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Road network density correlated with increased lightning fire incidence in the Canadian western boreal forest

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Abstract. This paper quantifies the influence of anthropogenic linear disturbances on fire ignition frequency in the boreal forests of western Canada. Specifically, we tested if linear features increase the frequency of lightning fires, and whether this relationship is affected by spatial resolution. We considered fires that ignited between 1995 and 2002 within a ~67 000 km^2 region of boreal mixed-wood forest in north-eastern Alberta where linear features are highly abundant and spatially heterogeneous. We constructed Poisson, Negative Binomial and Zero-Inflated Poisson models at two spatial resolutions (~10 000 and ~2400 ha), including covariates for linear feature densities, forest composition, weather–lightning indices and geography. We found a positive association between lightning fire frequency and road density; this association was consistent at both spatial resolutions. We suggest this occurs owing to increased availability of flammable fine fuels near roads. The effect was attributable neither to increased detectability of fires proximal to roads by human observers, nor to increased lightning strikes due to metallic infrastructure alongside roads or the topographic characteristics of road location. Our results suggest that, in the face of projected road developments in the region, the potential exists for important changes to the regional fire regime. Further research should elucidate the precise mechanisms in order to develop methods for mitigation.

Introduction

Human activities in natural forested ecosystems have the potential to modify not only landscape structure but also to alter the disturbance regime intrinsic to such ecosystems (Veblen *et al.* 2000; Lefort *et al.* 2003). In the Canadian boreal mixed-wood forest, lightning-caused fires are the dominant natural disturbance, accounting for 85% of the area burned (Weber and Stocks 1998). Lightning fire ignition and subsequent spread behaviour are traditionally explained in terms of the interacting factors of weather, topography and fuels (Agee 1997). Short-term weather conditions (wind, temperature, precipitation) determine the moisture properties of forest fuels; the number of lightning strikes increases with elevation; and forest stands are inherently variable in the amount and condition of fuels available for combustion.

Whereas lightning fire ignition locations may once have been determined entirely by these three environmental factors, there is now ample evidence that fire occurrence is increasingly influenced by patterns of human activity (Cardille *et al.* 2001; Donnegan *et al.* 2001; Lefort *et al.* 2003). In the boreal mixed-wood forest of north-eastern Alberta, Canada, the majority of human disturbances are conducted by the forestry and energy sectors. The direct legacy of these activities is an extensive industrial footprint in the landscape, which evidences itself in the form of a growing network of linear features, e.g. roads and pipelines (Schneider *et al.* 2003).

Linear features alter landscape structure by increasing forest fragmentation (Forman and Alexander 1998), changing vegetation cover from forested to non-forested (Revel *et al.* 1984) and facilitating human access to formerly remote areas (Schneider 2002). Subsequently, these landscape changes can affect several aspects of fire behaviour, such as fire spread and final size (Duncan and Schmalzer 2004). The present study is concerned with fire ignition. The processes by which a lightning strike may result in a detected and reported fire (a fire arrival, in the sense of Cunningham and Martell 1976) are described by Kourtz and Todd (1991). Linear features in the boreal forest are expected to influence these processes by altering the abundance, flammability and spatial distribution of fine fuels, particularly grasses, which are known to experience a marked decrease in foliar moisture content and thus are highly combustible during early spring and summer (Van Wagner 1983).

The frequency and spread of disturbances such as fires is affected by spatial heterogeneity in forest fuels or in other physical landscape characteristics (Turner 1989); however, spatial pattern and heterogeneity ultimately depend on the scale at which

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these are measured: in general, higher spatial complexity is captured with increasing resolution (Turner 1989). Following this line of thought, we expected that any effect linear features may have on lightning fire ignition would depend on the scale at which we chose to study these relationships.

For the present study, we developed statistical models to describe spatial variation in the frequency of lightning fires igniting over the period 1995 to 2002 within a ~67 000 km^2 region of boreal mixed-wood forest in north-eastern Alberta. As described before, this region contains a large and increasing abundance of anthropogenic linear disturbances; thus particular interest was placed on unravelling their current influence on lightning fire ignition patterns. Our first objective was to quantify the effect of linear features on the frequency of lightning fires; our second objective was to assess the sensitivity of detected relationships to the spatial resolution of analysis.

Data and methods

Study region

Our study region was a large (~67 000 km^2) forest estate in the boreal mixed-wood forest of north-eastern Alberta, Canada (Fig. 1*a*). The area is characterized by a continental climate (Strong and Leggat 1992) and moderate topographic relief, with elevations ranging from 200 to 850 m. Mature mixed stands containing either trembling aspen (*Populus tremuloides*) or balsam poplar (*Populus balsamifera*) and white spruce (*Picea glauca*) are characteristic of well-drained sites (Strong and Leggat 1992) and cover ~25% of the area. Rapidly draining sites are vegetated principally by jack pine (*Pinus banksiana*), and some white spruce and aspen. Poorly drained areas are dominated by black spruce (*Picea mariana*) and tamarack (*Larix laricina*). Various wetland types, e.g. sparsely treed or open bogs and fens, cover ~50% of the area.

The region was relatively undisturbed by human activity until the 1950s; however, most of the study region is now allocated to industrial development, mainly by the forestry and energy sectors. These developments create permanent or temporary clearings and persistent linear features in the form of seismic lines, pipelines and roads. Seismic lines are narrow corridors (≤8 m) constructed in the course of exploration for oil and gas reserves. They are revegetated using mixes of general agronomic species or allowed to revegetate naturally (Revel *et al.* 1984). Until 1995, most seismic lines were 8 m wide, but their widths now vary from 1 to 7 m with a mean of 5 m (Schneider 2002). Buried pipelines connect wells with intermediate processing facilities in the area. Pipeline rights-of-way are typically 25 m in width and are treated to prevent them from regenerating to forest in order to facilitate maintenance. Roads include winter roads, in-block haul roads, permanent industrial roads and all-weather provincial highways. Most industrial roads have clearings on each side ranging from 8 to 20 m wide, whereas provincial highways have 40-m clearings. Roadside clearings are also revegetated with general agronomic seed mixes of grasses and forbs. These developments have altered the spatial distribution and age structure of vegetation communities, and have markedly increased the density of linear features (Schneider 2002) (Fig. 1*b*). As of c.2000, ~3% of the study area had been disturbed by linear features and permanent clearings associated with the energy sector while 2.6% had been directly harvested by forestry companies.

Data

Sampling units

We estimated the relationship between the number of lightning fires per unit area and various biotic and abiotic factors at two spatial resolutions. For the coarse-resolution analysis, we used the Alberta township grid. Townships are land survey units with a mean area of 9230 ha, varying slightly in size owing to geographical corrections. This resolution has previously proved adequate to explore several issues in fire ecology (Cardille *et al.* 2001; Cumming 2001; Krawchuk *et al.* 2006). Of 806 townships within the study region, we selected 601 for analysis with a minimum size of 7000 ha and classifiable terrestrial surface area greater than 70% (Fig. 1*b*). These criteria excluded small townships, those having large water bodies or large areas of unclassified vegetation. For the fine-resolution analysis of objective two, we used quarter-townships: each township was divided into four equal-sized quarters of ~2370 ha each (Fig. 1*c*). This spatial resolution was equivalent to the fine-scale grid used by Cardille *et al.* (2001). Using the 70% classifiable surface area criteria, we selected 2370 quarter-townships for analysis.

