffer around the study area. To inform topographic influences on fire spread, we used a 500-m digital elevation model corresponding with the resolution of our fuel inputs (Jarvis et al. 2008). As a sensible modeling shortcut, only fires ≥200 ha were modeled (Parisien et al. 2005); these large fires are responsible for approximately 97% of the total area burned in Canada (Stocks et al. 2002).

Fire simulation—fire weather parameters

A primary input to Burn-P3 is daily fire weather, which consists of daily noon observations of surface air temperature, relative humidity, 10-m open wind speed, and 24-h accumulated precipitation, as well as corresponding Fire Weather Index (FWI) System (Van Wagner 1987) variables, which are used to track daily fuel moisture conditions and potential fire behavior. Following the methods of Wang et al. (2014), two of the FWI System variables, the duff moisture code (DMC, a scaled measure of duff fuel layer moisture content) and the FWI (a scaled indicator of fire intensity; Van Wagner 1987), were used to determine fire duration, which in turn constrains the size of a fire. The DMC was used to determine the rain-free periods during which fires can burn, whereby a DMC <20 results in extinguishment (Anderson 2010). During those intervals, only days with FWI ≥ 19 were used to simulate fire growth, as suggested by Podur and Wotton (2011).

Historical daily fire weather data were obtained from an interpolated 3-km resolution grid provided by the Canadian Forest Service based on surface observations taken between April 1 and September 30 from 1981 to 2010 (Wang et al. 2015). Future fire weather data for
all scenarios were from Wang et al. (2017), who applied monthly change anomalies to daily baseline values to translate future monthly climate projections from GCM simulations into future daily fire weather values for the periods 2011–2040, 2041–2070, and 2071–2100. One hundred and six points, separated by at least 40 km, were randomly sampled from the grid to represent daily fire weather conditions (i.e., pseudo-weather stations) for baseline and future time periods, stratified by fire zone.

Fire simulation—fire-regime parameters
For the unconstrained fire-regime scenarios, we assumed climate-related increases in fire-regime parameters—the number of escaped fires (Flannigan et al. 2006, Kasischke and Turetsky 2006) and the duration of fire spread conditions (Wang et al. 2017)—and estimated these parameters for future time periods based on daily fire weather projections. For the number of fires, we used linear regression analysis to relate the number of historical fires in a given ecoregion to monthly temperature (mean noon values) and precipitation values for the corresponding year. The resulting models (Appendix S2: Table S2) were applied to a sample of future weather values in order to generate future distributions of the number of escaped fires in each ecoregion. Resulting distributions were combined into a single distribution, according to

![Workflow diagram for (a) climate-driven and (b) fire-mediated scenarios. Green parallelograms represent point level data inputs; turquoise parallelograms are static raster data inputs; orange parallelograms are dynamic raster data inputs; blue parallelograms are static raster data outputs; red parallelograms are dynamic raster data outputs. White boxes are model processes. The elements outside the gray box represent the ecosite and vegetation modeling components; the elements within the gray box represent the iterative fire simulation and vegetation update components, which are repeated for three time periods: 2011–2040, 2041–2070, and 2071–2100.](image)
Table 1. Forest change scenarios evaluated (see Appendix S2: Table S1 for full specifications).

| ID  | Fuel scenario   | Fire-regime scenario | GCM          |
|-----|-----------------|-----------------------|--------------|
| 1   | Static fuels    | Constrained           | CanESM2      |
| 2   | Static fuels    | Constrained           | CSIRO        |
| 3   | Static fuels    | Constrained           | HadGEM2      |
| 4   | Static fuels    | Unconstrained         | CanESM2      |
| 5   | Static fuels    | Unconstrained         | CSIRO        |
| 6   | Static fuels    | Unconstrained         | HadGEM2      |
| 7   | Climate-driven fuels | Constrained        | CanESM2      |
| 8   | Climate-driven fuels | Constrained      | CSIRO        |
| 9   | Climate-driven fuels | Constrained      | HadGEM2      |
| 10  | Climate-driven fuels | Unconstrained      | CanESM2      |
| 11  | Climate-driven fuels | Unconstrained      | CSIRO        |
| 12  | Climate-driven fuels | Unconstrained      | HadGEM2      |
| 13  | Fire-mediated fuels | Constrained        | CanESM2      |
| 14  | Fire-mediated fuels | Constrained        | CSIRO        |
| 15  | Fire-mediated fuels | Constrained        | HadGEM2      |
| 16  | Fire-mediated fuels | Unconstrained      | CanESM2      |
| 17  | Fire-mediated fuels | Unconstrained      | CSIRO        |
| 18  | Fire-mediated fuels | Unconstrained      | HadGEM2      |

Note: GCM, global climate model.

