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Contributions of Ignitions, Fuels, and Weather to the Spatial Patterns of Burn Probability of a Boreal Landscape

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Abstract

The spatial pattern of fire observed across boreal landscapes is the outcome of complex interactions among components of the fire environment. We investigated how the naturally occurring patterns of ignitions, fuels, and weather generate spatial pattern of burn probability (BP) in a large and highly fire-prone boreal landscape of western Canada, Wood Buffalo National Park. This was achieved by producing a high-resolution map of BP using a fire simulation model that models the ignition and spread of individual fires for the current state of the study landscape (that is, the 'control'). Then, to extract the effect of the variability in ignitions, fuels, and weather on spatial BP patterns, we subtracted the control BP map to those produced by ''homogenizing'' a single environmental factor of interest (that is, the 'experimental treatments'). This yielded maps of spatial residuals that represent the spatial BP patterns for which the heterogeneity of each factor of interest is responsible. Residuals were analyzed within a structural equation modeling framework. The results showed unequal contributions of fuels (67.4%), weather (29.2%), and ignitions (3.4%) to spatial BP patterning. The large contribution of fuels reflects how substantial heterogeneity of land cover on this landscape strongly affects BP. Although weather has a chiefly temporal control on fire regimes, the variability in fire-conducive weather conditions exerted a surprisingly large influence on spatial BP patterns. The almost negligible effect of spatial ignition patterns was surprising but explainable in the context of this area's fire regime. Similar contributions of fuels, weather, and ignitions could be expected in other parts of the boreal forest that lack a strong anthropogenic imprint, but are likely to be altered in human-dominated fire regimes.

Key words: Fire; Boreal forest; Ignitions; Fuels; Weather; Burn probability; Simulation modeling; Structural equation modeling.

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Introduction

Large and infrequent fire disturbances characterize ecological dynamics over much of the boreal forest biome, whether in North America or Eurasia (Bonan and Shugart 1989). Although fire frequency, which is the calculated measure of fire likelihood for a given area and time period, varies greatly across large spatial scales (for example, $\geq 10^4$ km^2) (Soja and others 2004; Kasischke and Turetsky 2006), finer-scale heterogeneity in frequency within a landscape is often under-appreciated, in part because it is difficult to estimate from fire datasets covering a limited time span. In addition, the relative influence of ecological forces driving fine-scale variability are not well understood because of highly complex spatial and temporal interactions among fire ignitions, flammable vegetation (that is, fuels), and weather (Krawchuk and others 2009; Parisien and Moritz 2009). Evaluating the role of these environmental factors is critical to our understanding of ecological dynamics in fire-prone landscapes, given the interactive spatial effects between disturbance and vegetation (Green 1989; He and Mladenoff 1999) and a paradigm in forest management that aims to emulate them.

Fire regimes dominated by large stand-renewing events are controlled by a suite of environmental factors acting at multiple spatial scales (Turner and Romme 1994). In the North American boreal forest, fire-conducive weather conditions such as prolonged drought may affect a large part of the biome for weeks to months (Skinner and others 2002; Girardin and Sauchyn 2008). The intensity of hot, dry, and windy conditions, as well as the length of the rain-free interval, influences the size of fires, whereas the variability of weather—wind direction in particular—affects their shape (Anderson 2010). Weather, in conjunction with vegetation type, also affects the location and timing of ignitions (Krawchuk and others 2006). However, as only a fraction of ignitions lead to fires that burn large areas, high ignitions densities do not necessarily translate into increase area burned (≥200 ha) (Cumming 2005). Large, contiguous patches of highly flammable fuels promote fire growth, whereas slow-burning fuels and fuel breaks hinder fire progression (Hellberg and others 2004). Landscape features can cause ‘‘fire shadows,’’ which are distinct patterns in burn probability (hereafter, BP) downwind of the feature, as on the lee side of large lakes in boreal landscapes (Heinselman 1973). Together, these environmental factors generate the patterns of fire we observe on the landscape.

The episodic and extreme nature of boreal fires embodies the complexity and cross-scale interactions that lead to unpredictable patterns on the ground in any given year (Peters and others 2004; Moritz and others 2005). Because comprehensive spatially explicit fire datasets rarely span more than a century, it is impossible to obtain reliable estimates of relative fire likelihood at any point on a landscape. In fact, even if these estimates existed, they may not apply to the current state of the landscape due to non-stationary effects of climate and anthropogenic land use (Weir and others 2000). To address these limitations, models that simulate the ignition and spread of individual fires were created to produce high-resolution spatial estimates of the likelihood of fire (Miller and others 2008). The aim of these models, which are parameterized using detailed fire, weather, and landscape (fuels and topography) data, is to produce a fire likelihood estimate that depicts the probability each pixel on the landscape will burn for the current state of the landscape. These models do not simulate forest succession; rather, their strength lies in their ability to accurately depict fire likelihood for a snapshot in time (that is, the current landscape).

The correspondence between modeled BP and environmental covariates related to ignitions, fuels, and weather can be evaluated in a statistical framework to gain an understanding of what factors are most influential on BP patterns (Yang and others 2008; Beverly and others 2009). However, partitioning the specific contribution of each factor to BP is difficult because the factors are usually correlated (Parks and others, in press). Alternatively, the effect of environmental factors on BP can be estimated by manipulating individual model inputs and measuring the variation in outputs (Cary and others 2006). This approach to untangle the effect of various factors on BP is attractive because strong non-linear interactions among environmental factors can generate fire patterns that are highly complex yet can also produce persistent spatial organization (Peterson 2002). For example, Parisien and others (2010) showed that combining simple inputs in a fire simulation model of an artificial landscape yielded unanticipated, but explainable, patterns in BP.

The goal of this study was to determine how heterogeneity in ignitions, fuels, and weather shape the spatially explicit patterns of fire likelihood of a large boreal landscape where fire potential has enormous spatial variability (Larsen 1997). The study area, a large national park in western Canada, offers an excellent opportunity to examine fine-scale variability in fire patterns because, in addition to being one of the most fire-active areas of the North American boreal forest, it has been largely unaffected by fire suppression and changes in human land use. The factors affecting BP were isolated by using a fire simulation model to create a BP map, then systematically manipulating the inputs that represent key environmental factors controlling fire. We compared BP patterns produced using the full set of variables with those produced when a single factor of interest was homogenized. The factors included spatial ignition patterns, types and arrangement of flammable vegetation (fuels), and daily fire weather conditions. A structural equation modeling (SEM) framework was then used to assess relevant interactions and, ultimately, measure the relative contribution of ignitions, fuels, and weather to spatial BP.