Fire-day counts

The Government of Alberta's Forest Protection Division has on-line provincial-wide databases of fire records from 1961 to 2003 (ASRD 2004). We used a consistent version of these data assembled by S. Cumming (Boreal Ecosystems Research Ltd), containing information on fire cause, date of occurrence and geographical location for the fire ignition point, among other attributes (Arienti *et al.* 2006). From the database, we calculated a count response variable that quantified the total number of lightning fires per sampling unit over the interval 1995–2002 (Fig. 1*b*). This sampling interval was chosen as a compromise between minimizing temporal variation in landscape characteristics resulting from increasing industrial activities in the area, and maximizing the time window so as to reduce the effects of interannual variation in fire weather conditions. This 8-year study interval is negligible compared with the historical fuel-type-specific fire return intervals in the study region (Cumming 2001). Only those fires that occurred during the regional fire season were considered (30 April to 29 September; C. Tymstra, Alberta Sustainable Resource Development (Alberta SRD), pers. comm.). Multiple fires igniting on the same day within the same sample unit occurred infrequently. These multiple events were counted as only one fire in order to avoid statistical dependence among events likely resulting from the same weather and forest conditions (Krawchuk *et al.* 2006). Thus, the response variables were actually counts of fire-days per sampling unit over the study interval.

Model covariates

We modeled spatial variation in the response variables as functions of four classes of covariates: linear feature density, land cover class, fire weather and lightning, and geography (Table 1). We measured the explanatory variables from available spatial data layers using *ArcMap 9.1* (ESRI 2004).

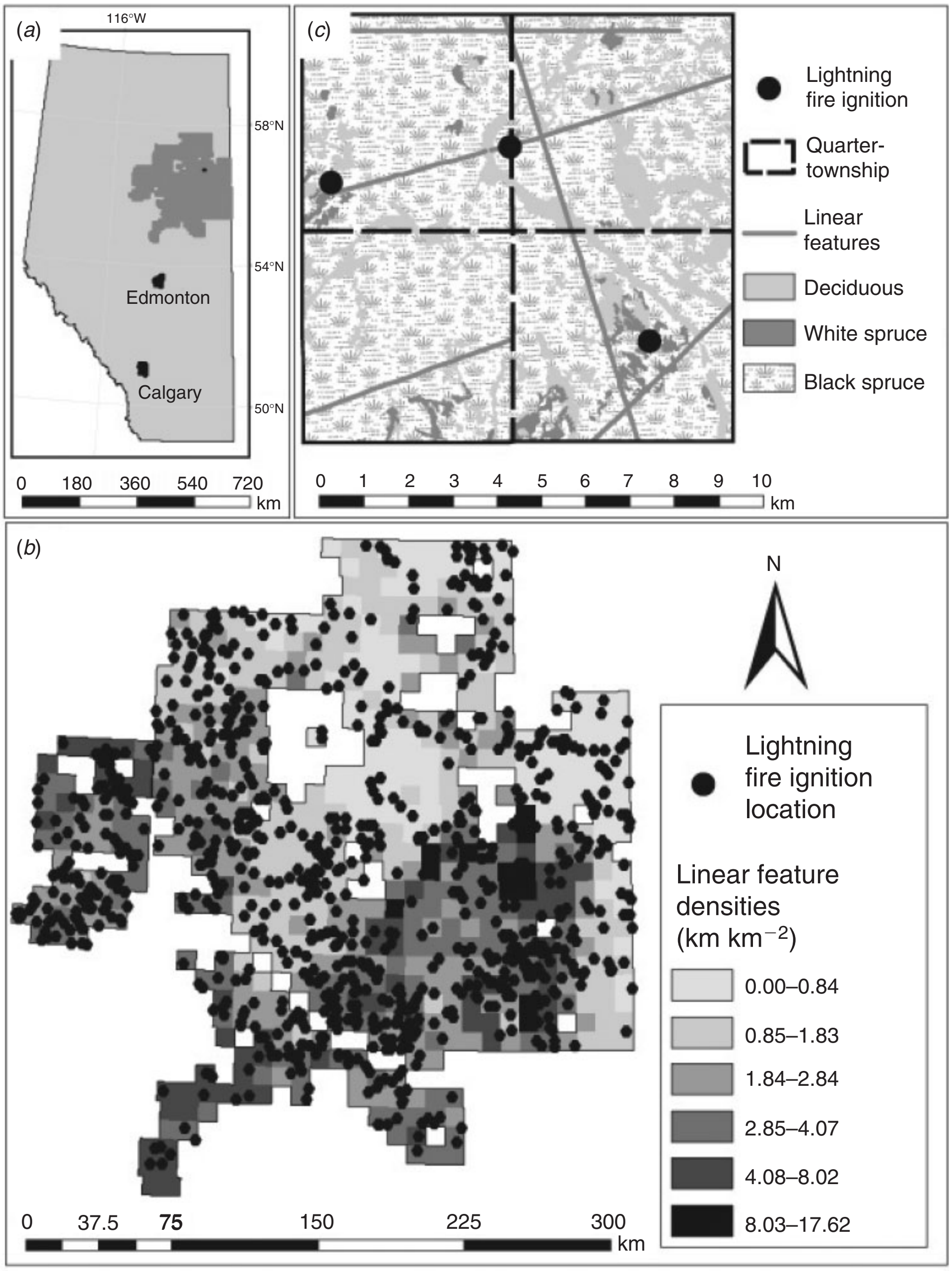

Fig. 1. The study area is a ~67 000 km^2 region of boreal mixedwood forest located in north-eastern Alberta, Canada (*a*). The study area was divided using the provincial township grid (*b*), yielding 598 cells of 9230-ha size on average. Linear feature densities, in km km^{-2} of dry land, were calculated for each township and are shown in different shades of grey. The black points on the map represent the ignition locations for the 919 lightning fires that were used for analysis. An example of variable collection for one township and four quarter-townships (*c*). Linear feature classes included roads, pipelines and seismic lines, while the forest stand types included were deciduous, white spruce, black spruce, pine, recent burns and cutblocks.

We considered three classes of linear features: roads, pipelines and seismic lines. Linear feature layers from the study area considered valid and complete up to the year 2003 were available for this study. Time-series spatial linear feature data for the area do not exist, and the construction dates of individual features cannot be determined in general; thus, it was necessary to assume that densities had remained constant over the 8-year sampling interval. The road layer did not include detailed attributes such as width, vegetation treatment or type of road, so it was necessary to consider that all delineated roads were equivalent. The available linear feature layers were intersected with the township and quarter-township grids, and densities of roads, pipelines

Table 1. A summary table of explanatory variables used for analyses

$\bar{x}$, mean; s.d., standard deviation; and 5–95%, 5th and 95th percentiles of the observed distribution. Easting, Northing and Area were included in analyses after scaling them down by a factor of 10^5, 10^6 and 10^3 respectively. See *Model covariates* section for details. Road, pipeline and seismic density (km km^{-2} of dry land); deciduous, white spruce, black spruce, pine, burn and cutblock (proportional area)