Burn-P3 input requirements, with the distribution across ecoregions stratified according to historical fire frequencies.

For fire duration, we estimated future spread-day distributions following the methods of Wang et al. (2014, 2017). We determined the FWI-based potential spread days in the baseline period and converted potential (i.e., weather-based) spread days to realized (i.e., actual) days of fire spread via a conversion factor obtained from simple linear regression (Wang et al. 2014). Future potential spread-day distributions were predicted from weather data and then used to estimate realized spread-day distributions using the conversion factor calculated for the baseline period, following Wang et al. (2017, see Appendix A). As part of the model calibration process, we truncated the baseline spread-day distribution so that the resulting fire-size distribution and number of fires best matched the observed distribution from historical data. Fires used for calibration were from the period 1980–2014 and were obtained from the Canadian National Fire Database (Canadian Forest Service 2015).

For the constrained fire-regime scenarios, we used future weather inputs, but held the number of escaped fires and spread-day distributions constant (Appendix S2: Table S1). To evaluate the relative contribution of the number of escaped fires vs. spread-day distributions, we ran an additional set of static-fuel scenarios holding each of these fixed at baseline conditions and manipulating the other factor (Appendix S2: Table S1).

Fire simulation—fuel parameters

Fuel inputs were directly derived from our vegetation model by converting vegetation types to fuel types as defined by the FBP System (Table 2), where each fuel type exhibits characteristic fire behavior depending on weather conditions and slope. For the 30-km buffer region, we used a mirrored representation of the input fuel grid. Fuel types can be broadly categorized as coniferous, deciduous, mixedwood, and grass. The coniferous fuel types are the most conducive to fire ignition and spread. The deciduous (D-1/2) and mixedwood (M-1/2) fuel types have a greater susceptibility to fire growth in the spring, before leaf flush, than later in the season. Fire spread potential in the grass (O-1) fuel type is also more flammable in the spring than in mid-summer because most of its biomass consists of dead material with very low moisture content during this season.

For the baseline period (1981–2010) and for 2011–2040, we used modeled fuels corresponding with historical climate normals from 1961 to 1990, which reflect the historical growing conditions for Alberta forests better than do current climate conditions (see Appendix S1 for vegetation modeling details). For future time periods, three sets of fuel scenarios were considered (Table 1). For static-fuel scenarios, historical fuels were held constant. For climate-driven scenarios, fuels were based on climate-projected potential vegetation for three GCMs. For fire-mediated scenarios, fuel inputs to 2041–2070 fire simulations were derived by updating the historical fuel layer according to 2011–2040 fire simulations (Fig. 2b). Given the stochastic nature of Burn-P3, we randomly selected one model iteration to reflect each year in the 30-yr period. Fire polygon outputs from 30 randomly selected years were combined to represent the area burned within the baseline period. For these burned areas, we updated the fuel layer based on future projected vegetation for 2011–2040 climate conditions. Elsewhere, baseline fuels were retained. Together
with other Burn-P3 inputs, these fuel modifications were the inputs for a single model run. This process was repeated 10 times to capture the stochastic variability across Burn-P3 iterations, and for vegetation projections from three different GCMs (listed in previous section), for a total of 30 runs x 300 iterations = 9000 individual Burn-P3 iterations for the 2041–2070 time period. The same process was repeated for inputs to the 2071–2100 fire simulations, with fuels for areas burned in the 2041–2070 runs updated according to projected 2041–2070 vegetation. Simulated fires from the end-of-century runs were used to update fuels according to projected 2071–2100 vegetation in areas burned. This was repeated for both sets of fire-regime scenarios—constrained and unconstrained—resulting in a total of 151 runs and 129,000 iterations (see Table 2. Ecosite and vegetation types considered.

