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Scale-dependent controls on the area burned in the boreal forest of Canada, 1980–2005

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Abstract. In the boreal forest of North America, as in any fire-prone biome, three environmental factors must coincide for a wildfire to occur: an ignition source, flammable vegetation, and weather that is conducive to fire. Despite recent advances, the relative importance of these factors remains the subject of some debate. The aim of this study was to develop models that identify the environmental controls on spatial patterns in area burned for the period 1980–2005 at several spatial scales in the Canadian boreal forest. Boosted regression tree models were built to relate high-resolution data for area burned to an array of explanatory variables describing ignitions, vegetation, and long-term patterns in fire-conducive weather (i.e., fire climate) at four spatial scales (10^2 km^2, 10^3 km^2, 10^4 km^2, and 10^5 km^2). We evaluated the relative contributions of these controls on area burned, as well as their functional relationships, across spatial scales. We also assessed geographic patterns of the influence of wildfire controls. The results indicated that extreme temperature during the fire season was a top control at all spatial scales, followed closely by a wind-driven index of ease of fire spread. However, the contributions of some variables differed substantially among the spatial scales, as did their relationship to area burned. In fact, for some key variables the polarity of relationships was inverted from the finest to the broadest spatial scale. It was difficult to unequivocally attribute values of relative importance to the variables chosen to represent ignitions, vegetation, and climate, as the interdependence of these factors precluded clear partitioning. Furthermore, the influence of a variable on patterns of area burned often changed enormously across the biome, which supports the idea that fire–environment relationships in the boreal forest are complex and nonstationary.

Key words: area burned; boosted regression trees; Canadian boreal forest; climate; ignitions; regression modeling; spatial scale; topography; vegetation; wildfire.

Introduction

The boreal forest, the world's largest terrestrial biome, forms a wide circumpolar belt of cold forests that have coevolved with large wildfires. In Canada, the boreal forest exhibits commonalities from the Atlantic to the Pacific coast, notably in the composition of dominant tree species. Although uniform in some respects, the boreal forest has important broad-scale geologic, pedologic, hydrologic, climatic, and vegetation gradients that translate into important spatial variation in fire regimes (Burton et al. 2008). However, fine-scaled fire patterns across the boreal forest are difficult to fully comprehend, as they appear to be the product of complex relationships and interactions among an array of biophysical and anthropogenic influences (McGuire et al. 2006). Moreover, fire–environment relationships that seem important in some parts of the boreal forest may not hold in other parts, which indicates that the factors controlling fire vary throughout this biome (Flannigan et al. 2005, Macias Fauria and Johnson 2008).

Although evidence of fire from modern observations and paleorecords shows that virtually every part of the Canadian boreal forest has experienced fire, there are notable discrepancies in the rates of fire activity (Stocks et al. 2002, Kasischke and Turetsky 2006). Broad latitudinal gradients in the severity of fire weather conditions, the length of the fire season, and the proportion of flammable vegetation combine to yield spatial variation in area burned (Payette et al. 1989).

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The northern boreal forest has a substantially shorter fire season than the south, but the greater summer daylight period and the dominance of conifers, which are much more flammable than deciduous species, can compensate for the shorter season. The boreal forest also has a broad-scale longitudinal moisture gradient, whereby areas west of central Ontario experience more frequent and more intense droughts than in eastern Canada (Skinner et al. 2002, Girardin et al. 2006), which results in greater fire weather severity (Amiro et al. 2004). However, important regional clusters of large fires do occur in the eastern boreal forest (Lefort et al. 2004). Localized weather patterns, such as those produced by large bodies of water (e.g., sea/lake breeze), can also yield dramatic spatial variation in area burned by affecting fire ignition and spread and, indirectly, by influencing vegetation patterns (Bergeron 1991, Parisien and Sirois 2003). The geographic distribution of area burned in the boreal forest of Canada therefore depends on environmental controls operating at various spatial scales.

Wildfire in any fire-prone biome has three environmental requisites: an ignition source, flammable vegetation (i.e., fuels), and weather conditions conducive to fire ignition and spread (Krawchuk et al. 2009, Parisien and Moritz 2009). To date, no long-term climatic limitation on fire ignition has been definitively reported for the Canadian boreal forest, but there are important discrepancies in ignition rates among seemingly similar areas (Wierzchowski et al. 2002). In contrast, there is ample evidence of strong relationships between area burned and weather (Bessie and Johnson 1995, Hély et al. 2001) and vegetation (Cumming 2001, Krawchuk et al. 2006), although the relative importance of these factors in controlling fire patterns is the subject of some debate. Assessing the relative contributions of ignitions, vegetation, and weather may appear straightforward, but is in fact extremely challenging because of the complex interrelationships among them. This complexity is further compounded by anthropogenic influences, which exert a positive effect on area burned through increased ignitions (Wotton et al. 2003), a negative effect through fire suppression (Cumming 2005, Martell and Sun 2008), and mixed indirect effects through the alteration and fragmentation of vegetation (Krawchuk and Cumming 2009).

Despite growing knowledge of the interannual controls on fires in the boreal forest, understanding of the controls on the cumulative (i.e., long-term) wildfire patterns across this biome is fragmentary. Multicentury examinations of the link between area burned and prolonged droughts in the boreal forest (Girardin and Sauchyn 2008) shows that drought-prone areas will also be the most prone to fire. Studies of recent fire activity have also underlined the importance of hot, dry, windy conditions in promoting fire occurrence in areas that are not biomass or ignition limited (Flannigan et al. 2005, Balshi et al. 2009). Although fuels seem unlimited within most of its range, the boreal forest is bounded in the north by a gradual depletion of burnable biomass (transition to tundra) and in the south by less flammable vegetation types and land use. In addition to varying with location, the environmental characterization of wildfire distribution or "pyrogeography" may be dependent on spatial scale, similar to the way species or biotic communities respond to hierarchical environmental controls (Pearson and Dawson 2003). Over small areas (e.g., stands or small landscapes), wildfire patterns are expected to vary mainly as a function of site-specific factors, such as the structure and composition of fuels, whereas across large areas climate gradients will prevail (Heyerdahl et al. 2001). In fact, for any given environmental covariate there appears to be a peak response in the fire activity across a range of spatial scales (Cyr et al. 2007).

The primary goal of this study was to identify the environmental controls on spatial patterns of fire activity, expressed as area burned, at various spatial scales in the boreal forest of Canada. To do so, we built statistical models of mean area burned for a 26-year period (1980–2005) at four spatial scales using 14 explanatory variables describing spatial patterns in ignitions, vegetation, fire-conducive weather (i.e., fire climate), and topography. This approach allowed us to determine the relative contributions of variables at each spatial scale, as well as the grouped contribution of ignitions, vegetation, and climate. Because we used a modeling method suitable for complex relationships, we were also able to evaluate how the responses of area burned to the explanatory variables changed among spatial scales. Finally, we examined the geographic patterns of the influence of explanatory variables to evaluate their fluctuations across the Canadian boreal forest.

Materials and Methods

Study area

The study area encompassed the boreal ecozones of Canada (5 581 096 km^2), as defined by the Ecological Stratification Working Group (1995) (Fig. 1). We did not include the portions of the boreal forest located in the United States (i.e., in Alaska and the Upper Midwest) because several of the required data sets were available only for Canada. The boreal forest biome has long, cold winters and relatively short, warm summers. Much of its northern half is underlain by continuous or semicontinuous permafrost. Wetlands, peatlands, and lakes are ubiquitous and often dominant features of the landscape. Geologically, the study area can be subdivided into three broad categories: the boreal shield, a flat to undulating area of granite and gneiss that overlies the Canadian Shield; the boreal plain, a fairly flat area of deep, ancient marine sediment; and the boreal cordillera, a more rugged area with heavy faulting and erosional features. All of the study area, excluding part of the