Name	Variable	Coarse-scale grid			Fine-scale grid		
		$\bar{x}$	s.d.	5–95%	$\bar{x}$	s.d.	5–95%
Road	Road density (km km^{-2} of dry land)	0.35	0.28	0–0.85	0.35	0.34	0–1.00
Pipeline	Pipeline density	0.29	0.35	0–1.08	0.29	0.49	0–1.17
Seismic	Seismic line density	1.77	1.67	0.12–3.88	1.77	2.02	0.04–3.86
Deciduous	Deciduous (proportional area)	0.20	0.15	0.01–0.48	0.21	0.18	0–0.53
White spruce	White spruce	0.05	0.05	0–0.16	0.05	0.66	0–0.19
Black spruce	Black spruce	0.45	0.20	0.12–0.79	0.45	0.24	0.08–0.85
Pine	Jack pine	0.08	0.09	0–0.27	0.08	0.11	0–0.30
Burn	Recent burns	0.07	0.17	0–0.54	0.07	0.20	0–0.62
Cutblock	Cutblocks	0.03	0.05	0–0.14	0.03	0.06	0–0.15
DMC-Lightning	Joint Duff Moisture Code-Lighting index	15.4	4.65	8–24	3.87	2.14	1–8
FFMC-Lightning	Joint Fine Fuel Moisture Code-Lighting index	16.8	4.29	10–24	4.21	2.16	1–8
Easting	North American Datum 27 Universal Transverse Mercator easting at cell centroid (in units of 10^5 m)	4.25	0.77	2.90–5.47	4.25	0.76	2.89–5.45
Northing	NAD 27 UTM northing at cell centroid (in units of 10^6 m)	6.24	0.07	6.11–6.37	6.24	0.08	6.11–6.37
Area	Sampling unit area (in units of 10^3 ha)	9.49	0.12	9.45–9.54	2.37	0.01	2.36–2.38

and seismic lines, in units of km km^{-2} of terrestrial surface area (hereafter referred to as 'dry land'), were calculated for each sampling unit (Fig. 1*c*). For the rest of this manuscript, variable names followed by subscript *t* indicate variables collected at the township scale whereas variable names followed by subscript *q* indicate those collected at the quarter-township scale.

We described the forest and vegetation composition of each sampling unit using digital forest inventory data (Alberta Vegetation Inventory (AVI), Nesby 1997). Mapped forested and other vegetated polygons, or stands, were classified mainly by dominant canopy species composition. The proportional areas of six forested classes were calculated for each sampling unit: deciduous, white spruce, black spruce, jack pine, recently ($\leq$30 year) burned and recently harvested areas (cutblocks) (Fig. 1*c*). Non-forested landscape elements, including water bodies, agricultural land and permanent human infrastructure were omitted from analysis. Based on the site associations and successional relationships between the forested fuel-types (Cumming 2001), there is no reason to expect significant endogenous cover-type changes over the study interval. However, forest composition varied widely among sampling units, providing the spatial contrast required for analysis (Table 1).

The ignition of a lightning fire requires the co-occurrence of a lightning strike under favorable fire weather conditions (i.e. low moisture) (Nash and Johnson 1996). To quantify this, we derived two joint fire weather and lightning indices (Krawchuk *et al*. 2006) from spatially registered lightning flashes and two spatially interpolated fire weather indices: the Duff Moisture Code (DMC) and the Fine Fuel Moisture Code (FFMC). These two components of the Canadian Forest Fire Weather Index System (FWI; Van Wagner 1987) measure moisture content of litter (DMC) or of fast-drying fine fuels and loosely compacted organic layers of moderate depth (FFMC). Geographic coordinates for lightning strikes were obtained from Alberta SRD detection stations; fire weather indices were calculated using daily measurements of temperature, relative humidity and precipitation obtained from weather stations in and around the region and interpolated across the study area. Lightning strike locations were spatially referenced to cells within the township and quarter-townships study grids; however, fire weather indices (DMC and FFMC) were interpolated only to the township grid because we assumed there would be small variation in these indices at the quarter-township scale. For further details on underlying data sources, interpolation procedures and consideration of spatial accuracy, see Krawchuk *et al*. (2006).

Following Krawchuk *et al*. (2006), fuel moisture conditions were considered 'favorable' or 'receptive' to fire ignition if DMC > 34 or FFMC > 87. For each township or quarter-township, we identified days with DMC above 34 or FFMC above 87, and at least one lightning strike. We then counted these days over the 8-year study period to compute DMC-Lightning and FFMC-Lightning (Table 1), which represent the number of days between 1995 and 2002 where fuel moisture conditions were low (DMC > 34 or FFMC > 87) and there was at least one lightning strike detected within a cell (township or quarter-township).

We included continuous covariates for latitude and longitude as proxies for unmeasured spatial gradients, e.g. in climate, or variation in other factors. The North American Datum 27 Universal Transverse Mercator (NAD 27 UTM) measure of northing and easting, in m, were calculated at each sample unit's centroid. These values were then scaled down by a factor of 10^6 and 10^5 respectively, in order to improve convergence of the numerical algorithms used for parameter estimation as in Kéry *et al*. (2005). Total cell (township or quarter-township) areas, in ha, were also calculated. These were incorporated after being scaled down by a factor of 10^3.

Anomalous sample units

Of the 601 coarse-scale cells initially selected for analysis, three adjacent townships had unusually high values of DMC-Lightning_t and FFMC-Lightning_t but no recorded fires. Within these three anomalous townships, most of the days with receptive fire conditions occurred during the summer of 1998, a year with mean annual temperature 1.2°C above provincial normals and below normal precipitation for the north-east region of the province (ASRD 2001). This was accompanied by a marked increase in the number of wildfires, with 1698 fires occurring that year (ASRD 2004), compared with a long-term provincial average of 852 fires per year. The three identified cells did not reflect the same response, and in fact were drivers of a negative relationship between joint fire weather and lightning indices and fire-day frequency; such a relationship is entirely implausible. These townships are adjacent to the Fort McMurray town site, within an area that is known for being wet and swampy (B. Bannerman, Alberta SRD, pers. comm.). Visual inspection of recent aerial photography revealed that at least two of these townships had high levels of industrial land-clearing not reflected in the forest inventory data. These clearings were associated with large industrial infrastructure related to surface mining or subsequent processing of tarsands. Given the massive physical alterations to the land surface of these townships, and their spatial adjacency, we considered they were likely to be outliers and dropped them from analysis.

Of 2370 quarter-townships considered for analysis, one had an extreme value for DMC-Lightning_q and FFMC-Lightning_q; this cell corresponds to the south-west quadrant of one of the three adjacent townships identified as outliers at the coarse-scale analysis. Accordingly, this cell was dropped from the fine-scale analysis.

Statistical analysis

We modeled the response variables, lightning fire-day counts per cell, as a function of the biophysical covariates within a general count regression framework. The R environment for statistical computing (R Development Core Team 2005), version 2.2.0 for Windows, was used for statistical analyses and to prepare graphics.

The simplest regression model for count data is the Poisson distribution (Cameron and Trivedi 1998), where the responses are assumed to be samples from a Poisson process with conditional mean given by some function of the covariates. We used a Generalized Linear Modeling (GLM) framework (McCullagh and Nelder 1989), where the log-conditional mean is a linear function of the covariates (the linear predictor). Poisson data have equal mean and variance; however, real-life data such as ours frequently display overdispersion (variance greater than mean) in the residual or raw data. Overdispersion in the residuals may result from neglected or unobserved heterogeneity that is inadequately captured by the covariates in the mean function. A standard approach in such cases is to use a Negative Binomial (hereafter NB) distribution, where the variance is assumed to be a function of the square of the mean ($\sigma^2 = \mu + \mu^2 \times \theta^{-1}$; where σ^2, variance; μ, expected mean; and θ, dispersion parameter) (Cameron and Trivedi 1998). Data generated by a NB model would be expected to have an excess of both low and high counts relative to the mean. The NB regression was also implemented within a GLM framework. Alternatively, the data may display overdispersion if the incidence of zero counts is greater than that predicted by Poisson, which in our case might be expected because appropriate fire weather conditions and a lightning strike are both prerequisites for a lightning fire to occur. Such data can alternatively be modeled using Zero-inflated Poisson (hereafter ZIP) regression (Lambert 1992).