| Code | Ecosite | Vegetation description | FBP | Cover type | Upland | Forest |
|------|---------|------------------------|-----|------------|--------|--------|
| 1    | PX      | Poor-Xeric Grassland   | O-1 | Grassland  | 1      | 0      |
| 2    | PX      | Poor-Xeric Jack Pine   | C-1 | Conifer    | 1      | 1      |
| 3    | PM      | Poor-Mesic Grassland   | O-1 | Grassland  | 1      | 0      |
| 4    | PM      | Poor-Mesic Pine        | C-3 | Conifer    | 1      | 1      |
| 5    | PM      | Poor-Mesic Black Spruce| C-2 | Conifer    | 1      | 1      |
| 6    | PG      | Poor-Hygric Black Spruce| C-2 | Conifer    | 0      | 1      |
| 7    | PD      | Poor-Hygric Black Spruce / Larch | C-1 | Conifer    | 0      | 1      |
| 8    | PD      | Poor-Hygric Shrub      | O-1 | Shrub      | 0      | 0      |
| 9    | MX      | Medium-Xeric Grassland | O-1 | Grassland  | 1      | 0      |
| 10   | MX      | Medium-Xeric Aspen Mix | M-1/2 | Mixedwood | 1      | 1      |
| 11   | MX      | Medium-Xeric Aspen     | C-1 | Conifer    | 1      | 1      |
| 12   | MX      | Medium-Xeric Spruce    | C-1 | Conifer    | 1      | 1      |
| 13   | MM      | Medium-Mesic Grassland | O-1 | Grassland  | 1      | 0      |
| 14   | MM      | Medium-Mesic Aspen     | D-1/2 | Deciduous | 1      | 1      |
| 15   | MM      | Medium-Mesic Boreal Aspen | M-1/2 | Mixedwood | 1      | 1      |
| 16   | MM      | Medium-Mesic Pine      | C-3 | Conifer    | 1      | 1      |
| 17   | MM      | Medium-Mesic Pine Mix  | C-3 | Conifer    | 1      | 1      |
| 18   | MM      | Medium-Mesic White Spruce | C-2 | Conifer    | 1      | 1      |
| 19   | MG      | Medium-Hygric Grassland| O-1 | Grassland  | 0      | 0      |
| 20   | MG      | Medium-Hygric Poplar Mix | M-1/2 | Deciduous | 0      | 1      |
| 21   | MG      | Medium-Hygric Spruce Mix | C-2 | Conifer    | 0      | 1      |
| 22   | MG      | Medium-Hygric Black Spruce Mix | C-2 | Conifer    | 0      | 1      |
| 25   | MD      | Medium-Hygric Shrub Fen | O-1 | Shrub      | 0      | 0      |
| 26   | MD      | Medium-Hygric Black Spruce Fen | O-1 | Conifer    | 0      | 1      |
| 27   | RM      | Rich-Mesic Grassland   | O-1 | Grassland  | 1      | 0      |
| 28   | RG      | Rich-Hygric Shrubland  | O-1 | Shrub      | 0      | 0      |
| 29   | RG      | Rich-Hygric Poplar     | D-1/2 | Deciduous | 0      | 1      |
| 30   | RG      | Rich-Hygric Lodgepole Pine | C-3 | Conifer    | 0      | 1      |
| 31   | RG      | Rich-Hygric Spruce     | C-2 | Conifer    | 0      | 1      |
| 32   | RD      | Rich-Hygric Grass Fen  | O-1 | Grassland  | 0      | 0      |
| 33   | RD      | Rich-Hygric Shrub Fen  | O-1 | Shrub      | 0      | 0      |
| 34   | RD      | Rich-Hygric Black Spruce | O-1 | Conifer    | 0      | 1      |
| 35   | SD      | Marsh                  | Nonfuel | Grassland | 0      | 0      |
| 39   | OW      | Open Water             | Nonfuel | None      | 0      | 0      |
| 41   | AG      | Agriculture            | Nonfuel | None      | 0      | 0      |
| 42   | UR      | Urban                  | Nonfuel | None      | 0      | 0      |
| 43   | NF      | Other Nonfuel          | Nonfuel | None      | 0      | 0      |