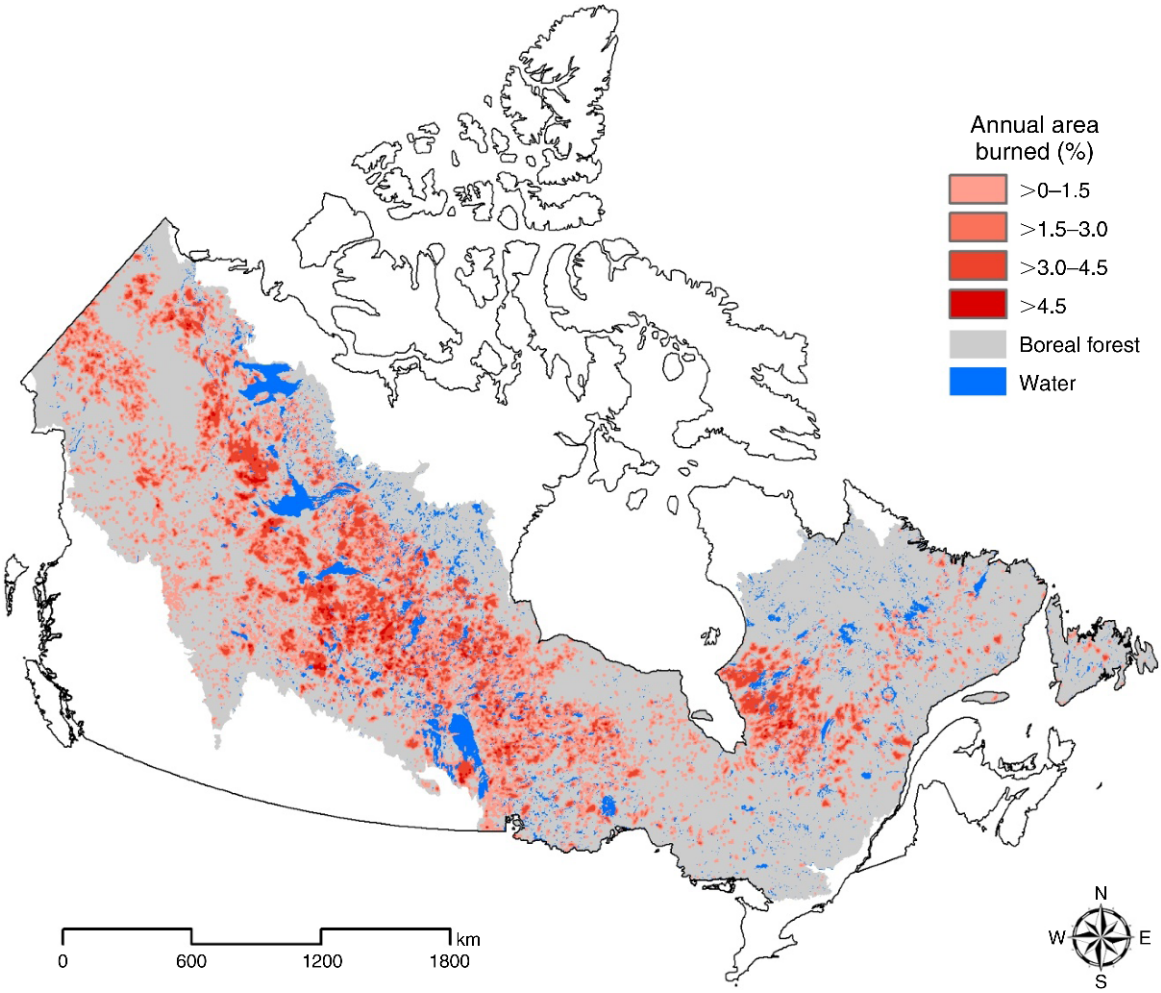

FIG. 1. The boreal forest of Canada (in gray) and the annual percentage of area burned per pixel from 1980 to 2005 within this area at the 10^2-km^2 spatial scale. The data for the three remaining spatial scales are included in Appendix A.

cordillera (i.e., Beringia), was glaciated during the late Pleistocene.

The study area supports a fairly small but geographically widespread group of dominant tree species of the coniferous genera *Picea* (*P. glauca*, *P. mariana*) and *Pinus* (*P. banksiana*, *P. contorta*) and the deciduous genus *Populus* (*P. tremuloides*, *P. balsamifera*). Coniferous and deciduous species are often intermixed, but the former group largely dominates the study area, except for some areas of its southern fringe. In addition, some grass- or shrub-dominated pockets occur in the western boreal forest. Most vegetation types, including wetlands, have variable degrees of tree cover; this variation, in conjunction with the numerous bodies of water and nonfuel features, leads to complex landscape mosaics. Landscape patchiness is further emphasized by highly variable stand ages, which result from wildfires that have been predominantly stand-renewing. Fires were actively suppressed in the southern part of boreal forest over the entire study period, but the extent of suppression varied by year and among fire management agencies. Anthropogenic land use, consisting chiefly of urban development and infrastructure, forest harvesting, agriculture, and mining, is mainly concentrated along the southern edge of the study area.

Data

We constructed regression models of the percentage of annual area burned (AAB_Pct) from 1980 to 2005 as the dependent variable (Appendix A), using an array of explanatory variables, which were categorized as being related to ignitions, vegetation, climate, and topography. The dependent and explanatory variables were averaged for the 1980–2005 period, and as such, did not address interannual variability in area burned. We built the models at four spatial scales (10^2, 10^3, 10^4, and 10^5 km^2), each of which consisted of the area of a circle around a sample point for which the dependent and explanatory variables were averaged. The finest scale was more than an order of magnitude smaller than the

TABLE 1. Dependent and exploratory variables used to model the spatial distribution of area burned in the boreal forest of Canada from 1980 to 2005.

Variable name	Description
Fire (dependent)	
AAB_Pct	Average annual area burned by fires, for 1980–2005 (%)
Ignitions	
Ltg_Dens	Average annual density of lightning strikes per unit area, for 1995–2005 (strikes per km^2 per year)
Road_Dens	Average density of roads for the year 2005 (km/km^2)
HumFoot	Average value of the Human Footprint, an index of human influence for the year 2005 (dimensionless; 0 = lowest, 100 = highest)
Vegetation	
Conif_Pct	Land cover of coniferous forest (%)
DecidMixed_Pct	Land cover of deciduous and mixed forest (%)
Nonfuel_Pct	Land cover of nonfuel (e.g., exposed rock, open water, glaciers) (%)
Water_Pct	Land cover of bodies of water across Canada (%)
CMI	Average annual climate moisture index (precipitation minus potential evapotranspiration) computed monthly for 12-month periods from 1 September to 31 August, 1980–2005 (mm)
GrowDays	Average duration of the defined annual growing period, starting when mean daily temperature $\geq$5°C for five consecutive days (as of 1 March) and ending when the average minimum temperature is $\leq$–2°C, 1980–2005 (number of days)
Climate	
Temp99	Average of the annual 99th percentile value of temperature for the period 15 May to 15 August, 1980–2005 (°C)
Wind95	Average of the annual 95th percentile value of wind speed for the period 15 May to 15 August, 1980–2005 (km/h)
ISI90	Average of the annual 90th percentile value of the Initial Spread Index, a CFFDRS index of ease of fire spread, for the period 15 May to 15 August, 1980–2005 (dimensionless)§
BUI99	Average of the annual 99th percentile value of the Buildup Index, a CFFDRS index of drought severity, for the period 15 May to 15 August, 1980–2005 (dimensionless)
Topography	
SurfArea_Ratio	Ratio of surface to area, an index of topographic roughness (dimensionless; 1 = flat)

† Computed from the smallest (i.e., 10^2 km^2) spatial scale.
‡ NASA is the National Aeronautical and Space Administration.
§ CFFDRS is the Canadian Forest Fire Danger Rating System.

largest wildfires, whereas the coarsest scale had a diameter of 357 km. Data were computed only within the boundaries of the study area. All of the model variables therefore consisted of continuous "moving window" surfaces across Canada, and were processed using a Lambert conformal conic projection at 1-km resolution. We opted for this approach, as opposed to a simple change of pixel size, in order to fully take advantage of the continuous nature of the data and to avoid a significant loss of information at the study area boundary (i.e., due to the squaredness of pixels).

The recently compiled geospatial atlas of fire polygons of Canada (Parisien et al. 2006) allowed a spatially explicit examination of patterns in area burned from 1980 to 1999. Although recently updated to include fires through 2005, the atlas still spanned a relatively limited period, and thus represented only a snapshot of fire activity. However, this fire atlas offered many advantages compared to other data sets: it was essentially comprehensive for the study period, it was spatially precise (relative to point data), and its data could be related to detailed environmental information for the same period. It comprised a large amount of data, representing 10 605 fires and a total area burned of 61996092 ha within the boreal forest (Fig. 1). Despite the fact that some undetected fires along the northernmost fringe were missing from the data set, as well as inaccuracies in perimeter mapping and omission of many unburned islands within fire perimeters, there was to our knowledge no systematic error at the defined spatial scales. The fire polygons were converted to a raster grid of 1-km pixels, where each pixel recorded the proportion of that pixel that burned over 26 years. The value could be >1 if the pixel or portions of that pixel burned more than once. This grid was then divided by 26 to obtain the percentage of annual area burned per pixel.

Fourteen variables selected for analysis were distilled from a larger set of variables according to a scheme that represented a compromise between retaining potentially informative and interpretable variables, while eliminating those that were strongly redundant (i.e., collinear), as detailed in Table 1 (Appendixes B and C). A large

TABLE 1. Extended.