Study Area

Wood Buffalo National Park (WBNP) (59.4°N, 113.0°W) is Canada's largest national park ($\sim$44,800 km^2) and a UNESCO world heritage site. The park is a northern boreal landscape dominated ($\sim$70%) by interconnected wetlands (Figure 1; Plate 1), and is remarkably flat, with the exception of two hilly areas: the Birch Mountains and Caribou Mountains. The entire area was glaciated during the Late Pleistocene, and most of WBNP is now underlain by discontinuous permafrost. The climate is cold continental, characterized by long, cold winters (mean January temperature −21.6°C) and short, warm summers (mean July temperature 16.6°C); the average annual precipitation is about 360 mm (McKenney and others 2007).

The land cover of WBNP is representative of the western Canadian boreal forest. The park is a complex mosaic of wetlands (fens and bogs), upland forest, and open water (rivers and lakes). Non-vegetated areas (mainly open water) cover 11.7% of the park. The dominant tree species on well-drained sites include jack pine (*Pinus banksiana*), white spruce (*Picea glauca*), trembling aspen (*Populus tremuloides*), and balsam poplar (*Populus balsamifera*). Black spruce (*Picea mariana*) and tamarack (*Larix laricina*) are common in treed bogs and fens, respectively. Wetland areas, most of which are dominated by graminoids, *Sphagnum* spp. mosses, or shrubs, have varying degrees of tree cover. Conifer-dominated areas in part of the boreal forest were reported to be 3–10 times more prone to burning than deciduous stands (Cumming 2001). However, this varies seasonally: low stand moisture in deciduous forests before ''green-up'' (that is, leaf flush) is more conducive to fire spread than after leaf flush. Fire managers often regard large deciduous stands as natural fuel breaks, especially after leaf flush in the spring. Similarly, the park's extensive sedge meadows are more prone to fire spread in the spring, when most of their aboveground biomass is dead or cured.

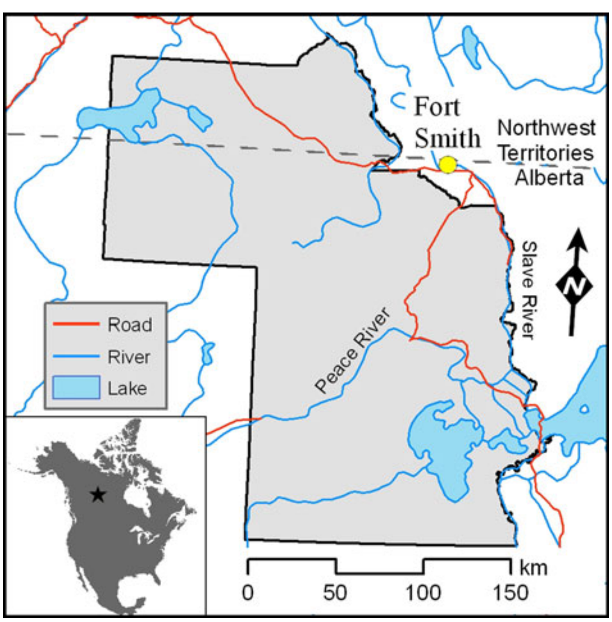

Figure 1. Map of Wood Buffalo National Park (marked in *gray*) and its location in North America (*inset*).

Despite the predominance of wet substrate, the climate of the area is sub-arid. Frequent intense droughts, in conjunction with a high incidence of lightning, offer excellent conditions for ignition and spread of fire. The fire season generally runs from May through mid-September, peaking between June and August (Kochtubajda and others 2006). Thunderstorms are frequent and intense in the summer; lightning IGNITIONS are responsible for about 95% of large fires (≥200 ha) and around 97% of the area burned. Fires, which are highly episodic, can achieve very large sizes of more than 100,000 ha and are lethal and stand-replacing for most of the area burned, though their perimeter usually comprises many unburned islands of vegetation. Fire suppression in the study area occurs only when human infrastructure inside or beyond the park is threatened. As a result, WBNP has a fire regime that is largely unaltered by recent human activity. During the period 1950–2007, the fire cycle for the entire area (excluding open water) was calculated to be about 62 years.

Methods

We used the Burn-P3 fire simulation model (Parisien and others 2005) to estimate BP in WBNP and determine how variability in ignitions, fuels, and weather influence spatial patterns of BP. The effect of topography was also tested, but was subsequently dropped from analysis because of its lack of

Plate 1. (*Left*) A vegetated landscape of Wood Buffalo National Park, Canada, illustrating the complex patch mosaic of lakes, wetlands, and forest stands (coniferous, deciduous, and mixed) originating from stand-renewing fires. (*Right*) A recent burn shows complex shape and fire severity patterns. Boreal fires burn as crown fires and are generally lethal to trees; therefore, the burn, like the underlying landscape, is highly patchy, with many unburned or lightly burned areas. Photo credits: Marc-André Parisien (*left*) and Simon Hunt (*right*).

influence on BP in the study area. The first step was to produce a ''control'' BP map that used the comprehensive set of inputs parameterized with real data from the study area for fuels, topography, ignition patterns, and daily weather conditions under which fires burn. In addition, BP maps termed ''experimental treatments'' were produced where a single input characterizing an environmental control on BP was either randomized or homogenized. The BP map of each experimental treatment was then subtracted (pixel-wise) from the control BP map. The resulting spatial pattern of BP residuals effectively depicts the spatial influence of each treatment while taking into account the effect of all the other inputs with which it interacts. Finally, using the BP residuals, the relative influence of each environmental factor on BP patterns was tested using SEMs (Grace 2006).

The two sections below provide a brief overview of the fire simulation modeling performed in this study. Refer to Appendix A in Supplementary Material for a more detailed description of the Burn-P3 model. Appendix B in Supplementary Material provides a comprehensive description of the state variables and modeling parameters, and how these were derived from the raw data.