Notes: Codes with * were patched in post-hoc based on remotely sensed 2000 landcover (Pan et al. 2014). FBP, Canadian Forest Fire Behavior Prediction System fuel type for input to Burn-P3; O, grass fuel; D, deciduous fuel; M, boreal mixedwood fuel; C, conifer fuel.
breakdown in Appendix S2: Table S1). Our exploration of fire-regime parameters (relative influence of number of escaped fires vs. spread-day distributions) for static-fuel scenarios resulted in an additional 12 runs and 36,000 iterations (Appendix S2: Table S1).

Fire and forest change analysis

To assess changes in wildfire activity in the future relative to the baseline period (Objective 1), we evaluated projected changes in area burned at the 500-m pixel level by calculating burn probability: the proportion of individual Burn-P3 iterations for which a given pixel was burned within a given time period, and for a given scenario and GCM. For fire-mediated scenarios, we combined results from 300 iterations for each of 10 fuel iterations, resulting in a total of 3000 iterations. For static and climate-driven scenarios, we ran 3000 iterations for each time period (a number of iterations deemed sufficient to assess the spatial patterns and overall mean change in burn probability).

To assess the influence of different sources of variation on simulated burn probability (Objective 2), we sampled a 20-km regular grid of 900 points within the study area and used a full-factorial three-factor ANOVA to partition the variance among the effects of time period, fuel scenario, fire-regime scenario, GCM, and residual spatial variation (representing differences across fire zones) on change in burn probability.

Projected changes in upland vegetation composition for each scenario were assessed based on a summarization of generalized cover types—grassland, deciduous woodland, mixedwood forest, and coniferous forest (Table 2)—by time period and GCM (Objectives 3 and 4). For fire-mediated scenarios, results were averaged over 10 fuel iterations per time period and GCM.

RESULTS

Predicted vegetation

Our random forest model predicted 52% of Alberta to be composed of vegetated natural uplands (Appendix S1). Within our northern Alberta study area, 57% (247,895 km$^2$) was composed of vegetated natural uplands and 28% (123,112 km$^2$) was natural wetlands with an OOB classification error rate for the ecosite model of 20%. Of the natural uplands, 83.5% were predicted to fall within the medium-mesic moisture/nutrient category (11% OOB error rate). Predicted upland vegetation within the study area amounted to 26.5% conifer, 64.3% boreal mixedwood, 9.0% deciduous, and <0.1% grassland. The OOB error rate for 40 vegetation types was 19% (accuracy = 81%); aggregated to FBP system fuel type, the error rate was 11%. Additional model accuracy results and predictions are described in Appendix S1.

Fire simulation

Across all scenarios, simulated burn probability at a given pixel across 3000 iterations increased over time, especially for unconstrained fire regime scenarios (Fig. 3, Appendix S3: Fig. S1). With constrained fire regimes, static-fuel scenarios increased monotonically, whereas fire-mediated and climate-driven scenarios exhibited a mid-century decrease in the number of fires, increasing again by the end of the century (more rapidly for climate-driven fuel scenarios; Fig. 4).

The largest source of variation (proportion of total sum of squares) in burn probability was future time period (0.39), followed by fire regime (0.36), GCM (0.10), and the interaction between fire regime and time period (0.10; Table 3). Other sources of variation were small across all scenarios, but differences among fuel scenarios were apparent under constrained fire regimes (Fig. 4).

With respect to the two manipulated fire-regime components (number-of-escaped-fires and spread-day distributions), the number of escaped fires had a larger effect on the total area burned in the northernmost Great Slave Lake fire zone, while the number of spread days had a larger effect in the Southern Cordillera and Southern Prairies zones (Appendix S2: Table S3). The two different components were largely additive in terms of their influence, although the combined effects were greater than the sum their parts in the Southern Prairies zone, and slightly less in the other two zones.