Source	Mean (range)†
Fire polygons from 13 Canadian fire management agencies; compiled as the Canadian National Fire Database (Parisien et al. 2006)	1.31 (~0 to 8.56)
NASA Global Hydrology and Climate Centre: annual high-resolution data on lightning (Christian et al. 2003)‡	1.62 (0.005 to 13.73)
Road network file, 2005 (Statistics Canada 2005)	0.179 (0 to 9.60)
Last of the Wild Project of Wildlife Conservation Society (Sanderson et al. 2002) (with maps updated from original publication)	3.21 (0 to 69.69)
Composite of time series of five land cover maps (1985–2005) derived from advanced high-resolution radiometer data (Latifovic and Pouliot [2005]; see *Materials and methods*)	60.7 (0 to 100)
Composite of time series of five land cover maps (1985–2005) derived from advanced high-resolution radiometer data (Latifovic and Pouliot [2005]; see *Materials and methods*)	9.7 (0 to 100)
Composite of time series of five land cover maps (1985–2005) derived from advanced high-resolution radiometer data (Latifovic and Pouliot [2005]; see *Materials and methods*)	8.8 (0 to 98.8)
Canada-wide 1-km water fraction, derived from National Topographic Data Base maps (Fernandes et al. 2001)	8.0 (0 to 52.5)
Canadian Forest Service, computed from Environment Canada weather station data (Hogg 1994)	22.1 (−3.4 to 113.5)
Canadian Forest Service, computed from Environment Canada weather station data (McKenney et al. 2007)	145.9 (87.1 to 201.9)
Canadian Forest Service, computed from Environment Canada weather station data	27.81 (22.57 to 31.27)
Canadian Forest Service; computed from Environment Canada weather station data	22.50 (17.55 to 41.39)
Canadian Forest Service; computed from Environment Canada weather station data	8.30 (5.44 to 11.17)
Canadian Forest Service; computed from Environment Canada weather station data	72.8 (26.7 to 119.9)
Canada 3D, produced by Centre for Topographic Information (Natural Resources Canada 2001)	1.00139 (1 to 1.0729)

number of variables is not an impediment to BRT modeling, as this technique "mines" the relevant information, but highly correlated variables would have blurred the effect of individual variables. Only variables with correlation $|r| < 0.7$ for at least three of the four spatial scales were retained, and the selection of a single variable from a collinear set was based on the highest Spearman correlation to AAB_Pct. We made an exception to this scheme for the GrowDays (fire season length) variable, which was correlated with Temp99 (extreme temperature) slightly above the $|r| = 0.7$ threshold (but not beyond 0.8), because we deemed it important to evaluate the influence of the length of the growing (and fire) season on AAB_Pct. Preliminary explorations showed that this correlation threshold, though arbitrary, guided the selection of a diverse set of environmental conditions without impeding model computation and result interpretability because of high collinearity.

The three ignition variables (Ltg_Dens, Road_Dens, and HumFoot) described both ignitions caused by natural lightning and proxies for human-caused ignitions (Table 1). Although the lightning data spanned only 11 years, they were assumed to adequately describe the dominant patterns of lightning occurrence in Canada. For human-caused ignitions, we used two proxy variables. The road density variable, Road_Dens, provided a good indicator of human access, whereby greater access may translate into greater frequency of ignitions or, conversely, greater fire-suppression efforts (Drever et al. 2008). The human footprint variable (Sanderson et al. 2002), HumFoot, incorporated information on population density, access, land use, and infrastructure. It was not possible to annually update Road_Dens and HumFoot because of lack of data or irreconcilable differences among data sets. Ignition variables were given a value of 0 over water, to avoid factoring in areas in which fire could not have ignited.

Six vegetation variables were used to capture the amount and structure of the biomass available for burning. These variables were subdivided into four land cover variables (Conif_Pct, DecidMixed_Pct, Nonfuel_Pct, and Water_Pct) and two climatic variables known to exert strong control over vegetation (CMI and GrowDays). The land cover variables were processed in a way that limited the spurious influence of postfire

vegetation resulting from the fires that we were attempting to model. This was achieved by using a temporal series of vegetation grids from 1985, 1990, 1995, 2000, and 2005 and reclassifying the pixels labeled "disturbance" to the vegetation type of the previous time step (i.e., replacing disturbed area with predisturbance vegetation). After these replacements, any remaining disturbance pixels that originated from the first (1985) grid were replaced with vegetation types from the 2005 grid. We did not distinguish between upland and lowland sites, as the resolution of the available data was too coarse to dichotomize drainage types. The climate moisture index (CMI), which characterizes the potential for drought, is strongly correlated with major vegetation types in the western boreal forest of Canada, as the zero CMI isopleth corresponds almost perfectly to the interface between aspen parkland and boreal forest (Hogg 1994). Growing degree days (GrowDays) indirectly measures the length of the fire season. Annual values of CMI and GrowDays were averaged across the 1980–2005 period.

The four selected climate variables represented a suite of long-term fire weather conditions known to be correlated with the ignition and spread of fires in Canada (Flannigan and Harrington 1988). As with the CMI and GrowDays variables, the climate variables consisted of mean values of the 26 years of data. Initially, we considered four variables for long-term weather station observations (temperature, relative humidity, precipitation, and wind speed) and the six corresponding fuel moisture codes and fire behavior indices from the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987) for a range of percentile values (i.e., 80th, 90th, 95th, and 99th percentiles). However, because of strong correlations among the percentile values for a given variable and also among variables, only four variable–percentile combinations (Temp99, Wind95, ISI90, and BUI99), representing complementary aspects of fire climate, were retained. Two of the variables retained were ISI, an index of the ease of fire spread (mostly driven by wind), and BUI, an index of the depth of burning (mostly driven by drought). At some spatial scales, drought-related indexes other than BUI were marginally better correlated with AAB_Pct, but BUI was selected because it represents the "drought" counterpart of ISI in the FWI System. The percentile values of these climate variables were not computed for the entire year, but instead from daily observations for the period from 15 May to 15 August, when 92% of the fires in boreal Canada were reported from 1980 to 2005. Although fires may burn before and after these dates, we chose this period to avoid skewing the means toward lower latitudes, which have a longer fire season. That is, we wanted to isolate the effect of the severity of fire climate from the effect of length of the fire season.

Given the broad-scale nature of this study, we assessed topography using a single variable, the surface area ratio (SurfArea_Ratio), an index of topographic roughness that has been previously correlated with fire activity (Stambaugh and Guyette 2008). Topography exerts an indirect effect on fire patterns by influencing patterns of ignitions, vegetation, and fire weather (and climate) (Agee 1993). Moreover, only a marginal effect of topography on area burned was reported in a recent study comparing various North American landscapes (Cary et al. 2006). However, because we cannot claim to have a comprehensive data set of environmental fire controls, the effect of topography was incorporated into the models in case it acted as a proxy for an unmeasured environmental factor.

Regression modeling

We constructed regression models of AAB_Pct at the four spatial scales using boosted regression trees (BRTs) for the 14 explanatory variables (Table 1). To ensure that the models produced at each spatial scale were generated in a parallel and unbiased fashion, we used a flexible modeling approach, the same explanatory variables, and the same settings for all models. The BRT method, a nonparametric machine-learning technique, is particularly well suited for this purpose, as it does not require any a priori model specification or test of hypothesis (De'ath 2007). Rather, its algorithm fits the best possible model to the data structure, including complex interactions among variables. It does so by building a large number of regression trees, whereby, through a forward stage-wise model-fitting process, each term represents a small tree built on the weighted residuals of the previous tree. The stage-wise procedure reduces bias, whereas variance is decreased through model averaging. The BRT method also employs "bagging," the use of a randomly sampled subset of data points, which typically improves model predictions but renders the model output stochastic. BRTs can accommodate virtually any data distribution; therefore, no transformations were required. Although the use of BRTs in ecology is relatively new, recent comparisons of distribution modeling techniques have shown that they consistently produce robust predictive estimates (Elith et al. 2006, Phillips et al. 2009).

For all models, we used the "gbm" package in R (Ridgeway 2006), along with a custom R script by Elith et al. (2008). The squared error loss function (Gaussian in gbm) was deemed the most appropriate for our data (Hastie et al. 2009). Models were built from a subset of randomly sampled data points from a pool of 10 000 points at each scale. The data points were sampled within the area-burned locations of the 10^2-km^2 scale, and these same points were used for all other scales. Because coarser spatial scales contained less effective information than finer ones due to spatial autocorrelation in the samples, random subsets of 4000, 2000, 1000, and 500 points were used for building the models at the 10^2-km^2, 10^3-km^2, 10^4-km^2, and 10^5-km^2 scales, respectively. The selected observations were further resampled

for model building using a bagging fraction of 50%. To limit the stochasticity in model outcomes caused by the subsampling and the bagging, we created an ensemble of 25 BRT models at each scale and then averaged the results. The different sample sizes among spatial scales did not significantly affect model outcomes; however, at equal sample sizes, a greater number of models of the finer spatial scales would have been required to produce a stable model ensemble.