The ZIP model assumes that a two-stage process generated the observations: the *transition stage* occurs when the observation moves from a state where the event of interest does not or cannot occur to one in which the event does occur according to a Poisson process with rate λ (the *events stage*). The probability of observation i making such a transition is denoted P, and the observed dependent variable takes on a value of zero for all the observations that do not make the transition; P is modeled using logistic regression. The covariates used for the logistic and count components may differ (Lambert 1992); in our case, only joint fire weather and lightning indices (DMC-Lightning or FFMC-Lightning) were included to model the zero inflation, while allowing all the explanatory variables to enter into the count component of the model. The absence of a lightning flash or high fuel moisture will tend to hold a cell in the transition stage; if conditions are receptive, then ignition may occur (the transition is made), and the number of lightning fires actually igniting may be influenced by landscape characteristics such as vegetation or linear features. We implemented ZIP regression using the R function *zeroinfl* contained in the package **pscl** (Jackman 2005). We also fitted Poisson and NB GLMs and used the Vuong test (Vuong 1989) to compare the best ZIP with the best Poisson or NB model. This is a formal test for non-nested models that determines statistically whether the zero-inflated model represents a significant improvement over the other alternatives.

We verified the linearity of the relationship between response and explanatory variables using Generalized Additive Models (GAMs), specifying a Poisson or a binomial error. These tests were conducted at both spatial resolutions separately. The results of such models were used to plot adjusted non-parametrically smoothed estimates of the effect of the covariates, which were visually inspected for non-linearities. If these were detected, appropriate non-linear transformations were included for the corresponding covariate terms. For example, a quadratic term was added to account for the non-linear relationship between fire-day counts and the proportion of black spruce forest within a township. We assessed collinearity between regressors using the Spearman pairwise correlation coefficient. The correlation between road and pipeline density was high at the coarse ($r_s = 0.78$) and the fine ($r_s = 0.72$) scales. According to Bonate (1999), when covariates showing a high degree of correlation ($r >> 0.5$) are included in the same model, standard error estimates may be inflated, indicating that one or both are not relevant to the structural model when in fact they are. In order to account for this confounding effect, we compared models including pipeline or road density, both, and their interaction. Remaining variables had pairwise correlation coefficients $r_s \leq |0.6|$ and we assumed that multicollinearity in these terms would not markedly affect our conclusions.

The main motivation for this research was to assess the effect of linear features on lightning fire ignition; however, we also included covariates for forest composition, weather and geography to control for the previously demonstrated effects of these factors (Krawchuk *et al*. 2006, and references therein). Other than as noted above for some linear feature covariates, we did not include interaction terms. We used a hierarchical model selection approach using Akaike's Information Criterion (AIC; Burnham and Anderson 1998) to determine the best model overall. A change in AIC ≥ 5 was considered evidence of a substantial change in the model's descriptive ability; if this change was <5, a simpler model was selected over a more parameterized one. For each objective (coarse and fine scale) separately, we first reduced a global linear feature model with all three classes of linear features by backward elimination to the most parsimonious model. Similarly, a global vegetation model was reduced to a simpler model. Finally, a global geography model including both easting and northing was also reduced. The reduced linear features, vegetation and geography models were combined into one model, to which one of the weather variables (DMC-Lightning or FFMC-Lightning) and total sample unit area were added. From these two models, the one with the lowest AIC value was selected (hereafter named LVGM) and further reduced in order to yield the final best model (BM). This process was repeated three times in order to select the best model fitted using Poisson (P-BM), NB (NB-BM) and ZIP (ZIP-BM) regression. These families of models were subsequently compared using the Voung test to determine the best model overall (BMO). We fitted also the null and global (including all covariates) models, but only for comparison purposes.

We checked for outliers in the selected BMO using graphs of deviance and Pearson residuals (Cameron and Trivedi 1998). If large residuals were identified, we assessed the change in the magnitude and significance of the coefficients in a model fitted to a dataset without such identified observations. Further graphical assessment of residuals was conducted following Cameron and Trivedi (1998, p. 144).

The adequacy of the BMO at the township and quarter-township scales was individually evaluated using a parametric bootstrapping procedure (Kéry *et al*. 2005). Using the BMO, we generated 1000 replicate datasets by random sampling from the appropriate distribution (Poisson, NB or ZIP) conditional on the covariate values at each spatial unit. For each bootstrapped dataset, model coefficients were re-estimated and a goodness of fit statistic (sum of squared errors (SSE)) was computed. This collection of simulated values of SSE forms the reference distribution with which the observed SSE was compared. We then calculated the proportion of the bootstrapped SSE distribution that had equal or more extreme values than the one obtained for the BMO; if this value was smaller than 0.05, it was decided that the model fit was not satisfactory. In effect, this procedure is a test of the hypothesis that the observed data were generated by the process represented by the fitted model. We assessed model performance by comparing observed proportions *v.* predicted probabilities for each count category (Lambert 1992). Finally, the selected BMOs at the township and quarter-township scales were individually validated using a 1 : 7 testing to training *k*-fold validation procedure (Harrell 2001). This technique randomly divides the original dataset into seven groups; the model is trained iteratively on a dataset without each group, and then tested on the omitted group. The mean squared error

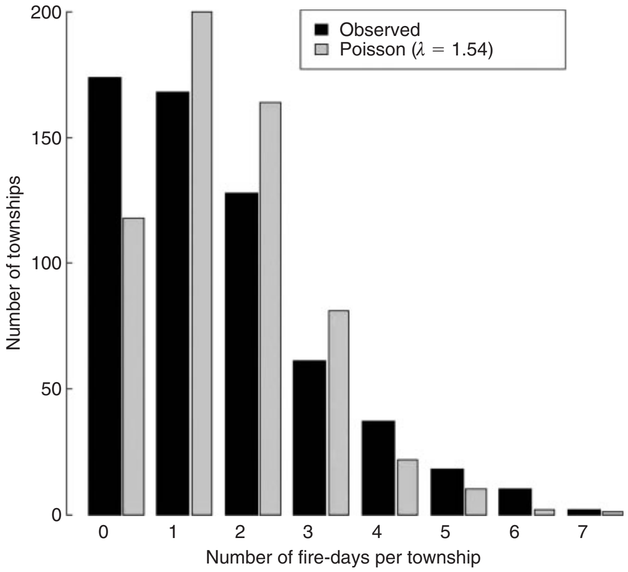

Fig. 2. Histogram of the number of lightning-caused fire days per township ($\sim$10 000 ha). The grey bars show the expected number of fire days under a Poisson distribution with parameter $\lambda = 1.54$. The sample consisted of 919 single fire day events that occurred within 598 townships between 1995 and 2002.

((observed − predicted)^2) from this testing procedure was calculated and reported as a measure of predictive accuracy.

Finally, we used the selected BMO obtained from the coarse-resolution analysis to estimate the number of lightning fire-days that would have occurred in the study area during the 8-year interval under two hypothetical scenarios: (1) no roads present, and (2) a 'road-saturated landscape', where every cell was assigned a road density of 0.85 km km^{-2}. This last value corresponds to the upper 95th percentile of the current road density distribution in the study region.