Forest composition

Under climate-driven change scenarios, dramatic changes in vegetation types were projected for the next century (Appendix S3: Figs. S2, S3), with a nearly 250,000-km$^2$ increase in grassland area projected by the end of the century for all GCMs (Fig. 5). Climatic potential for upland
Vegetation projections from the fire-mediated scenarios were less extreme in comparison with the climate-driven scenarios, especially under constrained fire regimes (Figs. 6, 7). Under these scenarios, upland conifer and mixedwood forest were projected to decrease by <50% on average, whereas deciduous woodland was projected to increase rather than decrease, and grassland increases were less than half of the climate-mediated projections (Fig. 5). The unconstrained fire-regime scenario projections (Appendix S3: Fig. S4) were generally intermediate to the climate-driven and constrained fire-regime scenarios, resulting in a much smaller divergence from the climate-driven scenario (Fig. 5; Appendix S3: Fig. S5).
DISCUSSION

The speed at which ecosystems will respond to climate change within upcoming decades is a subject of great importance for climate-change adaptation and planning, yet still subject to great uncertainty. This is particularly true in the boreal forest of western North America, where an
already-dry climate is on the cusp of being unsuitable for widespread forest-dominated vegetation (Hogg and Hurdle 1995, Price et al. 2013, Gauthier et al. 2015) and the potential for large wildfires is almost certain to increase substantially (Flannigan et al. 2001, Balshi et al. 2009, Boulanger et al. 2014). We used a novel hybrid modeling approach based on topo-edaphically constrained projections of climate-driven vegetation change potential, coupled with weather- and fuel-based simulations of future wildland fire activity, to address this issue for upland forests in Alberta. Our simulations demonstrated how climate-driven changes in upland boreal forest vegetation could be delayed if disturbance is necessary to initiate vegetation transitions, as has been suggested previously (Schneider et al. 2009). Nevertheless, we found that if our conservative, constrained fire-regime projections are borne out, approximately a one-half reduction in the area of upland mixedwood and conifer forest (ranging from approximately one- to two-thirds), accompanied by an increase in grassland, should be anticipated by 2100, with net changes in deciduous forest depending on GCM. Under an unconstrained fire regime, extremely fire-conducive weather conditions could increase fire-mediated vegetation transitions to a level approaching the future climatic potential, resulting in a near-complete replacement of upland forest with grassland-dominated systems.

**Climate-driven changes in vegetation**

Projections from our topo-edaphically constrained empirical model suggested the potential for dramatic climate-driven changes in vegetation by the end of the 21st century. If disturbance were not required for vegetation transitions to occur, our models would indicate the potential for more than 95% of current upland conifer, mixedwood, and deciduous forests to be replaced by grassland, or novel grassland-dominated ecosystems that still retain trees and other forest elements. Substantial variation among GCMs was only evident in projections for deciduous forest. This is generally in line with other high-end (~1000 ppm CO₂ equivalent) projections for the region (Schneider 2013, Rooney et al. 2015), as well as pollen records suggesting that the current boreal region may have been grassland-dominated during the warmer (by 2°C) Hypsithermal period, 9000 to 6000 yr before present (Strong and Hills 2003), and contained substantially more graminoids during the Medieval Warm period ~500 yr ago (Larsen and MacDonald 1998). Our incorporation of topo-edaphic constraints resulted in particularly dramatic projected losses of upland forest, however. If wetlands do indeed persist in their current locations as we assumed, our simulations suggest a novel landscape juxtaposition of peatlands surrounded by deciduous forest and eventually grasslands over the next century, as discussed by Schneider et al. (2016). Indeed, peatland complexes, and to some extent, hydrologically connected uplands, may serve as hydrologic refuges under climate change (McLaughlin et al. 2017).