The BRT settings and model-building methods were similar to those used by Parisien and Moritz (2009). The learning rate, which represented the proportion of learning that could be achieved for each successive tree of a BRT model, was set at 0.05. The tree complexity, representing the number of nodes or variable interactions within each tree, was set at 5. This combination of learning rate and tree complexity allowed the BRT models the flexibility to fit complex multivariable responses to our data where these existed, while retaining a reasonable number of trees per model (between 1000 and 5000). The number of trees in each BRT model of the ensemble was selected automatically using 10-fold cross-validation to avoid overfitting the model, as recommended by Elith et al. (2008). This technique splits the data in 10 equal subsets, then builds a model with 9 subsets for every unique combination, for which the remaining subset is used for model testing. Ten BRT models are produced simultaneously using the training data sets, and the average stage-wise reduction in deviance is computed using the test data. This approach provides a more robust and less conservative estimate of the optimal number of trees than using the fraction of observations not used in building individual trees (i.e, the out-of-bag fraction) (Ridgeway 2006). Final fitted BRT models were produced for the optimal number of trees and evaluated using the deviance explained and correlation of the models' fitted values with those of values withheld for evaluation purposes (i.e., bagging fraction).

Analysis of data

The relative importance of environmental controls on AAB_Pct was assessed for individual variables, as well as for the grouped variables for ignitions, vegetation, climate, and topography (Table 1). The BRT method determines the contribution of a variable by averaging the number of times it is selected as a tree node over all trees and the squared improvements resulting from these nodes. The relative contribution, expressed as a percentage, was plotted for each variable and spatial scale. A variable was considered important if its relative importance was >5%. This threshold is considered conservative because the correlation among variables may somewhat decrease the relative importance of these variables, without, however, masking their respective effects (Hastie et al. 2009). To estimate the degree of similarity among variable contributions among spatial scales, a rank (Spearman) correlation was performed on the mean contribution values of variables in pair-wise combinations of scales. A lack of significance ($P \geq 0.05$) in a correlation indicates that the relative importance of environmental controls differ among scales. The contributions of the grouped variables for ignitions, vegetation, and climate were determined simply by tallying the percentage contributions of their constituent variables. The summed variable contributions could thus be incorporated into a ternary plot representing the "fire regime triangle" (Moritz et al. 2005). Because the GrowDays and CMI vegetation variables also influence fire climate by measuring the length of the burning season and the drought potential, respectively, they were included in the vegetation grouping in one scenario and in the climate grouping in another.

The relationship between AAB_Pct and the explanatory variables was examined by plotting the partial dependence of AAB_Pct at each spatial scale for a selected set of variables that performed well, and averaged for the 25 models of each ensemble. The partial dependence represents the estimated marginal effect of an exploratory variable on the AAB_Pct prediction when the responses of all other variables are held constant at their mean. This approach illustrates the shape of the relationship according to the model, which may be different from the simple relationships of the predicted values of AAB_Pct and the raw values of the variable of interest. Partial-dependence plots must be interpreted with caution when the variables are strongly correlated because of confounding effects among these variables. However, we minimized this problem by removing the highly correlated variables, as described above, and by presenting the results for the variable to which AAB_Pct responded the most strongly.

It is impossible to fully assess the geographic variation in the relative influence of explanatory variables from the partial-dependence plots because the values of the marginal effect are averaged for "bins" of exploratory variable values. That is, the same value of a given explanatory variable can have a different effect on AAB_Pct depending on location (Hastie et al. 2009). Therefore, we mapped the partial dependence of AAB_Pct on explanatory variables by evaluating partial-dependence values of individual sampled observations. In order to obtain the partial-dependence values at each geographic coordinate, the models had to be built using the TreeNet 2.0 software (Salford Systems, San Diego, California, USA). Although different sets of BRT models than those described above were produced for this purpose, the settings for the learning rate (0.05) and tree complexity (5) were identical. However, instead of using an ensemble of models, a single model was built at the 10^4-km^2 spatial scale and the data were extrapolated for visualization purposes using kriging. To reduce the intermodel stochasticity, no bagging was allowed and a larger number of points was used for model building (4000, as opposed to 1000). Although outputs from a single model invariably deviated

TABLE 2. Mean and standard deviation of the number of regression trees and the predictive performance of boosted regression tree models of area burned at each spatial scale.

Spatial scale (model)	No. regression trees ± SD	Deviation explained ± SD (%)	Correlation ± SD
10^2 km^2	1520 ± 76	25.4 ± 0.3	0.51 ± 0.003
10^3 km^2	3208 ± 159	49.7 ± 0.4	0.71 ± 0.003
10^4 km^2	3734 ± 52	79.5 ± 0.3	0.89 ± 0.002
10^5 km^2	1958 ± 22	95.7 ± 0.07	0.98 ± 0.0004

Notes: The values were calculated using 10-fold cross-validation and averaged for an ensemble of 25 models. The deviation explained and correlation both measure the degree of correspondence between the fitted values and those of the cross-validated proportion.

somewhat from the 25-model ensembles, explorations indicated that they were adequate for visualization and successfully depicted the main spatial trends in partial dependence of AAB_Pct. Results were shown for the same set of variables as the previous analyses.

RESULTS

The deviance explained (25.4% to 95.7%) and the correlation (0.51 to 0.98) between fitted and withheld data (Table 2), as well as plots of predicted vs. observed values (Appendix D), suggest that our BRT model ensembles adequately described the environmental controls on AAB_Pct at each spatial scale. The performance improved substantially with increasing spatial scale size, as the fine-scale models were inherently noisier than coarse-scale models. However, this did not impede our comparison among scales.

The relative contribution of the variables fluctuated substantially within spatial scales (Fig. 2). Using a 5% threshold of relative importance, all variables but Road_Dens provided valuable information to the models for at least one spatial scale. Whereas the relative contribution of some variables also changed considerably among scales, the relative importance ranking of others, notably Temp99 and ISI90, was remarkably stable across scales. Some variables (specifically Ltg_Dens, CMI, GrowDays, and BUI99) exhibited a consistent decreasing trend with increasing scale, whereas

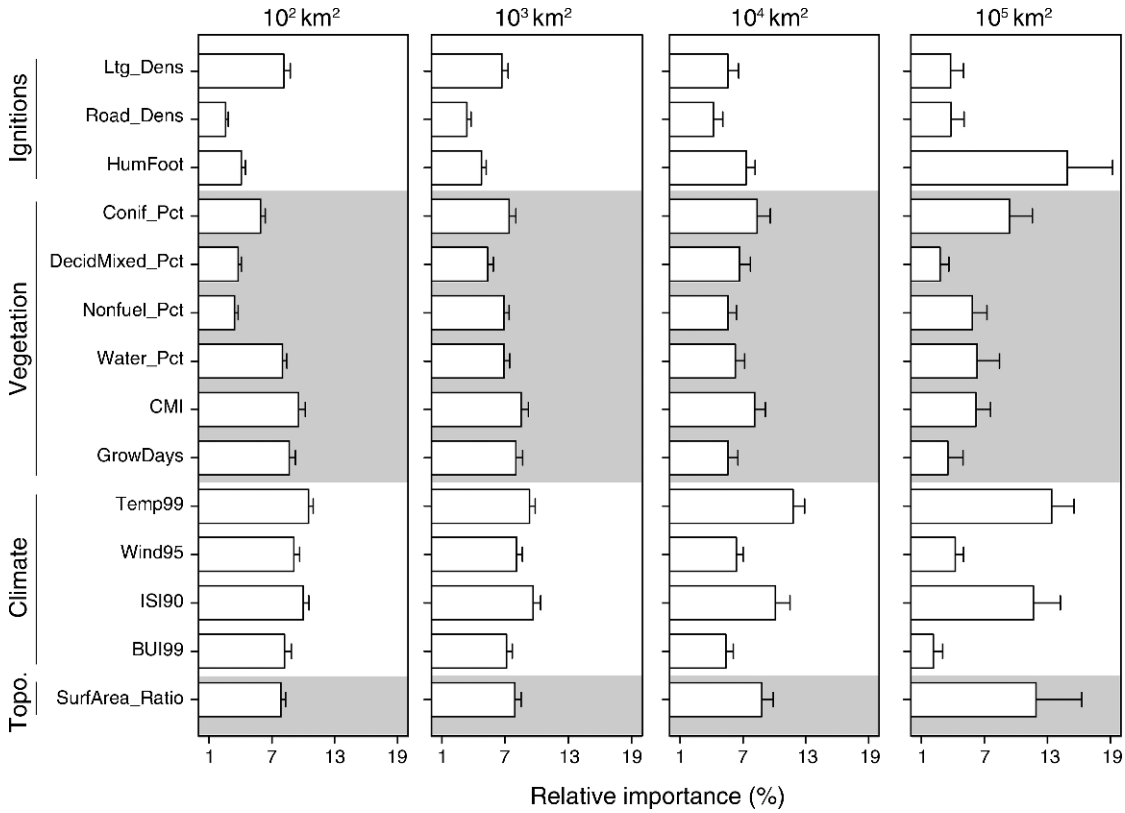

FIG. 2. The relative contribution of explanatory variables to boosted regression tree models of area burned (mean + SD) at the four spatial scales of the study. See Table 1 for definitions of the variables.