Simulation Model: Modeling Processes

The Burn-P3 model estimates the BP of each point on a landscape by simulating the ignition and spread of individual wildfires. One time step represents 1 year and the simulation of this same year is repeated a very large number of times (hereafter, 'iterations'). For instance, in this study 10,000 iterations (~65,000 simulated fires) were used to generate BP estimates for most simulation runs (see Appendix A in Supplementary Material). Individual fires are modeled using a daily time step. The spatial extent of the study was that of Wood Buffalo National Park, whereas the spatial resolution (that is, pixel size) was 200 m. A 50-km buffer surrounding the park was added to avoid edge effect by letting fires ignite outside the park and burn within its boundary. This buffer area was ultimately removed.

In Burn-P3, the vegetation is static and does not change from year-to-year; however, the model attempts to capture all of the possible situations in which fires might burn. It does so by probabilistically drawing from the model inputs. In each iteration, the number of fires is determined from a probability distribution. Then, each fire is assigned a season in which it burns by also drawing from a probability distribution. The next step consists of determining the ignition location of each fire, which is drawn from a spatial grid of ignition likelihood. Once these inputs are determined for a given iteration, weather information must be attached to each fire.

To adequately characterize the effect of weather on fire spread, Burn-P3 models weather variability in two ways. First, the length of the burning period (analogous to the ''rain-free'' period) is sampled from a probability distribution of number of spread-event days (see below). Second, fire weather conditions are attached to each spread-event day by sampling from an extensive list of daily fire weather observations that is stratified by season and by weather zone, which consist of three zones of distinct fire weather in the study area. Fire spread is then simulated using the Prometheus fire growth model (Tymstra and others 2010) and the areas burned in each iteration are recorded in a raster grid. The process is repeated for each iteration, and the grids of all iterations are ultimately compiled into a cumulative grid of area burned. Burn probability represents the proportion of times a given pixel burned relative to the total number of iterations (mathematically defined in Appendix A (Supplementary Material)).

All Burn-P3 inputs used in this study were based on observed data characterizing vegetation (that is, fuels), topography, season, spatial patterns of ignitions, and weather. Because fires ignited at different locations and burned under varying daily fire weather conditions (affecting their sizes and shapes), the simulated spread of each fire in Burn-P3 burned according to a unique set of conditions that yielded a unique fire perimeter. In this study, we have attempted to incorporate as much observed natural variability in the fire regimes of Wood Buffalo National Park as possible. Furthermore, the inter-annual variability in fire activity was captured among iterations, whereby the fire activity in some years was low (or nil), some years moderate, and some extreme. Modeling fires in this manner is computationally intensive, but incorporating the temporal and spatial variability in which fires ignite and burn leads to more realistic fire patterns (Lertzman and others 1998).

Simulation Model: State Variables and Modeling Parameters

All inputs for this study were based on relatively recent historical data (that is, the last few decades) and thus represented the modern conditions under which fires ignite and burn in the study area. Slight mismatches occur among the temporal span of datasets (for example, fire occurrence data and daily weather observations). However, this is not a limitation within the modeling framework because we are not attempting to re-create specific past fires, but rather ensuring that we generate the full range of fire patterns that may occur in the current environment.

Historical fire atlas data were used to build numerous key inputs to Burn-P3 (see Appendix B). A comprehensive database was compiled of fires of a predetermined minimum size of 200 ha, from 1950 to 2007. Only large fires were modeled to limit computation time; these fires are responsible for virtually all of the area burned (~97%) in the study area (Stocks and others 2002). These data were used to determine the variability in the number of fires per year. The fire data were also used to partition the proportion of fires burning in each season (listed below). Another use of these data was to determine the spatial patterns of ignitions across the study area—that is, how likely is a fire to ignite in each pixel. Because the ''ignitibility'' of any given point in the study area is chiefly dependent on fuel type, the fire data were used to produce a density grid of probability of ignition.

The weather data used in Burn-P3 comprised daily noon weather station observations of temperature, relative humidity, wind speed, wind direction, and 24-h rainfall, as well as the corresponding Canadian Forest Fire Weather Index System (Van Wagner 1987) fuel moisture codes and fire behavior indexes (hereafter 'fire weather') for 13 weather stations from 1957 to 2006. The main use of the daily fire weather data in Burn-P3 was to model the daily fire spread of individual fires. The large number of years and weather stations ensures that any possible set of conditions under which fires grow are incorporated into the modeling. In addition, these data, in conjunction with the fire data and the documented plant phenology of the area, were used to define three seasons: spring, early summer, and late summer. Similarly, weather data were used to delimit three geographic zones which experience similar weather: the most prevalent zone comprising the flat area of the park, and two hilly areas (Caribou and Birch Mountains).

Although boreal fires may be ''active'' for weeks or even months, they typically achieve most of their spread during one or a few days (hereafter 'spread-event days') of high to extreme fire weather conditions (Podur and Wotton 2011). In this study, only spread-event days and the weather with which these are associated were used to simulate fire (that is, weather promoting substantial fire growth). We built a frequency distribution of spread-event days per fire by compiling a database of fire progression perimeters of fires at least 200 ha from daily fire detection data from MODIS (USDA Forest Service 2008) and identifying the days of high spread. To model fire spread, Burn-P3 used daily fire weather from each spread-event day of each fire. All days that were not associated with fire-conducive conditions were removed from the daily fire weather database (compare Parisien and others 2005), without, however, altering the temporal sequence of spread-event days.

Fuels were represented as FBP System fuel types (Forestry Canada Fire Danger Group 1992), whereby each fuel type exhibits different fire behavior depending upon weather conditions and slope. Fuel types can be broadly categorized as coniferous, deciduous, mixedwood, grasses, and slash. The deciduous and mixedwood fuel types have a greater propensity for fire growth in the spring, prior to leaf flush. The grass fuel type is also more flammable in the spring, when most of its standing biomass is dead; conversely, its spread potential is greatly reduced in the late summer when the grass has fully re-grown, whereas the early summer represents a transition in terms of flammability. The seasonal variations within these fuel types were captured in the modeling. Topography was obtained through a standard digital elevation model.

Experimental Treatments

We used six experimental treatments to evaluate the relative importance to BP patterns of the natural variability in ignitions, fuels, topography, and weather (Figure 2). The ''ignition pattern'' treatment was used to examine the effect of spatial patterns of ignitions on BP by completely homogenizing ignition probability.