Based on this assumption that boreal wetland vegetation will remain static over the next century, upslope migration of boreal upland conifer and mixedwood forest will likely be constrained by large permafrost wetland complexes at higher elevations (Schneider et al. 2016) and additionally affected by near-term permafrost thaw dynamics (Baltzer et al. 2014). Paradoxically, we found that the regions with greatest persistence probabilities for conifer and mixedwood forests were southern latitude foothill regions with lower rates of wildfire. Thus, in the absence of large-scale rapid permafrost melt and drying of

| Variance component     | Proportion |
|------------------------|------------|
| Fuel                   | 0.002      |
| Fire regime            | 0.361      |
| Time period            | 0.387      |
| GCM                    | 0.096      |
| Fuel × Fire regime     | 0.000      |
| Fuel × Time period     | 0.001      |
| Fire regime × Time period | 0.095  |
| Fuel × GCM             | 0.001      |
| Fire regime × GCM      | 0.024      |
| Time period × GCM      | 0.027      |
| Fuel × Fire regime × Time period | 0.000 |
| Fuel × Fire regime × GCM | 0.000  |
| Fuel × Time period × GCM | 0.000   |
| Fire regime × Time period × GCM | 0.006 |
| Fuel × Fire regime × Time period × GCM | 0.006 |
| Spatial variation      | 0.360      |

*Note:* Values are proportions of explained deviance based on a Poisson generalized linear model with four time periods, three fuel scenarios, two fire-regime scenarios, and three global climate models (GCM).

Table 3. Proportional deviance contributions for projected burn probability, based on 900 regularly spaced sample points.
peatlands, upland conifer and mixedwood species in Alberta may be dependent on fire refugia—that is, “places that are disturbed less frequently or less severely by wildfire than the surrounding landscape matrix” (Krawchuk et al. 2016), based primarily on topography and isolation (e.g., lakeshores and islands, Nielsen et al. 2016). Due to the relatively coarse (500-m) resolution of inputs, our simulation did not lend itself to the identification of local fire refugia. For this, finer-scale simulations will be necessary.

Alternatively, and over the long term, forest-associated species may rely heavily on northward expansions in the Northwest Territories and Yukon Territory, but such vegetation transitions are also constrained by permafrost wetland dynamics (Lara et al. 2016), soil development limitations, and mountain geometry (Elsen and Tingley 2015). Thus, in contrast with the traditional paradigm of faster rates of climate-change response on the leading edge of species’ distributions where competition is reduced (Ordonez and Williams 2013), the situation may be reversed in the western boreal region. That is, northern and elevational shifts are constrained by wetlands that are likely to persist longer than upland habitats. Meanwhile, southern margins along the boreal-grassland ecotone are most vulnerable to changes in available moisture and associated tree mortality (Michaelian et al. 2010), exacerbated by anthropogenic landscape fragmentation, resulting in low “vegetation

Fig. 5. Projected change in upland vegetation cover type over time by global climate model (GCM) and scenario. clim = climate-driven, fire_c = fire-mediated, constrained fire regime, fire_uc = fire-mediated, unconstrained fire regime. CanES (CanESM2), CSIRO, and HadGE (HadGEM) represent different GCMs. Dashed line represents no change scenario. Forest area units are km².
Fig. 6. Predicted proportional change (blue = increasing, red = decreasing) in conifer, mixedwood, deciduous, and grassland vegetation types for current and three future time periods under a fire-mediated scenario based on a constrained fire regime (blue = increasing, red = decreasing). Proportions based on 10 fuel realizations × 3 global climate models. Baseline modeled vegetation shown in green in first column. Black = open water; gray = nonfuel; beige = wetland vegetation.
Fig. 7. Difference between climate-driven and fire-mediated proportional change (blue = larger increase, red = larger decrease) in conifer, mixedwood, deciduous, and grassland vegetation types for three future time periods under a fire-mediated scenario based on a constrained fire regime. Proportions based on 10 fuel realizations × 3 global climate models. Baseline modeled vegetation shown in green in first column. Black = open water; gray = nonfuel; beige = wetland vegetation.
intactness” (Watson et al. 2013). Thus, forest retreats along the southern edge could happen faster than advances along northern margins.