TABLE 3. Spearman correlation coefficients and associated P values (in parentheses) evaluating the mean variable contributions among spatial scales, as presented in Fig. 2. The lack of statistical significance ($P > 0.05$, in boldface type) indicates differences in the contribution of variables among scales.

Scale	10^2 km^2	10^3 km^2	10^4 km^2	10^5 km^2
10^2 km^2	1			
10^3 km^2	0.86 (0.00006)	1		
10^4 km^2	**0.42 (0.14)**	0.58 (0.03)	1	
10^5 km^2	**0.16 (0.58)**	**0.28 (0.33)**	0.78 (0.002)	1

others (HumFoot, Conif_Pct, and SurfArea_Ratio) had increasing contributions with increasing scale. Pairwise rank correlations of relative variable contributions among spatial scales are significant for each adjacent scale, but not for nonadjacent scales (Table 3). Therefore, adjacent scales are more similar in terms of variable importance rankings than nonadjacent ones.

Despite the interscale variability apparent in Fig. 2, when contributions of individual variables were tallied according to ignitions, vegetation, and climate, the environmental controls appeared fairly similar among the four spatial scales (see Fig. 3a). Overall, the summed variable contributions of climate (35.7% to 41.0%) and vegetation (38.7% to 46.8%) were similar and larger than the ignition (16.1% to 25.6%) contributions. Using these somewhat arbitrary groupings, the 10^5-km^2 scale appears to be the most distinct spatial scale, where ignitions had relatively greater importance than at finer scales, whereas the respective contributions of vegetation and climate were slightly lower. When CMI and GrowDays were grouped with the other climate variables, the relative importance of vegetation (23.0% to 29.5%) and climate (46.7% to 60.8%) among scales changed (Fig. 3b). There was an inversion, albeit marginal, in the ranking of vegetation contributions for the finest and coarsest spatial scales. In addition, climate had a larger range of contributions among scales with this grouping of variables than with the original grouping.

The functional response of AAB_Pct to a selected set of explanatory variables, as described in the partial-dependence plots, fluctuated among spatial scales for some variables but not others (Fig. 4). In fact, the polarity of some relationships shifted across scales for some variables (Ltg_Dens, Conif_Pct, and ISI90), for at least part of their respective ranges of values. For example, the partial dependence of AAB_Pct generally decreased with Conif_Pct at the 10^2-km^2 scale, whereas it increased at the 10^5-km^2 scale. In contrast, there appeared to be scale-invariant responses for some variables, such as HumFoot, Temp99, and SurfArea_Ratio. The smaller amplitude for the fitted values of AAB_Pct as a function of scale does not imply a weaker effect, but rather a decrease in the response variable as a result of averaging over areas that encompass greater unburned area, on average. Note that the tails of the relationships, generally where confidence intervals are visible, may be unreliable, because they are based on a relatively small number of data points.

Maps of partial dependence of AAB_Pct at the 10^4-km^2 scale helped visualize geographic patterns in the influence of the explanatory variables (Fig. 5). Coherent with the partial-dependence plots, the partial-dependence maps show that the relationship between AAB_Pct and each individual variable may be complex (i.e., nonlinear). For example, the greatest dependence of AAB_Pct on the Ltg_Dens and Conif_Pct variables occurred at intermediate values for these variables.

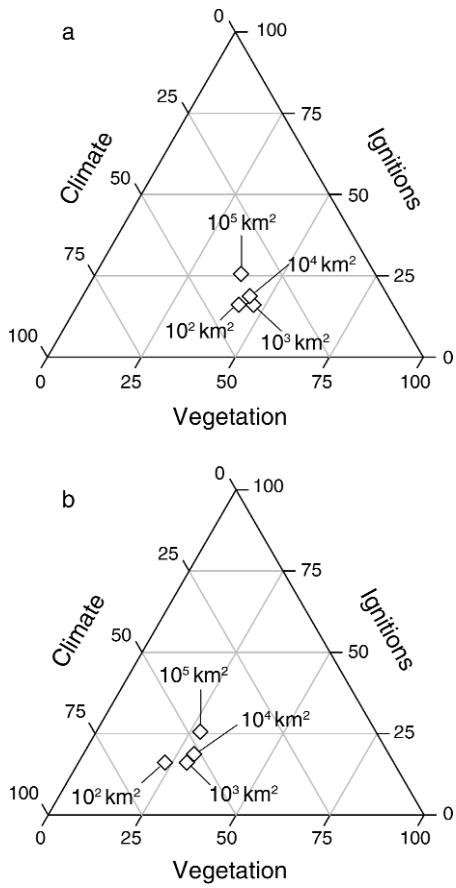

FIG. 3. Ternary plots showing the relative contributions of ignitions, vegetation, and climate under the initial variable classification (a) as described in Table 1, and (b) with the CMI and GrowDays variables classified as climate variables instead of vegetation variables.