The influence of fuels was examined via two treatments: the ''fuels:configuration'' and ''fuels: fuel breaks'' treatments. In the fuels:configuration treatment, we removed the patch structure (that is, clustering) of fuel types by randomizing the pixels of the fuel data in the same proportion as the original fuels grid while retaining existing non-fuel areas. In the fuels:fuel breaks treatment, we removed fuel breaks by randomly filling in the non-fuel areas with fuels while leaving areas of existing fuel cover unaltered. To fill in the non-fuel areas, we assigned a valid fuel type to non-fuel pixels according to the proportions in the original fuel grid. For both fuels treatments, we estimated BP using several randomized fuel grids and averaged the results to avoid any effect of a single spatial arrangement. We determined that five fuel grids were needed to reduce the variability among output BP grids to less than 5%.

Topographic variability was removed in the ''topography'' treatment by making the area flat (slope = 0). This treatment did not consider the indirect effects of topography on vegetation, ignition, and weather patterns, but rather evaluated the direct effect of topography on the shape and size of fire spread.

The effect of weather on BP was examined via two treatments. In the ''weather:duration'' treatment, instead of using a frequency distribution of spread-event days, each fire was allowed to burn for exactly 4 days (the mean value of the distribution). The influence of varying daily weather conditions was examined in the ''weather:daily conditions'' treatment. To homogenize weather conditions for this treatment, the average daily fire-conducive conditions were used: wind speed = 18 km/h, temperature = 22°C, relative humidity = 30%, and precipitation = 0 mm. We only homogenized the conditions conducive to fire spread, as opposed to homogenizing all days of the fire season, because fires simply do not grow under average weather conditions in the North American boreal forest. To homogenize wind direction in this treatment, we applied an equal probability of wind direction from the eight major cardinal points instead of using a single wind direction. Wind direction interacts with the spatial arrangement of fuels (Parisien and others 2010) and using a single wind direction would have produced BP patterns that could not be generalized to the other directions.

Statistical Analysis

The BP map for each experimental treatment was subtracted from the control BP map, which resulted in six maps of BP residuals. In referring to the experimental treatments as explanatory variables in the statistical analysis, we used the prefix ''rBP.'' For example, the BP for the ignition pattern treatment was subtracted from the control BP, and the residuals between these two BP maps consisted of the explanatory variable ''rBP-ignition pattern.'' The patterns of BP residuals effectively depicted the spatial influence of a treatment while taking into account the effect of all the other inputs with which it interacts. These residuals were used as explanatory variables in a statistical framework that was in turn used to evaluate the relative importance of ignitions, fuels, and weather variability on the control BP (response variable) (Figure 3). Initial explorations allowed us to discard topography from the statistical framework: given that almost all of the study area is flat, this treatment exerted a negligible effect on BP relative to the control.

A statistical technique in which multiple and indirect interactions could be specified was required, given the complex relations among the environmental factors affecting BP. To this end, the data were incorporated into a structural equation model (SEM), a statistical modeling framework for evaluating multiple relations and complex systems. The technique is largely confirmatory and is designed to test specific hypotheses on the basis of in-

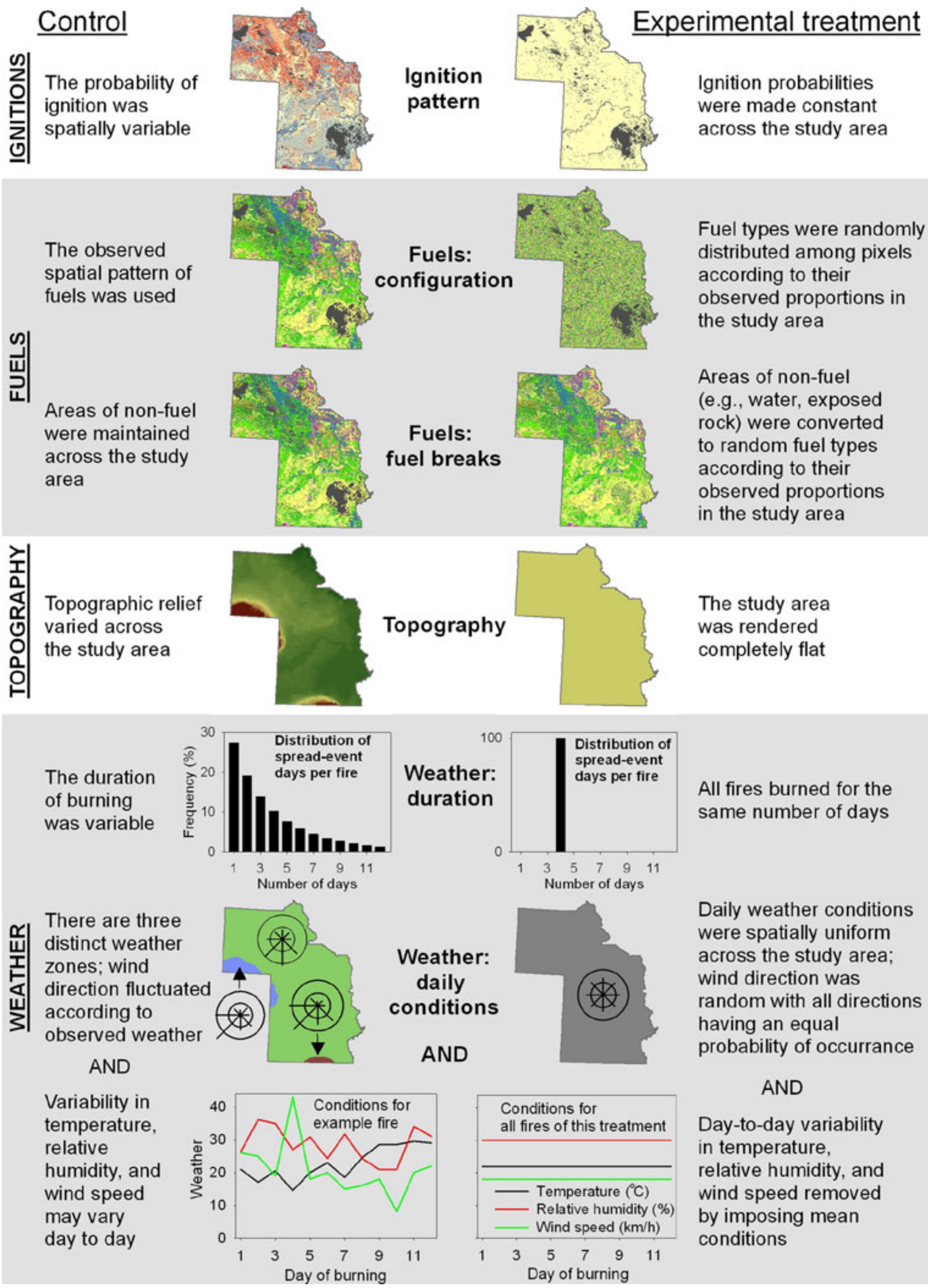

Figure 2. Visualization of the changes made to the fire simulation modeling inputs to evaluate the effect of ignitions, fuels, topography, and weather on the spatial patterns of burn probability (BP). The inputs on the left are those devised for the ''control'' BP map, whereas the six ''experimental treatments'' are described on the right. A full description of the inputs is available in Appendix B in Supplementary Material.