Fire-mediated vegetation projections

Imposing fire-mediated vegetation transitions yielded considerably slower rates of change compared to purely climate-driven projections. This was especially true under the constrained fire-regime scenarios, for which our simulations suggest a negative feedback process by which a warmer climate and more extensive near-term fires lead to an increase in deciduous forest (dominated by trembling aspen, *Populus tremuloides*) that in turn, due to its relatively low flammability, leads to a long-term reduction in area burned (Terrier et al. 2012). Under current warming trajectories, however, such states may be short-lived or depend on human intervention to be maintained. By the end of the century, as grasslands were projected to become more prevalent, our simulated burn probabilities increased accordingly. This temporary reduction in fire activity, in spite of increases in extreme fire weather conditions (Wang et al. 2015), reflects the important influence of vegetation composition (i.e., fuels) on wildfire occurrence, at least under modern-day fire regimes. It is consistent with Wang et al. (2016), who also found a projected decrease in burn probability over time in the western interior forests of British Columbia, Canada, where an increase in fire-conducive weather had a modest influence on fire likelihood compared to that of reduced fuel flammability.

With an unconstrained fire regime, however, the weather-driven increase in fires more than compensated for the reduction in fuel flammability, and fire activity increased dramatically regardless of fuel scenario, driving a rapid climatic transition to grass-dominated systems. Despite low biomass, grasses provide highly flammable fuels when dry (Thompson et al. 2017b). Within a forested landscape, increased grassland prevalence may facilitate wildfire ignition and spread (Gartner et al. 2012), in contrast to deciduous forest (Parisien et al. 2011b). Furthermore, the high prevalence of interspersed boreal wetlands can also facilitate fire spread, with rapid accumulation of highly flammable fuels (Thompson et al. 2017b). Thus, in the absence of fire suppression, eventual grass- and wetland-dominated landscapes could experience a higher frequency of fire than parts of the current boreal forest mosaic. Although we did not directly examine severity due to computational constraints, a grass-dominated fire regime would likely be comprised of lower-severity fires rather than high-severity crown fires, which is currently the norm (Whitman et al. 2018). Possible current analogs may be found in highly flammable grass-understory pine forests of the interior western United States and British Columbia (Arno 1980, Veblen et al. 2000), or potentially in the open, larch- and pine-dominated forests of Siberia (de Groot et al. 2013).

Sources of uncertainty

The wide range of possible future outcomes that we found highlights the high levels of uncertainty associated with future vegetation trajectories in the highly dynamic boreal forest region of Alberta. Overall, the largest source of variation in burn probability was fire regime (specifically, number and duration of fires), closely followed by directional changes in climate (i.e., increases in fire-conducive weather) over time and differences among fire zones. Global climate model-related uncertainty in burn probability was substantial, but swamped by directional changes in climate, consistent with various correlative model predictions for this region (Stralberg et al. 2015, Boulanger et al. 2016a, but see Boulanger et al., in press).

On the one hand, our constrained fire regime, which assumes that current fire characteristics remain constant, may be unrealistically conservative as extreme fire weather conditions increase (although reduced fuel flammability could eventually make it too extreme). On the other hand, our unconstrained fire-regime scenario is undoubtedly too extreme over the long term, given Burn-P3’s largely additive treatment of different fire-regime components (spread duration and number of fires). Although climatic controls on various components of some existing boreal (Boulanger et al. 2012) and western mountain (Whitman et al. 2015) fire regimes have been described, there is insufficient information about future fire regimes to inform more moderate scenarios (Williams and Abatzoglou 2016). This is largely due to the widespread disequilibrium between climate and fuels that is anticipated in upcoming decades, resulting in no-analog fire environments.
Our study has highlighted substantial knowledge gaps that should be addressed before we can claim to make accurate projections of future fire activity in the boreal forest. Perhaps the most important of these gaps is the lack of understanding of how long fires will burn in fire environments that have no current analogs (Wang et al. 2017). The duration of burning can have a dramatic effect on fire sizes due to the fact that wildfire growth follows a power function over time (Van Wagner 1969). In other words, small changes in duration can lead to disproportionally large changes in final fire size. While our estimates of future fire-regime parameters were strictly a function of weather, changing vegetation types and landscape configurations (Miller and Urban 2000, O’Donnell et al. 2011, Marchal et al. 2017) will undoubtedly play a role. Evaluating the effects of these factors on potential fire duration is thus a critical step in improving future projections of fire activity. For example, a regime consisting largely of grass-fueled surface fires could emerge in Alberta as forests become more open and grass-dominated. In that case, our spread-day (duration) projections would be overestimates, given the lower potential for combustion to persist in low-soil biomass grasslands than in forest stands. Conversely, our projections for the number of escaped fires could be underestimates, depending on the wetland portion of the fuel mosaic.