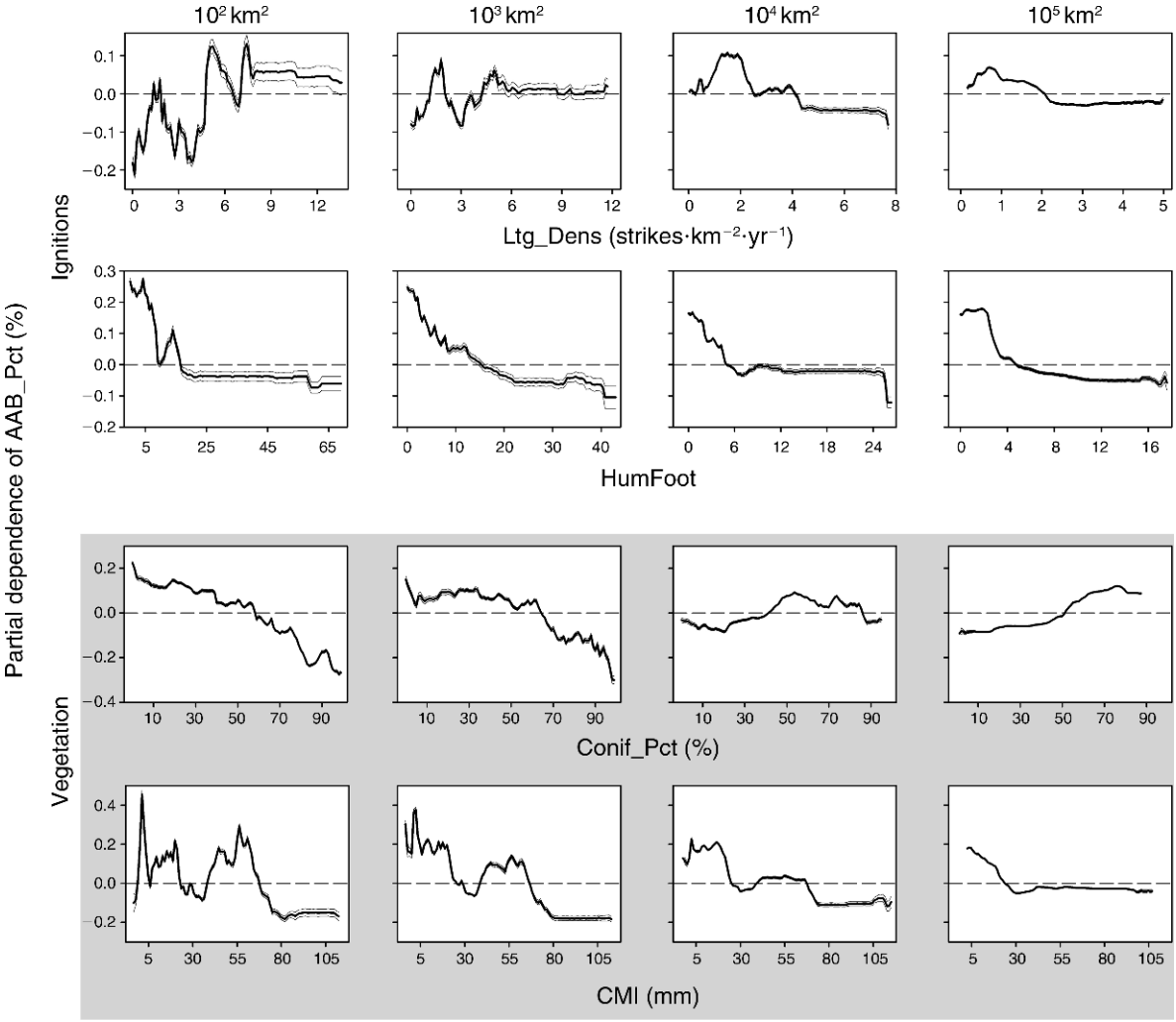

FIG. 4. Partial dependence of percent annual area burned (AAB_Pct; *y*-axis) on seven selected exploratory variables at each spatial scale of study. Any *x*-axis variables without units are dimensionless. Partial dependence, as computed in the boosted regression tree models, expresses the expected response in area burned for a variable of interest when all other variables are held constant. The curves represent the average (thick line) and 95% confidence intervals (thin lines) of an ensemble of 25 models. The curves were standardized around zero (dashed horizontal line) to facilitate comparison. The range of the *y*-axis varies among variables, and the range of the *x*-axis varies within the scales of some variables. The plots of remaining variables are found in Appendix E.

Unlike the plots, partial-dependence maps can discern areas where similar values of the explanatory variables exerted drastically different influences on AAB_Pct, as illustrated in the comparison of partial-dependence maps to their corresponding data maps. For example, the partial dependence of AAB_Pct was generally much higher at low values of the SurfArea_Ratio variable (i.e., flat areas), but this was not true for all flat areas, which suggests that the role of other variables overrides that of this variable in certain areas. There also appeared to be instances when pairs of variables, such as Temp99 and ISI90 (both of which were top-performing variables at a spatial scale of 10^4 km^2), complemented each other's spatial patterns of influence on AAB_Pct.

DISCUSSION

Ignition, vegetation, and climate controls on spatial patterns of fire activity

Within the boreal forest of Canada, combinations of environmental metrics, broadly grouped to characterize ignitions, vegetation, and climate, illustrated the biophysical controls over recently observed patterns of wildfires. Despite the diverse set of explanatory variables used in this study, spatial pattern in temperature extremes was the most important determinant of patterns of area burned in boreal Canada from 1980 to 2005 across all but one spatial scale (10^5 km^2, where it ranked second), consistent with studies of interannual variability in area burned (Duffy et al. 2005, Flannigan

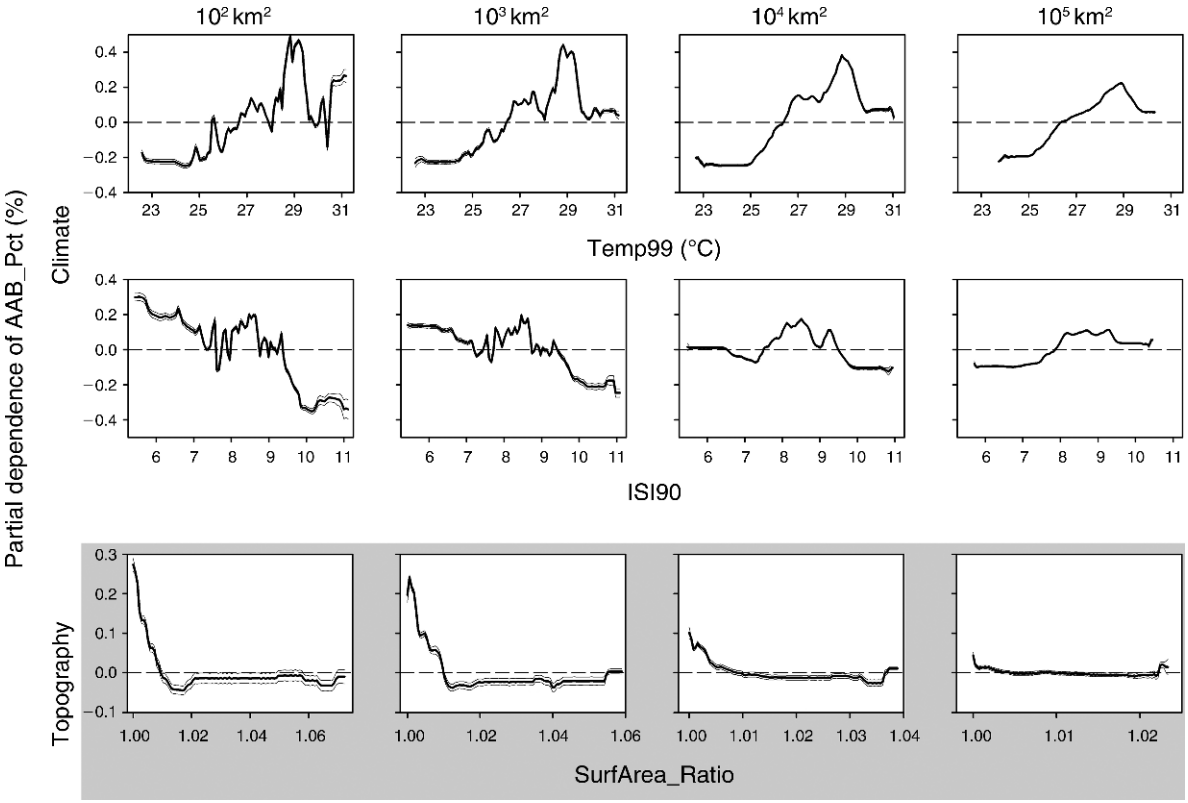

FIG. 4. Continued.

et al. 2005, Balshi et al. 2009). This result suggests that the influence of this variable is largely insensitive to spatial scale. However, as for most of the other reported relationships, the relationship between extreme temperature and area burned for the 1980–2005 period was not linear: even though area burned was associated with high-temperature areas, the warmest parts of the boreal forest experienced relatively less fire activity. This is partly because the increased moisture deficit promotes vegetation that is less conducive to fire ignition and spread, notably aspen parkland (Price and Apps 1996).

A warming climate across Canada may lead to changes in fire weather and more extreme temperature in the boreal forest. If temperature were the only variable governing fire activity, a general warming of the boreal forest might be anticipated to cause some areas to become more fire prone and some areas that are currently highly suitable for wildfires to become marginal. However, because temperature is not the only influential variable, we conclude that wildfire responds to the interplay of multiple controls, many of which may counteract the generally positive effect of temperature. Krawchuk et al. (2009) showed that the global distribution of fire is likely to experience major geographic shifts with climate change and that increases in some areas may be counterbalanced by decreases in others, through the interaction of precipitation and temperature. However, Flannigan et al. (2009) suggested that, in the Canadian boreal forest, ignitions and area burned will generally increase with climate change, primarily through warming (as a function of increased evapotranspiration leading to decreasing fuel moisture, unless precipitation increases significantly), through the occurrence of more lightning activity (which generally leads to increased ignitions [Price and Rind 1994]), and through a lengthening of the fire season (Westerling et al. 2006). In testing the sensitivity of landscape fire models to climate change and other factors, Cary et al. (2006) also found that area burned increased with higher temperatures, even when precipitation was high, although the increase in area burned was greatest for the warmer and drier scenario in their study.

The importance of the ease of fire spread (represented by the wind-driven ISI90) in defining spatial patterns of area burned lends credence to the claim of many fire managers that high-wind events drive large boreal fires (Hirsch et al. 1998). However, the erratic and generally decreasing relationship of this variable to the area burned at the finest spatial scale was not logical. This is a potentially because ISI90, a climatically based index that varies across large areas, is not well represented at finer scales. This may be compounded by some inaccuracies in the climate data. This variable also appeared to interact considerably with others, notably temperature

extremes. In fact, the partial-dependence maps at the 10^4-km^2 spatial scale suggested that the ease of fire spread may compensate for the lack of hot days in parts of the northern boreal forest, as its pattern of influence on area burned appeared complementary to that of the temperature variable (Fig. 5).

Drought conditions, as described by BUI99, appeared to be only a moderate control on area burned across spatial scales during the 1980–2005 time period. However, this is probably misleading, because the CMI water balance metric captures—perhaps better than BUI99—a large proportion of the information pertaining to droughts. It was impossible to completely disentangle the long-term influence of CMI on vegetation patterns from its shorter-term influence on the flammability of fuels. The partial-dependence map of CMI (Fig. 5) clearly shows a stronger influence of water balance in western Canada, which experiences drought stress more frequently than eastern Canada (Price and Apps 1996). In fact, high winter precipitation is thought to fully recharge the soils during most years in the east, but not the west (Lawson and Dalrymple 1996). As such, the moisture recharge of soils appeared to be a key determinant of area burned in the boreal forest of Canada, as reported by Drever et al. (2008) in western Ontario.