depth knowledge and expectations of a system (Grace 2006). There is, however, some flexibility in the framework, which allows for cautious exploration. A great strength of the approach is its ability to specify direct and indirect interactions among variables that cannot be tested using modeling techniques based on linear combinations of parameters. The SEM modeling was carried out with Mplus software (Muthén and Muthén 2007) using the maximum likelihood method of parameter estimation.

A conceptual model of BP as a function of the experimental treatments (rBP) was put forward in which the effects of treatments were partitioned into the three main environmental factors: ignitions, fuels, and weather (Figure 3). The effects of the fuels:configuration and fuels:fuel breaks treatments made up the composite variable FUELS, weather:duration and weather:daily conditions treatments defined the WEATHER variable, and the ignition pattern treatment described IGNITIONS. Because ignition probability was a function of fuel

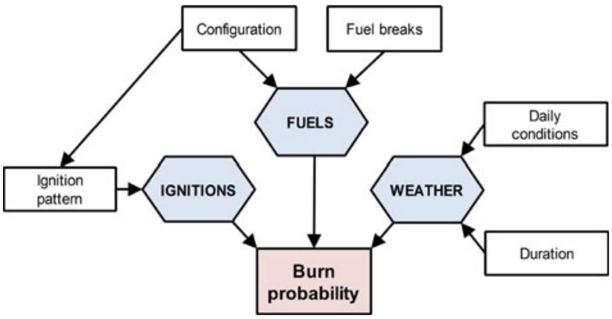

Figure 3. Proposed structural equation model of burn probability (BP) as a function of the five experimental treatments retained for analysis. The treatments (*square boxes*) consist of the residuals between a BP map produced with a single factor of interest homogenized or randomized and the ''control'' BP map, which was built using all of the original inputs. The values of the five experimental treatments were assigned to composite variables (*hexagonal boxes*), which were in turn used to predict BP.

type, we expected the patterns in rBP-fuel:configuration to affect the rBP-ignition pattern variable. Furthermore, the rBP-ignition pattern variable exhibited a non-linear relation with the ignition pattern variable, which was best described by adding a quadratic term. Non-linear relations require special treatment in SEM, but the use of composite variables (see below) greatly simplifies the incorporation of non-linear responses. Each path in this conceptual model was evaluated using SEM.

The values for the response and predictor variables were highly spatially autocorrelated, which was a concern because samples that are not independent of each other lead to artificially inflated statistical significance. To address this concern, we built our SEM models with sub-samples of the data. To identify a suitable number of observations, we built a generalized additive model (GAM) of control BP (response variable) as a function of the six treatments (rBP) and then evaluated the spatial structure of the model residuals. We used the range distance of the semivariogram of GAM residuals to define the minimum sampling distance between points (~15 km) to obtain the suitable sub-sample size (n = 168 points). This number of points was randomly sampled within the study area. Although no longer autocorrelated, working with so few sample points sacrificed a substantial amount of information. To counter this, we selected 100 different sub-samples and averaged their outputs in the modeling described below. For the study area, such a large number of replicate sub-samples were necessary to adequately capture the relationship among the response and predictor variables.

Conceptually, the components of composite variables in SEM are considered to represent the variables perfectly (Grace and Bollen 2008). As such, these variables are assigned a variance of zero to enable model computation. Furthermore, it is standard practice when using composites to assign a magnitude of 1 to one of the observed components of the composite to allow the others to be scaled. This assignment does not preclude the estimation of model coefficients, but it does prevent significance testing. The strength of the relation is presented in terms of standardized model coefficients (that is, correlations), whereas the significance of the path with respect to the entire model structure is computed from the standardized coefficient using a t test (compare Grace and Bollen 2008). Model fit was assessed by comparing the observed covariance matrix to the one implied by the proposed model using a chi-square test, where values of P greater than 0.05 indicate concordance (that is, the proposed model provides a good fit to the data). The coefficient of determination (R^2) of the dependent variable (BP) was also computed.

The relative importance of ignitions, fuels, and weather was further assessed by omitting a single composite variable and its components from the SEM and evaluating the relative reduction in R^2. In addition, because SEM is fairly new to the ecosystem sciences, we ran a parallel analysis using a GAM, where BP was explained by the residuals of the six experimental treatments. No interactions between variables were specified because of the difficulty of specifying interactions analogous to those in the SEM.

Results

The control BP map used as the baseline for the analysis showed spatially clustered BP patterns (Figure 4). Visual inspection of the residual BP maps for each experimental treatment revealed their highly divergent effects on BP. The rBP-ignition pattern variable appeared to correspond spatially to the ignition density grid (Figure 2), which was in turn similar to the patterns of dominant fuel types. The rBP-fuels:configuration patterns tended to track major fuel groups in most areas, whereas the rBP-fuels:fuel breaks variable consisted of highly localized effects that always translated into an increase in BP. The rBP-weather:duration showed extensive decreases in BP in all areas except those with the least flammable fuels (deciduous). In contrast, the rBP-weather:daily conditions generally translated into an increase in BP. The