Results

Do linear features increase the frequency of lightning fire-days per township?

Over the study interval, the final sample of 598 townships had 1043 lightning-caused fires, which burned a total area of 1905 km^2. Only 13% of cells recorded multiple fires on the same day (see *Fire-day counts* section). After counting these multiple fire events as single fire-days, a total of 919 fire-days remained for analysis (Fig. 1*b*). Of these, 58% had been detected from a fire tower, 37% from the air and 5% from the ground.

The mean fire-day count was 1.54 (s.d. = 1.49) and the variance to mean ratio was 1.44, indicating the data was over-dispersed. Almost 60% of the townships had fire-day counts of 0 or 1. The frequencies of 0 and 1 counts were roughly equal, indicating an excess of zeros relative to expectation under a Poisson process (Fig. 2). Fire-day counts varied among seasons, with 13, 65 and 22% occurring during spring, summer and fall respectively.

Seismic lines were the most abundant linear feature class at the coarse-resolution grid, with a mean of 1.77 km km^{-2} and a maximum value of 16.1 km km^{-2} (Table 1). The proportional

Table 2. Township-scale regression models

Zero-inflated (ZIP), Poisson (P) and Negative Binomial (NB) models for the number of lightning fire-days per township (~10 000 ha) over the period 1995–2002, with relative measures of model support. Models were fitted to a sample of 598 townships located in north-eastern Alberta. Note: the best model overall is shown in bold. Variable names are described in Table 1. k, number of parameters in the model; AIC, Akaike Information Criterion; ΔAIC, increase in AIC score in any one model with respect to the model with the lowest AIC score; λ, expected number of fire-days; *P*, probability of occurrence of a fire-day; LVGM, linear feature, vegetation and geography model

Model	Terms	k	AIC	ΔAIC
$Null_t$	λ ~ 1	1	2020	124
$ZIP\text{-}Global_t$	*P* ~ DMC-Lightning + FFMC-Lightning λ ~ road + pipeline + seismic + burn + deciduous + white spruce + black spruce + black spruce^2 + pine + cutblock + DMC-Lightning + FFMC-Lightning + easting + northing + area	22	1907	12
$ZIP\text{-}LVGM_t$	*P* ~ DMC-Lightning λ ~ road + burn + deciduous + white spruce + black spruce + black spruce^2 + cutblock + DMC-Lightning + easting + northing + area	14	1898	3
$ZIP\text{-}BM_t$	*P* ~ DMC-Lightning λ ~ road + burn + deciduous + white spruce + black spruce + black spruce^2 + DMC-Lightning + easting	11	1895	0
$P\text{-}Global_t$	λ ~ road + pipeline + seismic + burn + deciduous + white spruce + black spruce + black spruce^2 + pine + cutblock + DMC-Lightning + FFMC-Lightning + easting + northing + area	16	1917	22
$P\text{-}LVGM_t$	λ ~ road + burn + deciduous + white spruce + black spruce + black spruce^2 + cutblock + FFMC-Lightning + easting + northing + area	12	1910	15
$P\text{-}BM_t$	λ ~ road + burn + deciduous + white spruce + DMC-Lightning + easting	7	1907	12
$NB\text{-}Global_t$	λ ~ road + pipeline + seismic + burn + deciduous + white spruce + black spruce + black spruce^2 + pine + cutblock + DMC-Lightning + FFMC-Lightning + easting + northing + area; θ	17	1909	14
$NB\text{-}LVGM_t$	λ ~ road + burn + deciduous + white spruce + black spruce + black spruce^2 + cutblock + DMC-Lightning + easting + northing + area; θ	13	1902	7
$NB\text{-}BMO_t$	**λ~ road + burn + deciduous + white spruce + easting; θ**	**7**	**1898**	**3**

areas of the six forest types ranged from 0 to 92% cover, with black spruce the most abundant (mean, $\bar{x} = 0.45$, s.d. = 0.20) and cutblocks the least abundant class ($\bar{x} = 0.03$, s.d. = 0.05). DMC-$Lightning_t$ had a maximum of 30 and a mean value of 15.4 days; the maximum and mean values for FFMC-$Lightning_t$ were 34 and 16.8 respectively (Table 1).

The two best models in the ZIP and NB categories were ZIP-BM_t and NB-BMO_t (Table 2), the latter having ΔAIC = 3 relative to the former. The best Poisson model had ΔAIC = 9 (Table 2), consistent with the overdispersion detected in the raw data. Predictions from models P-BM_t, NB-BMO_t and ZIP-BM_t fell very close to the observed proportions (Fig. 3); however, the Poisson model showed the largest discrepancy, particularly for the zero and one fire-day counts. Although the best ZIP model's predictions were closest to the observed values and this model had the lowest AIC score, it was not a significant improvement over the best NB model based on the Vuong test statistic (1.22, $P = 0.11$). The best NB model lacks the fire weather covariate present in ZIP-BM_t. Therefore, it is much more convenient for use in predictive applications because there is no need to project or simulate a complex weather variable. As, in addition, the evidence favouring one over the other was weak or inconclusive, we selected NB-BMO_t as the BMO.

The maximum likelihood estimates and standard errors for each term included in NB-BMO_t are shown in Table 3. Increasing road density and the proportion of white spruce stands per cell is correlated with an increase in the expected number of fire-days (Fig. 4*a*, *d*). Increasing proportions of recently burned areas and deciduous-dominated forest have a negative effect on the conditional mean (Fig. 4*b*, *c*). Finally, we found a negative influence of easting. We measured the effect-size of individual covariates as the ratio of the conditional means calculated at the lower 5th percentile and upper 95th percentile of the covariate values sampled (Table 1). Road density increased the conditional mean by a

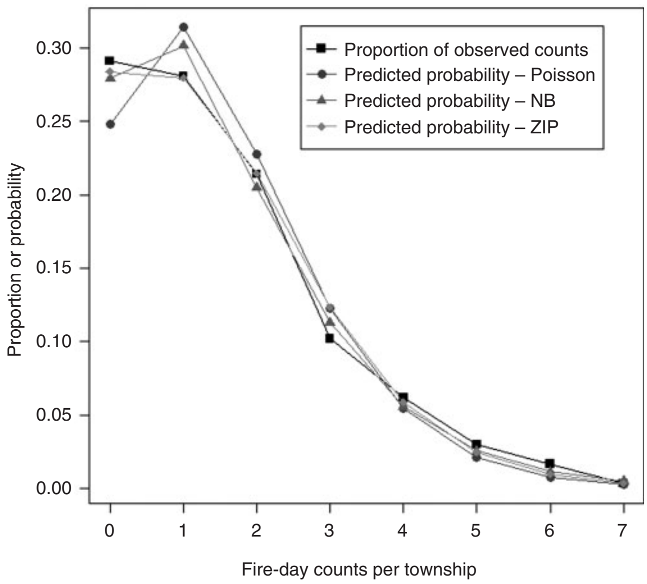

Fig. 3. Observed distribution of lightning fire-day counts per township (~10 000 ha cell), compared with the predicted probability for each count category under a Poisson, Negative Binomial (NB) and Zero-Inflated Poisson (ZIP) regression model. Predicted probabilities were calculated using models P-BM_t, NB-BMO_t and ZIP-BM_t respectively (Table 2).