Our results indicate that the landscape dominance of conifers is more important in explaining broad-scale than fine-scale patterns of area burned. The observed negative relationship with area burned at finer scales, which is not intuitive, appears to be a result of interactions with other environmental factors. For example, although conifer species are much more flammable than deciduous species in the boreal forest, they often dominate wetland areas, whereas deciduous trees are usually confined to the drier uplands. The changing relationships of the Conif_Pct variable according to scale likely resulted from its broad categorization, given that the "conifer" category used in this study encompassed upland as well as waterlogged areas, such as muskegs, some of which burn rarely, if at all. However, many of the wetland areas of the boreal forest do burn, often at high frequencies, but only under drought conditions, when the functional connectivity of the landscape is increased (Turetsky et al. 2004). In fact, a strong interaction between Conif_Pct and BUI99, an index of drought, at the 10^4-km^2 scale (Fig. 6) supports claims that the combination of high conifer dominance and high drought-proneness generally leads to substantially greater area burned.

Although the vegetation and climate variables used in our models probably represent good characterizations of these factors, the ignition variables undoubtedly lack pertinent information, such as details of the timing of ignitions (Krawchuk et al. 2006). Even so, it appears that ignitions had an important effect on area burned in the Canadian boreal forest. Our results suggest that moderate densities of lightning strikes are important at certain spatial scales in the "mid latitudes" of the boreal forest, but not at its southern fringe, where lightning is most frequent. This may be a consequence of greater fire suppression effort and less flammable (i.e., deciduous) fuel. In the northern boreal forest, it is plausible that a lack of lightning may limit the area burned, but this phenomenon appears to be fairly localized, as suggested by the scale-dependent response of fire activity. At the broadest spatial scale, lightning appears to be less limiting, as evidenced by the relatively flat curve of the partial-dependence plot. Lack of lightning during the fire-conducive period of a particular fire season is not rare (Flannigan and Wotton 1991), but our results suggest that low lightning density may be limiting area burned in some areas over a period of decades.

The high level of human impact (HumFoot) probably dampens the capacity of lightning strikes to become large fires. Although both natural and anthropogenic ignitions are more frequent in the southern boreal forest, human pressures in the south may largely negate their effects. The negative relationship of the proxies for human-caused ignitions with area burned are coherent with results for boreal Alaska (Calef et al. 2008) and Saskatchewan (Parisien et al. 2004), where the patterns of human-caused ignitions, including very small fires, were inversely correlated with the area burned. Our results support claims that anthropogenic effects in these areas are multipronged, in that increased rates of ignitions by humans are largely countered by enhanced detection and effective initial attack (Arienti et al. 2006), in conjunction with fragmentation and isolation of flammable fuels.

Some relevant "direct" information about wildfire controls is undoubtedly missing from our models, as evidenced by the contribution of topographic roughness, an indirect control on fire activity. This metric may be a proxy for several factors. The partial-dependence map revealed that it is not the ruggedness of a particular area that determines fire activity, but rather its flatness. We speculate that the "missing" information is related to the continuity and configuration of flammable features, which is generally larger in flatter areas, but such fine-scale analysis was beyond the scope of this study.

Scaling effects on the perceived importance of controls on fire activity

Studying ecological phenomena across a range of scales allows the examination of different aggregations ranging from individual fire events at fine scales to populations of events at coarser scales (Johnson 1980). At the finest spatial scale (10^2 km^2), the model of area burned could almost be considered a model of fire presence, as most data points would contain data from a single fire or a small cluster of fires. We focused on areas for which there were data for area burned; therefore, this spatial scale contained very little information about the factors precluding the ignition and spread of fire. Every sample can therefore be considered to have conditions at least somewhat suitable to fire activity within its neighborhood. However, because many fires are larger than 10^2 km^2, an aliasing error is

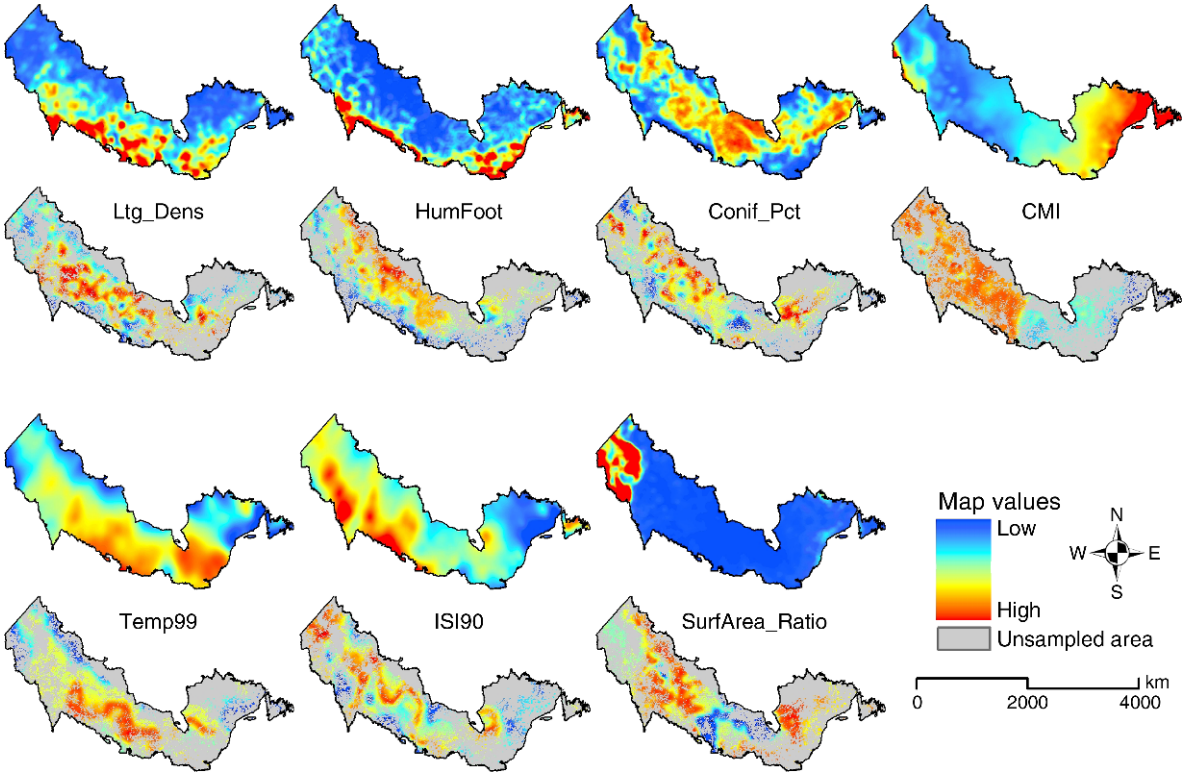

FIG. 5. Maps of selected explanatory variables (top map of each pair) and the corresponding maps of partial dependence of area burned (bottom map of each pair) for the 10^4-km^2 spatial scale. The variable maps consist of "moving window" surfaces, whereas the partial-dependence maps were smoothed from 4000 data samples using kriging to improve their appearance. The maps of the remaining variables can be found in Appendix F.

likely to occur, whereby the true biophysical response of area burned is distorted. This type of error may explain the rather noisy and sometimes unintuitive fire–environment relationships, with stable estimates requiring an area at least a few times as large as the largest wildfires (Johnson and Gutsell 1994). At finer spatial scales, the BRT models extracted relevant information in spite of the noise, but ideally a longer time period is required to better depict the fire–environment relationships. Enlarging the spatial scale leads to the inclusion of areas less suitable for fire activity and helps to refine fire's response to environmental factors and produce better model fits, but at the same time sacrifices fine-scale information. There is thus a benefit in evaluating fire–environment relationships at more than one spatial scale.