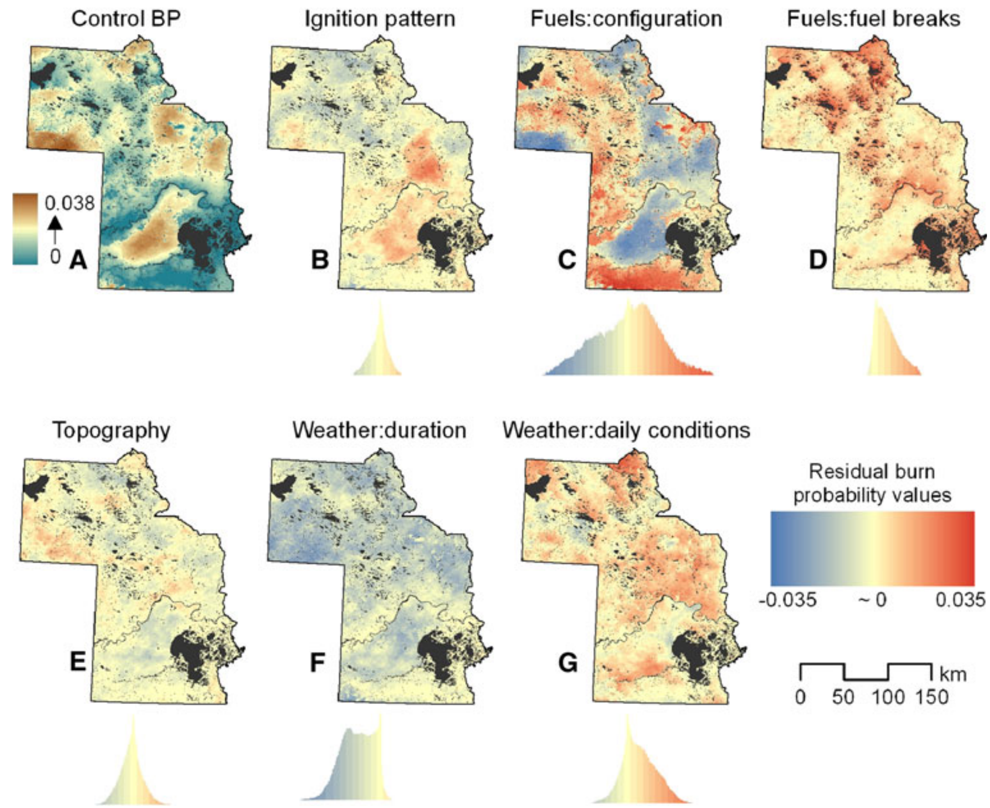

Figure 4. Maps showing the estimated burn probability (BP) for the control (**A**) and spatial residuals for the six experimental treatments (**B–G**). Note that the *color* legends for the control and residuals maps are different. The residuals maps were created by subtracting the BP map of each treatment from that of the control. In parts **B–G**, areas shown in *red* represent areas where the BP of the experimental treatment was greater than the control BP, whereas *blue* indicates that BP was lower in the treatment. A corresponding plot of frequency distribution accompanies each residual map; the plots were standardized according to their *y*-axis range to facilitate visualization.

topography treatment was responsible for only faint patterns, most of which appeared to be noise.

The SEM analysis showed that the relationships in our data were well described by the proposed model (Figure 3), but some adjustments were necessary. The composite variables of FUELS, WEATHER, and IGNITIONS, in that order, were the best predictors of BP. The rBP-fuels:configuration and, to a lesser extent, rBP-fuels:fuel breaks were also significant contributors to the overall model (both significant in 100% of sub-samples) (Figure 5). The WEATHER variable was mainly defined by rBP-weather:duration, but the rBP-weather:daily conditions had a moderate influence (significant in 88% of sub-sets). The IGNITIONS variable contained both the linear and quadratic terms of rBP-ignition pattern, neither of which were strong predictors of BP. Furthermore, although a path was not specified from WEATHER to rBP-ignition pattern^2 (squared) in the initial model, one was added after an examination of model diagnostics (that is, residuals and SEM modifying indices). Despite its very low correlation and despite it being generally insignificant, the model was not significant without this new path. We determined that the addition of this path was justified because it was conceptually sound (see ''Discussion'' section). The final R^2 of the model with this additional path was 0.84, and this structure was significant in about 85% of sub-sets ($P > 0.05$; df = 2; $\chi^2 = 5.99$).

Evaluating the relative importance of the natural variability in ignitions, fuels, and weather by omitting composite variables from the SEMs produced slightly different estimates of the importance of variables than those generated by the direct paths from the composite variables to BP. The reduction in R^2 of the models indicated contributions of 67.4% for fuels, 29.2% for weather, and 3.4% for ignitions. The discrepancies between the path coefficients of the composite variables and the reduction in R^2 suggest that the added path from WEATHER to rBP-ignition pattern slightly increased the relative importance of both these

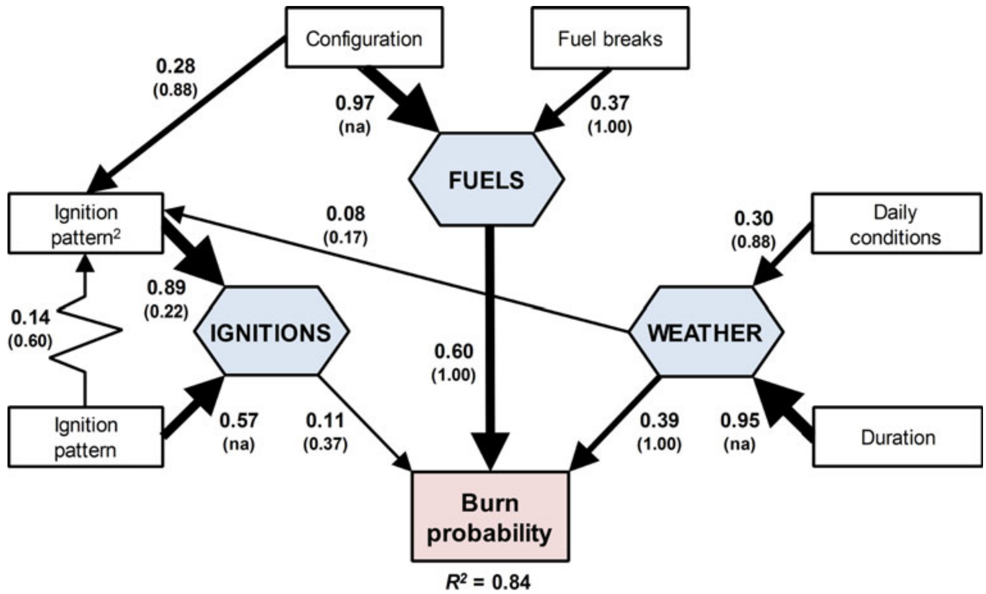

Figure 5. Results of the structural equation model of burn probability (BP) as a function of the five experimental treatments retained for analysis. *Square and hexagonal boxes* represent the observed and composite variables, respectively. The model was built using 100 random sub-sets of data (n = 168) for which the results were averaged. Standardized (that is, correlation) coefficients are presented for each path and the thickness of the *lines* represent the size of the correlation. The coefficient signs have been removed because they are not meaningful in this context. The proportion of sub-sets for which the path was significant at the $P \leq 0.05$ level, as calculated from the unstandardized coefficients, is shown in parentheses; paths with the notation ''na'' (not applicable) were those to which a value of 1 was assigned for scaling of the composite variable. The *crooked line* indicates the correlation between the linear and quadratic term of the 'ignition pattern' variables. This proposed model structure was significant ($P > 0.05$) for approximately 85% of the random sub-sets (df = 2; χ^2 = 5.99).