Caveats and limitations

Fire-regime parameters aside, our fire-mediated, constrained fire-regime scenarios for vegetation change were conservative in the sense that they do not account for continued future increases in drought, insect defoliation, or anthropogenic disturbances that can also result in reduced tree growth (Girardin et al. 2008, Hogg et al. 2017) and increased tree mortality (Allen et al. 2010, 2015, Zhang et al. 2015), further facilitating ecosystem transitions. The static treatment of wetland vegetation was also a conservative assumption that was deemed more plausible than the alternative option (climatic modeling and projection of wetland vegetation types). Although some lag in boreal peatland conversion appears inevitable (Schneider et al. 2016), there is high uncertainty about rates of change (Camill and Clark 2000). Scenarios of rapid drying, due to a lowering of the water table, are also possible (Turetsky et al. 2015, Thompson et al. 2017a) and would lead to more dramatic vegetation changes, but also greater potential for encroachment and persistence of upland forest types.

Climatically, however, our projections may have been too extreme with respect to climate-change projections in the Rocky Mountain Foothills and central highlands. Our vegetation model projects a large climate-driven conversion to grasslands within this region, as do other models specific to Alberta or western North America (Schneider et al. 2009, Mbogga et al. 2010). Yet future climate projections suggest that it will retain a moisture surplus in the future (Schneider et al. 2003); thus, an increase in temperature may not result in a conversion to the grassland systems found in warmer portions of Alberta. Other continental-scale analyses suggest that the foothills climate regime could more closely resemble that of eastern deciduous forests in terms of vegetation (Rehfeldt et al. 2012) and passerine birds (Stralberg et al. 2015), but with a high probability that future conditions will have no contemporary analog (Rehfeldt et al. 2012, Mahony et al. 2017).

Finally, our empirical vegetation model was relatively simplistic in that it did not consider stand age or successional stage. As such, some vegetation types, such as medium-mesic white spruce and aspen, may have been driven by site disturbance history and forest age rather than climate or topo-edaphic conditions, thereby reducing the precision of our models. Alberta has a clear north–south human disturbance gradient, which could have partially confounded the influence of climate on vegetation type, potentially increasing the magnitude of projected climate-driven vegetation change. However, the ABMI vegetation dataset upon which our model relies includes many off-grid sites that were selected specifically to reduce the correlation between latitude and anthropogenic disturbance. Thus, we concluded that any such bias would be minor.

Conclusion

While climate-change uncertainty is formidable, the ability to anticipate alternative future change timelines and trajectories will be invaluable to climate-change adaptation and conservation planning efforts. Model generality and
simplicity are prized in many circumstances. However, the magnitude and scope of anthropogenic climate change, along with the potential for nonanalog conditions and prolonged states of disequilibrium, suggests the need for novel, hybrid modeling approaches that address critical local dynamic processes while considering a spatial scale broad enough to capture the range of anticipated future variability (Gustafson 2013, Williams and Abatzoglou 2016). We have presented such an approach for the western boreal region of North America, where it is impossible to consider future climate change in isolation from wildfire, and where topo-edaphic legacies have major influences on biota that are not captured with equilibrium climate models. Our ecosite-based model, combined with fire-mediated vegetation transitions, provides a moderated range of estimates for future vegetation in boreal Alberta, but suggests ample opportunity for fire (and other disturbance) to facilitate rapid vegetation change, approaching its future climatic potential. To accommodate change while preserving boreal ecosystems and resources, managers should prepare for rapid transitions and protect higher-elevation refuges and large peatland complexes in which boreal forest systems are most likely to persist. Meanwhile, models should continue to be refined as the relationships between fire, climate, and fuels become better understood. Contingent upon proper parameterization, our model framework may also be applied to other circumboreal regions—and even other fire-prone biomes—in order to evaluate the generality of these findings.

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Supporting Information

Additional Supporting Information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/ecs2.2156/full