The decrease, albeit marginal, in the importance of climate for area burned as a function of increasing spatial scale was counter to our expectations. However, it may not be the general importance of climate that changes among spatial scales; rather, there may be a gain in information from the ignitions and vegetation patterns. Although the fire triangle is an attractive construct, it is difficult to specify with certainty the true contributions of the variables assigned to ignitions, vegetation, and climate variables, if such a categorization is even possible, because of the strong interdependence among

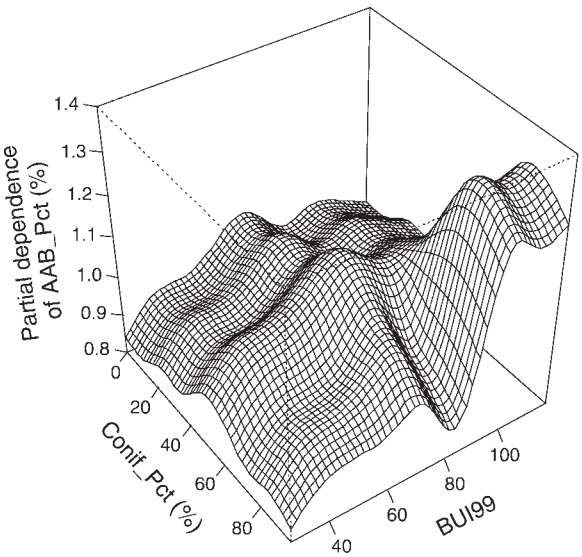

FIG. 6. Variation in the predicted area burned in response to interactions between Conif_Pct (%) and BUI99 (dimensionless) explanatory variables, as predicted by the boosted regression tree model of area burned at the 10^4-km^2 spatial scale. The response was smoothed to show the dominant trends.

these environmental factors. Not only are many of the explanatory variables correlated, but many also have an indirect relationship with area burned. For example, in some of the most fire-prone parts of the North American boreal forest, less flammable (i.e., deciduous) species tend to dominate the postfire landscape, thus exerting negative feedback that is largely independent of climate (Johnstone and Chapin 2006). In fact, Higuera et al. (2009) showed that the effects of climate on fire regimes have been greatly altered by vegetation throughout the Holocene, and that over broad timescales, the impact of climate-mediated changes in vegetation may be more important than the direct impact of climate.

The multiscale aspect of this study underlined certain subtleties associated with the concept of environmental controls on wildfire activity. The relative importance of a variable or group of variables is usually viewed as the amount of information or power that it provides in "explaining" fire activity. However, over large areas, it is perhaps more relevant to interpret the importance of an environmental control as the extent to which it limits fire activity (van der Werf et al. 2008). Overall, our results support the synthetic model of global fire regimes proposed by Meyn et al. (2007), which postulates that the area burned in the North American boreal forest is limited by the frequency of fire-conducive weather, not by flammable biomass. We suggest that although this may be borne out to some extent in the "interior" boreal forest, where fuels may not be as limiting or as functionally heterogeneous, it may not hold true closer to the biome's limits, where the availability of fuels appear to be more limiting, at least at the spatiotemporal scales of this study. However, at the southern fringe of the study area, this relationship may be blurred by the more effective fire suppression. In fact, in this part of the boreal forest HumFoot is probably a better characterization of fire suppression than ignition density.

Because environmental controls on fire regimes are complex and because some are sensitive to scale (Falk et al. 2007), it is crucial to frame the interpretation of one's results according to the temporal and spatial scale of the study. This is particularly relevant given that most broad-scale fire–environment studies, especially those involving projections of climate change, have been conducted at very coarse resolution (e.g., 1° cells), which may obscure key processes or relationships. For example, Randin et al. (2009) showed that the projected persistence of alpine plants in a changing climate varied with the spatial extent and resolution of the study. They speculated that this dependence on scale might explain the "Quaternary conundrum" (Botkin et al. 2007), which posits that there were many fewer species extinctions during the last Ice Age than would be predicted by models. Similarly, prior debates about the role of wildfire controls or the effect of fire suppression in the Canadian boreal forest may have suffered from a lack of recognition of scaling effects, both temporal and spatial. We therefore suggest that branding biomes or ecosystems as being dominated by fuels or by weather or climate may be misleading and overly categorical, because the rate-limiting factors for area burned will invariably change across regions and over spatial scales. This said, despite the effort to use spatial scales ranging four orders of magnitude, there are assuredly environmental controls acting over larger areas than that of the 10^5-km^2 scale. For example, atmospheric high-pressure ridging, which exerts a strong influence over cumulative area burned across expansive (i.e., up to half) areas of the boreal forest (Skinner et al. 2002), could not be directly taken into account in this study, only indirectly through surface weather measurements.

Methodological limitations of the analysis

Although the tools, data, and modeling assumptions used in this study allowed us to assess the scale dependence in fire–environment relationships, they were not without limitations. For example, the sampling scheme combined with the moving window approach maximized the information input to our models, but by the same token, also limited the type of statistical inference that could be carried out. This is partly due to the intersections, often substantial, among circular windows that led to an overlap in sample information, hence autocorrelation, which was particularly pronounced at the broader spatial scales. We partly countered this problem by adjusting the sample size according to scale and by subsampling the main pool of samples, but there was no formal attempt to account for the spatial dependence in the observations. Our sampling scheme, which was designed to ensure the consistency of the comparisons among scales, thus impaired our ability to identify a scale at which we were best able to predict area burned.

By averaging the annual area burned and exploratory variable values for the 1980–2005 period it was possible to compare variables that fluctuate greatly from year to year (i.e., climate) to those that are mainly spatial (i.e., ignition proxies and vegetation). Characterizing conditions over a longer time frame, as opposed to annually, allows us to assess the environmental bounds within which the area burned is observed. However, data averaging may mask spatial variability through time that is relevant to the area burn patterns in the boreal forest of Canada, as shown in studies that evaluated fire occurrence or area burned as a function of year-to-year changes (Flannigan et al. 2005, Drever et al. 2008, Balshi et al. 2009). We feel that the annually based and averaged model frameworks nicely complement each other; however, the extent to which this is true warrants formal examination using parallel data and modeling approaches.

The validity of temporally averaged models hinges on the ability of the exploratory variables to accurately characterize the time period's environmental conditions. As such, the mismatch in time period between the ignition variables (Ltg_Dens, Road_dens, and HumFoot) could appear problematic. However, there is good

reason to believe that the spatial patterns of Road_dens and HumFoot are representative of the 1980–2005 time period, and interannual fluctuations in these variables are minor compared to climate variables. Although there were changes in human settlements throughout the study time period, most of the urban development occurred south of the study area. Similarly, because of significant lightning activity in much of the boreal forest, the 11 years of data should be sufficient to capture its main spatial patterns. With respect to climate, which fluctuates substantially from year to year, a subanalysis was performed on a subset of variables (ISI90, Temp99, and BUI99) to evaluate the stability of their averages. Using a randomizing procedure, we measured the relative change for a given variable as we add individual years of data by random resampling and reshuffling of individual years to obtain a reliable measure of relative change. The results show that, for 26 individual years of data, the following mean degree of uncertainty exists in the selected variables: ISI90 = 1.0%; Temp99 = 0.2%; and BUI99 = 0.8%. In light of this minimal change, we consider the climate data for the 1980–2005 time period to represent reliable "normals."

Concluding remarks

Although by no means exhaustive, this study highlights the relative contributions of ignition sources, the resources available for burning (vegetation), and the weather conditions conducive to combustion in the boreal forest at four spatial scales. Research to discriminate among these three fire-promoting agents is critical to an understanding of historical and future wildfire, yet their individual contributions are often aggregated, in part because they are difficult to parse. The results also provide strong support for the premise that the environmental space in which wildfire occurs is complex, with numerous permutations of the environmental controls associated with fire proneness (Krawchuk et al. 2009, Parisien and Moritz 2009). This is consistent with studies of other fire-prone systems, even those that differ substantially from the boreal forest, such as the sub-Sahara (Archibald et al. 2009), the western United States (Littell et al. 2009), and Australia (Russell-Smith et al. 2007). These studies have shown that although a few dominant, overarching biophysical gradients are present, wildfire–environment relationships vary on a regional basis.

Acknowledgments

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APPENDIX A

The annual percentage of area burned for the period 1980–2005 at spatial scales of 10^2, 10^3, 10^4, and 10^5 km^2 (*Ecological Archives* A021-039-A1).

APPENDIX B

Raw data for the 14 explanatory variables used in the multiscale statistical wildfire models (*Ecological Archives* A021-039-A2).

APPENDIX C

The minimum, mean, median, maximum, and standard deviation of each variable by spatial scale (*Ecological Archives* A021-039-A3).

APPENDIX D

The relationship between the observed values used in the boosted regression trees and those predicted by the models (*Ecological Archives* A021-039-A4).

APPENDIX E

Partial-dependence plots showing variation of the response in area burned (y-axis) as a function of the seven explanatory variables not shown in Fig. 4 at each spatial scale of study (*Ecological Archives* A021-039-A5).

APPENDIX F

Maps of selected explanatory variables (top map of each pair) and the corresponding maps of partial dependence of area burned (bottom map of each pair) for the 10^4-km^2 spatial scale for the variables not presented in Fig. 5 (*Ecological Archives* A021-039-A6).