composite variables. The relative contributions of composite variables calculated from a GAM were generally similar to those of SEM with omission: 66.4% for fuels, 33.2% for weather, and 0.4% for ignitions. When included in the GAM, the topography treatment contributed nothing (0.0%) to reducing model deviance, providing further support to our decision to omit it from the SEM.

Discussion

The Relative Importance of Fire Controls on Shaping Spatial Fire Likelihood

In some ways, WBNP appears ecologically simple: there are only a few dominant vegetation types, the terrain is mostly flat, and there is minimal anthropogenic influence. However, the disturbance dynamics that regulate many landscape-level processes are extremely variable in time and space. That the study area is largely unaffected by human land use and virtually free of fire suppression—attributes that are increasingly rare in the North American boreal forest (Stocks and others 2002)—allowed the detection of the rather subtle effects of some environmental factors. For example, weather (duration and daily conditions), whose temporal variability is much greater than its spatial heterogeneity in the study area, is not generally considered a major control of spatial patterns of fire likelihood in flat boreal landscapes. However, removing temporal variability had a pronounced effect on spatial patterns of BP. In contrast, spatial ignition patterns appeared to have a surprisingly minor influence on BP in the study area, especially relative to their effect in the ''commercial'' boreal forest, where ignitions are more often human-caused and spatially clustered (Wang and Anderson 2010). As such, the results of this study outline the importance of studying unmanaged landscape disturbance dynamics, because ''natural'' controls on fire regimes may be muted in human-dominated boreal fire regimes.

The question of the relative influence of vegetation and weather on fire activity in the North American boreal forest has been the object of some discussion over the years. Bessie and Johnson (1995) found little evidence for the effect of the landscape mosaic on annual area burned in a Rocky Mountain landscape that was similar to many boreal landscapes. By contrast, in a much larger area in central Alberta, Cumming (2001) found a significant ''preference'' of fire for certain forest types, and concluded that both weather and vegetation controlled fire patterns. However, no significant effect of land-cover composition on area was observed in a similar study in Ontario (Podur and Martell 2009). Although weather was dominant, a dual influence of vegetation and weather was reported in a study of daily fire behavior patterns in a boreal landscape of eastern Canada (Hély and others 2001), as was the case in a simulation study that manipulated the landscape mosaic in a manner similar to our study (Hély and others 2010). Not surprisingly, these results show fire-environment relationships that vary as a function of location in the boreal biome, spatial and temporal scales of observation, and metrics of fire or environmental covariates used.

We found that the spatial randomization of fuels led to a dramatic re-distribution of BP. Whereas the relative proportion of flammable fuel influences a landscape's overall potential for fire spread (Finney 2003), the influence of the spatial arrangement of flammable fuels is less well understood. Our results suggest that the response of fire spread to different arrangements of fuels is complicated. For example, areas with large contiguous stands of a ''fast'' fuel type (coniferous forest or grassland) have proportionally higher fire likelihood than those with numerous small stands interspersed among other ''slower'' fuel types, as documented by Ryu and others (2007). From a management standpoint, it is thus possible to determine the extent of fuel modification necessary to substantially increase marginal benefits of fuel treatments in some landscapes (Ager and others 2010).

Accordingly, we also observed a threshold relation in BP as a function of the size of natural fuel breaks: when we removed fuel breaks from the landscape, there were large increases in BP around very large lakes or connected systems of lakes, but only negligible increases around small, isolated patches of non-fuel materials. Ecologically significant old-growth stands are expected to be more common in these ''fire shadows,'' which may serve as refugia for certain species. In fact, within the study area, Larsen (1997) demonstrated that mean fire intervals were on average almost twice as long in areas located 0–3 km from water bodies (81 years) than in areas more than 6 km distant (49 years). In the eastern boreal forest, an even more dramatic discrepancy was reported by Cyr and others (2005), who estimated mean fire intervals at 36 and 682 years, respectively, within and beyond a 2-km distance of potential firebreaks. The distance to which a BP shadow extends is a function of the size of both fires and fuel breaks. However, the shadow effect is also a function of variability in wind direction (Parisien and others 2010), with dominant and prevailing wind directions creating stronger shadows. It is conceivable that highly variable wind direction, in conjunction with large fires, as in WBNP, results in fire shadows that may be spatially extensive but weak with respect to any reduction in BP.

Of the three main types of factors affecting spatial BP patterns in WBNP (ignitions, fuels, and weather), ignition pattern contributed the least, even though it represented a strictly spatial control. This may be partly due to an oversimplification of inputs to the model. For instance, spatial ignition patterns may fluctuate according to the seasonal curing and greening cycle of vegetation. We did not incorporate this in our simulations because we did not find evidence of this in the study area. However, even if we had included seasonal variation, other results suggest that the effect of ignitions would still likely have been relatively minor (Barclay and others 2006). Despite the different fuel-based ignition probabilities we modeled, ignitions that become large fires (for example, >200 ha) do not appear to be strongly clustered in space in WBNP (Wang and Anderson 2010). The spatial pattern of ignitions may be a greater determinant of BP in other areas of the boreal forest that experience numerous human-caused ignitions, which are typically strongly clustered. However, it remains to be assessed whether increased human-caused ignitions translate into increased number of large fires, given that access by humans also enhances fire-suppression capabilities (Calef and others 2008).

A more subtle effect of the spatial ignition pattern on BP is modulated by the interaction between fire size and ignition locations. The effect of non-random ignition locations on spatial BP patterns is lessened in landscapes where fires achieve most of their spread under extreme fire weather conditions and concomitantly grow very large (Bar Massada and others 2011). In WBNP, where very large fires (for example, $>10{,}000$ ha) are responsible for the vast majority of the total area burned ($\sim$90%), we would expect a diluted influence from spatial ignition patterns. In contrast, we would expect landscapes experiencing smaller fires to be strongly influenced by ignition pattern (Yang and others 2008; Beverly and others 2009).