Table 3. Township-scale selected best model

Maximum likelihood estimates, standard errors and *P* values for each term included in model NB-BMO$_t$ (Table 2). Variable names are described in Table 1. ΔAIC = increase in AIC when each term is removed from the model

Term	β	s.e.	*P* value	ΔAIC
β_0	1.27	0.24	<0.01	
Road	0.63	0.13	<0.01	20.7
Burn	−1.14	0.29	<0.01	14.7
Deciduous	−1.97	0.31	<0.01	39.6
White spruce	3.96	0.74	<0.01	24.2
Easting	−0.20	0.05	<0.01	13.5
Theta (θ)	6.67	2.22		

factor of 1.7, while the effect size of white spruce forest cover was 1.8. Similarly, burned and deciduous stands decreased the conditional mean by a factor of 1.8 and 2.5 respectively. The relative importance of individual covariates was assessed by the difference in AIC value resulting from their removal from the final model (Table 3, last column). The importance of roads, white spruce and deciduous forest was higher than burned stands and geographical location.

Seven-fold validation of model NB-BMO$_t$ yielded an estimate of prediction error of 1.09. Graphical inspection of residuals identified one potential outlier. When we refitted the selected best model to a dataset excluding this point, the significance and signs of the coefficients did not change while their magnitudes remained within one s.e. of the original value, supporting the robustness of NB-BMO$_t$. Based on the parametric bootstrap, the selected BMO fits the data adequately, as evidenced by an SSE value of 1127, which fell well within the simulated distribution of SSEs ($P = 0.68$, upper-tailed test).

Using model NB-BMO$_t$ (Table 3), we estimated that had there been no roads in the study area, only 732 ± 135 (135 = 1.96 × s.e.) fire-days would have occurred during the study interval, which represents a 20% reduction with respect to the original value recorded. However, if the study region were covered by 'road-saturated landscapes' (see *Statistical analysis* section for definition), one would expect 1255 ± 249 fire-days, representing a 37% (approximate 95% confidence interval, CI: 9, 64%) increase with respect to the actual value recorded.

Does the apparent effect of linear features change when the spatial resolution is increased?

The mean fire-day count was 0.39 (s.d. = 0.68) at the quarter-township scale. Spatial heterogeneity and contrast among linear feature densities and forest composition increased at the finer (quarter-township) resolution, as expected (Table 1). Only 4% of cells were devoid of linear features, and the proportions of all forest-cover classes ranged from 0 to 99%.

The best ZIP and NB models were equivalent based on AIC scores (Table 4) and Vuong test statistics (0.02, $P = 0.49$), and contained the same covariates. The best Poisson model was relatively poor based on AIC (ΔAIC = 13; Table 4). Accordingly, we selected NB-BMO$_q$ as the BMO at the quarter-township scale. The signs and magnitudes of parameter estimates included in NB-BMO$_q$ differed little from the estimates at the township scale, so we do not report the parameter estimates. Road density was again found to exert a significant positive effect, increasing the expected frequency of lightning fire-days by a factor of 1.6. The proportion of white spruce stands per cell was found to increase the expected number of fire-days, while recently burned areas, deciduous-dominated forest and easting had the opposite effect. Additionally, we detected a quadratic relationship between the proportional harvested area and the conditional mean. The selected model fitted the data adequately (SSE = 1038, $P = 0.50$), and analysis of residuals supported its robustness. Seven-fold internal cross validation yielded an estimate of prediction error of 0.52.

Discussion

Lightning fire ignition results from the interaction between broad-scale weather patterns and the flammability properties of the fuels on which lightning flashes strike. We found that this process is also positively influenced by at least one class of anthropogenic linear feature, namely roads. The influence of roads was consistent between the fine (∼2400 ha) and coarse (∼10 000 ha) scales of analysis, indicating that our inference was not an artifact of the model spatial resolution.

Potential mechanisms behind the road effect

Roads have been demonstrated to produce significant changes in landscape structure and composition (Forman and Alexander 1998; McGarigal *et al*. 2001). For example, roads may serve as a conduit for the movement of organisms across the landscape, including the deliberate or accidental spread of non-native plant species (Forman and Alexander 1998). Of particular interest in our case is the increase in fuel-bed flammability resulting from native and exotic grass invasions along roadsides, which have the potential to affect the frequency, size, spatial pattern and, in some cases, intensity of fires (D'Antonio and Vitousek 1992; Brooks *et al*. 2004).

In the boreal mixed-wood forest of Saskatchewan, Sumners (2005) found that vegetation quadrats next to roads contained the highest amount of exotics, with 40% of the non-native species belonging to the Gramineae family. This addition of non-native species of grasses to the native pool already thriving along roadsides represents a new source of fuel (Stoner *et al*. 2004), as many perennial grasses tend to produce litter that is highly combustible (Hogenbirk and Sarrazin-Delay 1995). We suggest this might be the underlying mechanism for the positive road effect we detected. Thus, it is not the case that lightning flashes are somehow attracted to roads, as the paved or gravelled surface of a road is not flammable *per se*. We suggest that when a lightning flash discharges close to a roadside, it is likely to strike an area with a higher proportion of flammable fine fuels than is generally available within forested areas.

Alternatively, it might be the case that roads are associated with an increased frequency of lightning strikes. Tall pieces of metallic infrastructure such as radio and communication towers or transmission lines, which are generally found along the sides of roads, might be attracting lightning activity (Byerley *et al*. 1999). Equally, road density and well counts are correlated ($r_s = 0.62$), and metallic well heads and associated equipment