Our manipulation of the fire duration, which strongly controls fire size, affected BP across the entire landscape. Imposing an average constant number of spread-event days reduced BP relative to the control which included a variable distribution for the duration of burning. Although the mean burning duration of the treatment was equivalent to that of the control, variable durations yielded much larger fires on average, because of a non-linear (power function) relation between area burned and duration. These results agree with claims that a modest increase in days with fire-conducive weather may cause a disproportionate increase in fire size in the North American boreal forest (Tymstra and others 2007). More variable weather is also likely to amplify the year-to-year variability in fire activity (Flannigan and others 2005), a phenomenon that may be particularly pronounced in WBNP, given the current inter-annual fluctuations.

In contrast to the duration of burning, manipulating the variability of daily weather conditions had a relatively mild yet statistically significant impact on BP across the WBNP landscape. Removing the day-to-day variability in temperature, relative humidity, and wind speed, in addition to making wind direction equally probable from each cardinal direction, brought an average increase in fire size throughout the area (19,059 and 23,000 ha, respectively). This increase was likely due to constant change in the direction of burning, whereby fire flanks often became the fire front with a change of wind direction. That is, the fires lost their directionality on average and this effect was important enough to override the loss of ''explosive'' fire weather conditions in the experimental treatment. Because weather variability mainly affects the shape of the fire, its impact was a more local one, expressed through phenomena such as fire shadows. Even then, the shadows are not particularly pronounced because wind direction is already fairly variable in the study area. A greater effect on BP would be seen when imposing random wind directions on landscapes where fire-conducive weather is usually brought in by powerful and strongly directional foehn-type winds (Pereira and others 2005; Moritz and others 2010).

The results of this study strongly suggest that fuel configuration is the overall dominant environmental factor controlling spatial patterns in BP in the study area. This may be the case in other similar parts of the boreal forest that have expansive tracts of a given vegetation type (or conversely, nonfuel), features that are disappearing from some areas due to the cumulative impact of land use (Wulder and others 2008). However, we caution against extrapolating the results of this study beyond its spatio-temporal frame. The BP as described here is an inherently spatial metric of fire likelihood rather than a temporal one. To focus on the spatial aspect, the temporal variability in BP was purposely under-emphasized in this study, as the variation among conditions driving the ignition and spread of each fire was ultimately averaged in our computation of BP. Area burned in the boreal forest is indeed strongly dependent on year-to-year—or even day-to-day—changes in the fire environment (Turetsky and others 2004; Drever and others 2008). Inter-annual variability in weather conditions may have a greater net effect on fire frequency than was measured in our simulation study of landscape-level fire likelihood, but this remains an open question.

The Advantages of Combining Fire Simulation Modeling and Structural Equation Modeling

The BP-residual approach used here allowed us to isolate the influence of individual environmental factors that contribute to spatial variability in fire. Although by no means exhaustive, the five experimental treatments (excluding topography) appeared to capture most of the factors affecting BP in WBNP. The use of residuals produced a set of predictors of BP for the SEM model that were relatively independent from one another. Individual pixels on the landscape, on the other hand, were far from independent due to spatial autocorrelation in BP. Spatial structure of the environment varies with the scale and focus of study, and accounting for autocorrelation in statistical analysis of a data set can be tricky. We addressed this concern in a simple, though sensible, manner by drawing a small subsample of cells and repeating this operation a large number of times. However, the appropriate size of the subsample in conjunction with an appropriate number of replicates cannot be prescribed: it is important to tailor the sampling to the structure of the landscape, as each is unique.

The SEM framework is well equipped to examine the role of multiple interacting processes in a complex system by simultaneously testing multiple hypotheses. Although a GAM framework may point to similar conclusions with respect to the relative influence of variables, the GAM is ill suited for the specification and evaluation of causal pathways, given that predictors are sequentially selected for model learning (Grace and Bollen 2005). For example, the addition of a path to the proposed SEM model that linked weather to ignition pattern was not only justified but also necessary to adequately predict BP. Such a relationship cannot be accommodated in a GAM. The SEM thus provided a more interpretive structure that helped enhance our understanding of the causal processes affecting BP and, in addition, may inform whether or not the specified model is the right one. However, SEM is not without limitations. For example, working with strongly non-normal data or response data that do not vary linearly as a function of its explanatory variables can be challenging (Grace 2006). In such instances, techniques such as GAMs can be useful to provide insights on system processes.

Although uncommon in ecological studies using SEM, the use of composite variables allowed us to ''bin'' variables into what is widely considered the three major environmental controls on boreal fire regimes: ignitions, fuels, and weather. This general framework could conceivably be applied to any fire-prone landscape. In fact, the approach used in this study could be particularly useful in rugged areas (for example, those described by McKenzie and others 2006), as the complex indirect influence of topography on ignitions, fuels, and weather could be explicitly specified. A comparison of landscapes where heterogeneity is manifested in different ways (for example, complex versus simple terrain) would prove useful for testing this framework. This said, the approach used here is not limited to spatial fire likelihood: it could be used to examine other fire-related data such as fire histories from tree rings, or it could be applied to landscape-scale studies with any type of relevant data, such as analysis of fire scars, fire atlases, or even paleorecords of charcoal.

Conclusions

Incorporating natural variability increases the accuracy of modeled fire patterns but also increases complexity, making it challenging to isolate the influence of environmental factors on spatial BP. The ''homogenize-one-factor'' approach developed here, combined with SEM, appeared to successfully, though arguably incompletely, disentangle the effects of environmental factors affecting spatial patterns in BP in WBNP. The work suggests that in this study area, the extensive heterogeneity in fuel configuration acts as a strong control over BP, whereas the effect of spatial patterns of ignitions was negligible. Somewhat surprisingly, weather, which fluctuates considerably more temporally than spatially in this flat study area, significantly influenced spatial BP, though substantially less so than fuels. It appears that much of the complexity inherent to the shaping of BP patterns is due to non-linear relations among components of the fire environment, as suggested by Peters and others (2004). This general framework funnels specific factors into three major types (ignitions, fuels, and weather), which can potentially be expanded upon to account for complex topography and anthropogenic effects. As such, it would provide a common baseline from which highly divergent landscapes could be studied and compared.

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