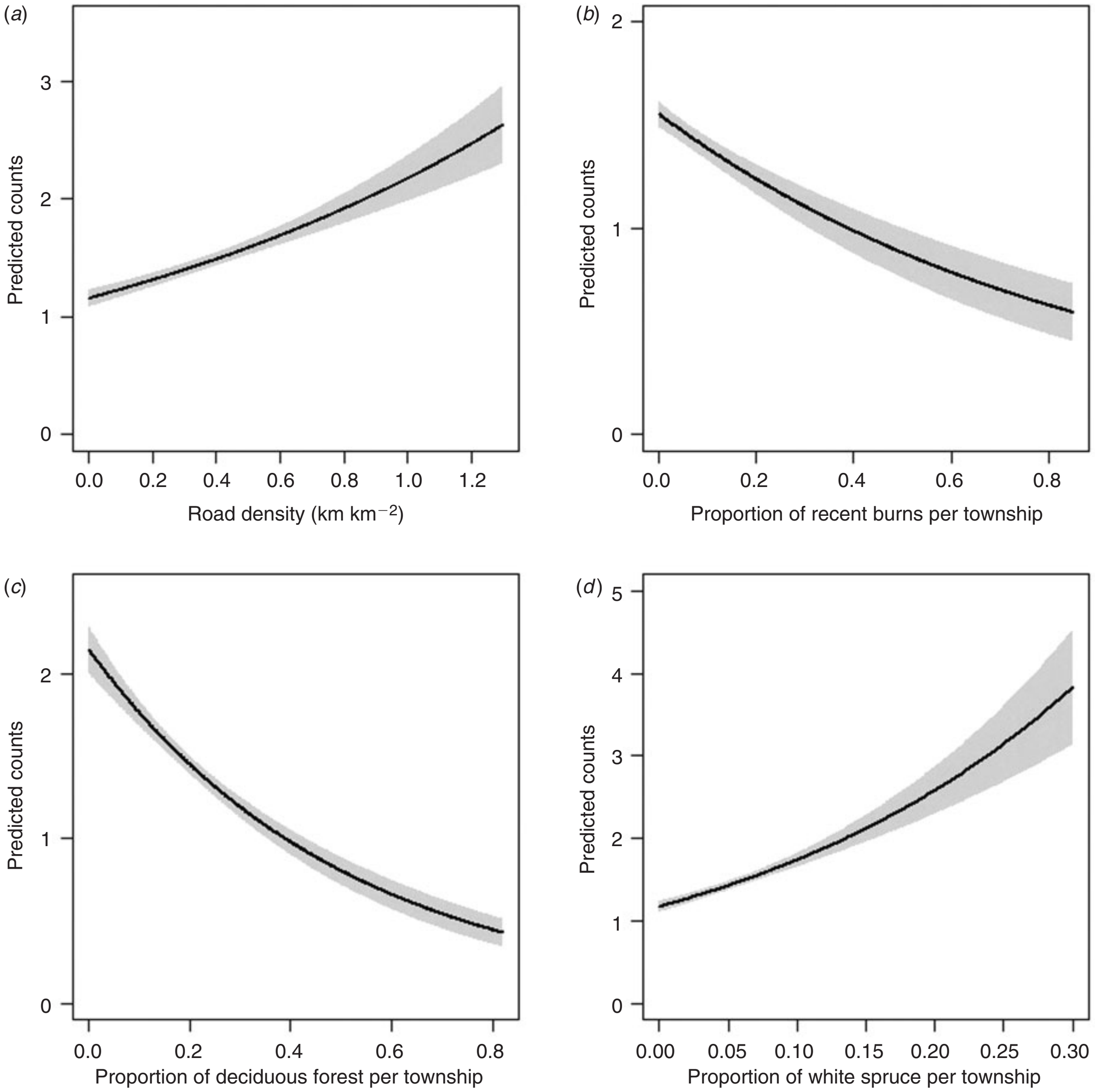

Fig. 4. Predicted lightning fire-day counts per township (black lines), together with 95% confidence interval (grey envelopes), as a function of (*a*) road density (km km^{-2} of dry land); (*b*) proportion of recent burns; (*c*) proportion of deciduous-dominated forest; and (*d*) proportion of white spruce-dominated forest. Fitted frequencies were calculated using model NB-BMO$_t$ (Table 3), and the mean values for the remaining covariates in the model. Note: the scale of the *y*-axis differs between (*a*), (*b*), (*c*) and (*d*).

might act as lightning attractors as well. If such was the case, the positive correlation between road density and lighting fire ignition frequency would derive simply from an increased frequency of lightning strikes next to roads. However, this explanation is not supported for our study region, given the low correlation between lightning strike frequency and road density ($r_s = 0.10$) or well count ($r_s = 0.12$) within townships.

A third competing hypothesis is that the observed relationship between road density and lightning fire frequency is simply the outcome of increased detection and reporting activity resulting from people using the road network. However, 95% of the fires we considered for our analysis had been detected either from the air or from a lookout tower. The remaining 5% of fires detected by roadside observers represent a small proportion (roughly 1/4) of the estimated effect size. Given that at least some, if not most of these, would have eventually been detected by other means in the absence of any roads, it cannot be concluded that the correlation we found is an artifact of higher detection rates along roads. Therefore, we consider this third alternative hypothesis can be rejected as well.

A fourth hypothesis, advanced by Alberta Forest Protection staff (Alberta SRD), is that the observed correlation between roads and lightning fires is not causal, but reflects a correlation between road location, topography and lightning incidence. Although the region has limited topographic relief, low-lying areas are frequently dominated by wetlands where

Table 4. Quarter-township scale regression models

Zero-inflated (ZIP), Poisson (P) and Negative Binomial (NB) models for the number of lightning fire-days per quarter-township (~2400 ha) over the period 1995–2002, with relative measures of model support. Models were fitted to a sample of 2369 quarter-townships located in north-eastern Alberta. Note: the best model overall is shown in bold. Definitions and terms are as in Table 2

Model	Terms	k	AIC	ΔAIC
$Null_q$	$\lambda \sim 1$; $P \sim$ DMC-Lightning + FFMC-Lightning	1	3915	160
ZIP-$Global_q$	$\lambda \sim$ road + pipeline + seismic + burn + deciduous + white spruce + black spruce + pine + $pine^2$ + cutblock + $cutblock^2$ + DMC-Lightning + FFMC-Lightning + easting + northing + area; $P \sim$ FFMC-Lightning	20	3767	12
ZIP-$LVGM_q$	$\lambda \sim$ road + burn + deciduous + white spruce + pine + cutblock + $cutblock^2$ + FFMC-Lightning + easting + northing + area; $P \sim 1$	14	3759	4
ZIP-BM_q	$\lambda \sim$ road + burn + deciduous + white spruce + cutblock + $cutblock^2$ + easting	9	3755	0
P-$Global_q$	$\lambda \sim$ road + pipeline + seismic + burn + deciduous + white spruce + black spruce + pine + $pine^2$ + cutblock + $cutblock^2$ + DMC-Lightning + FFMC-Lightning + easting + northing + area	17	3776	22
P-$LVGM_q$	$\lambda \sim$ road + burn + deciduous + white spruce + pine + cutblock + $cutblock^2$ + DMC-Lightning + easting + northing + area	12	3770	15
P-BM_q	$\lambda \sim$ road + burn + deciduous + white spruce + pine + cutblock + $cutblock^2$ + easting	8	3768	13
NB-$Global_q$	$\lambda \sim$ road + pipeline + seismic + burn + deciduous + white spruce + black spruce + pine + $pine^2$ + cutblock + $cutblock^2$ + DMC-Lightning + FFMC-Lightning + easting + northing + area; θ	18	3764	9
NB-$LVGM_q$	$\lambda \sim$ road + burn + deciduous + white spruce + pine + cutblock + $cutblock^2$ + DMC-Lightning + easting + northing + area; θ	13	3757	2
NB-BMO_q	**$\lambda \sim$ road + burn + deciduous + white spruce + cutblock + $cutblock^2$ + easting; θ**	**9**	**3755**	**0**

road construction is difficult and where lightning ignitions may be inhibited by high fuel moisture. Roads are preferentially constructed on and over drier upland sites that may attract lightning or where fuels may be more susceptible to ignition, independently of the presence of roads. However, the topographic features and site characteristics that favor road construction are also associated with aspen and white spruce forest (Bridge and Johnson 2000). Because we controlled for forest composition and found no significant correlation between road density and lightning strikes, we consider the 'topography hypothesis' to be unlikely. An explicit test could be made if a sufficiently high-resolution digital elevation model was available.

As in many other regions subject to wildfire, the frequency of human-caused fires is correlated with road density in our study region (Cumming *et al.* 1995; Vega Garcia *et al.* 1995). Therefore, we must consider the possibility that our results are an artifact of classification errors in the data. For a review of fire management history in Alberta, see Cumming (2005) and references therein. It is sufficient here to note that the study region is completely surveyed by a network of fire towers established before 1968 and by a lightning detection system that has been in place since the early 1980s. All fires over the period of record (1961 through to the present day) were assigned a cause whether by lightning or some human activity, or were classed of unknown cause when no specific determination could be made. Cause determination is the responsibility of the initial attack crew leader. To summarize discussions with M. Kakoullis (Alberta SRD, pers. comm.): lightning leaves physical evidence in the form of tree scars and characteristic flame patterns that are easily recognizable by initial attack crews; determination of lightning cause would have been supported by lighting strikes observed from the nearest fire tower, or by the remote detection system; human fires are evidenced by tyre tracks, traces of accelerants and camp fires; crew leaders would have human causes in mind in the vicinity of roads; formerly many lightning fires were erroneously attributed to cigarettes while lightning fires ignited in brush piles may still be misclassified. The level of training and the precision of cause determination have increased over time, culminating in 1999 with the adoption of a standardized training and investigation system (NFPA 2008). Training and investigative efforts were less intensive before 2000, but serious efforts have been made since at least the late 1980s. Under the current system, which was in place for the last 3 years of our 8-year study period, the misclassification rate is at most 2% (M. Kehr, Alberta SRD, pers. comm.). Over our study interval and region, there were 1049 lightning fires, 247 human-caused fires and 33 fires of unknown cause. For the last 3 years of this period, classification errors are believed to have been negligible; error rates for the first 5 years were presumably somewhat higher but no estimate is available. However, given that the total number of recognized human-caused fires was only 18.6% of the total number of fires recorded, we do not consider that misclassification rates could have been high enough to compromise our results.

Lack of effect of other linear features

The high and increasing densities of seismic lines and pipelines in our study area, coupled with anecdotal reports and expert opinion, led to the concern that these features might in some way increase the number of lightning fires. This study was initially undertaken to address this concern. Pipelines and seismic lines are revegetated using similar general agronomic grass mixes as roadsides (Revel *et al.* 1984); and several non-native species of grasses have been found established on seismic lines (MacFarlane 2003). Thus, one might expect pipelines and seismic lines to have a positive effect on lightning fire ignition as well. We found no evidence for any such effect. Cameron *et al.* (1997) noted that areas that are subjected to consistent disturbance favor the establishment and survival of exotic and weedy species; roadsides are continuously disturbed for maintenance purposes (e.g. to maintain visibility for wild animals crossing), whereas seismic lines experience a broad range of disturbance frequencies, from complete abandonment after initial construction to yearly reuse for oil and gas exploration (MacFarlane 2003). This suggests that seismic lines and roads should differ in the relative abundance of grasses on them, with grasses being a more consistent and long-term inhabitant of the latter. Seismic lines are also narrower than roads, so it is expected that their microclimatic conditions will be strongly affected by the adjacent forest canopies (Carlson and Groot 1997). Thus in some mixed-wood stands, the shadow provided by nearby tall trees might help retain plant moisture, whereas in more open areas, adjacent to cutblocks or on the intersection between lines for example, direct sunlight might reduce the water content of the vegetation on the seismic line (Revel *et al.* 1984). Additionally, Lee and Boutin (2006) noticed that tracked use of seismic lines adjacent to black spruce bogs alter their local hydrology, converting them into a very wet fen dominated by sedges. This suggests that the influence of individual seismic lines on the ignition of lightning fires will be positive or negative depending on the particular details of their moisture condition, an attribute that would be very hard to measure at the scale required for the present analysis.

Pipelines are less abundant than roads within our study region; but their spatial distributions are similar, and pipelines are also consistently disturbed for maintenance. We found that road and pipeline densities were positively correlated at both scales of analysis (see *Statistical analysis* section), which could confound statistical inference. We addressed this issue by assessing the relative strengths of evidence for alternate models with covariates for road density, pipeline density, both, as well as their interaction. We found that the effect of roads consistently dominated that of pipelines, with pipeline density being a significant predictor only when no other linear feature covariates were present in the same model. This suggests that the road effect disguises the influence pipelines may potentially have, and indicates that the approach we followed was not able to conclusively tear apart each separate effect, but more likely identified roads as a surrogate for the effect of other anthropogenic linear features such as pipelines.

Influence of weather and fuels

All of our models incorporated covariates for fire weather and lightning through a joint fire weather and lightning index. Krawchuk *et al.* (2006) demonstrated the influence of these indices on annual rates of lightning fire ignition; however, we did not detect this. We suspect the reason lies in the differences in temporal scale between these studies. The joint fire weather and lightning indices quantified the total number of days over 8 years where lightning and appropriate low moisture conditions were detected within a cell; in prior studies, these have been measured at annual scales. Thus, interannual variation in weather–lightning conditions within cells, averaged over several years, might attenuate a true annual effect. This is supported by Krawchuk *et al.* (2006), who found no evidence for stable interannual spatial patterns in joint fire weather and lightning indices in this region over an earlier interval (1983–93).

We found evidence of a strong influence of forest composition on spatial variation in fire-day counts. Previously burned areas and deciduous-dominated stands decreased the expected mean, whereas white spruce-dominated stands had a positive influence. These results are consistent with findings by Krawchuk *et al.* (2006) for the same study region and will not be further discussed here.

Observed spatial patterns, and the relationship between pattern and process are a function of the spatial scale of analysis (O'Neill *et al.* 1996). Rare landscape elements are typically less well represented as resolution decreases and spatial complexity decreases as well (Cain *et al.* 1997). In this instance, increasing the spatial resolution did not reveal an effect of pipelines or seismic lines, which was what we expected. However, increasing the spatial resolution from ~10 000 to ~2400 ha did reveal an effect of harvested areas. Despite the 50+ years of harvesting history in the study region, and its recent intensification, recently (<30 year) harvested areas are not yet a widespread element in this landscape, covering only 2.6% of the area. However, harvested areas do tend to be spatially aggregated where they occur and, as might have been predicted from Cain *et al.* (1997), the effect of this 'rare' fuel type was evident only after increasing the spatial resolution of analysis.

We conceived lightning fire-day frequency per unit area as a two-stage process: a *transition* stage, where a particular cell might or might not experience appropriate weather–lightning conditions conducive to fire ignition; and a subsequent *events* stage, where the number of fires per 'transitioned' cell is then determined by local landscape characteristics. Accordingly, we fitted ZIP regression models (Lambert 1992), but found no evidence to favor these over simpler NB models. The lack of significance of joint fire weather and lightning indices at both analyzed spatial resolutions might be responsible for the poor performance of the ZIP models we detected. We conclude though that, over the long term, spatial variation in fire-day frequency per unit area is better described by a simpler one-stage point process determined by a single parameter, the process intensity or mean, which varies among landscapes depending on their local characteristics and, to some degree, regional climatic trends.

Well-quantified relationships between the biophysical environment and the frequency of fire ignitions are essential to form a complete understanding of fire regimes in boreal and other ecosystems. After accounting for the influences of forest fuels, weather and lightning conditions, and geography; we found a significant effect of one anthropogenic linear disturbance, roads, on the frequency of lightning fires in the boreal forests of north-eastern Alberta. Our results also showed that a hypothetical 'road-saturated' study region (Schneider *et al.* 2003) would experience a 37% (95% CI: 9, 64%) increase in the frequency of days where lightning fires occur, implying a slightly larger proportional increase in the number of lightning fires. This suggests that projected increases in road density, associated with future industrial developments in the region, may lead to major changes in the local fire regime and possibly to subsequent ecosystem-level transformations (Mack and D'Antonio 1998). In terms of land cover and development trajectory, the study region is fairly typical of the 650 000 km^2 Boreal Plains Ecozone (Wiken 1986). The increased incidence of fire that, our models imply, will result from the developing road network may have serious implications for sustainable forest and ecosystem management of this very large area. Thus, we recommend further research to verify our findings, elucidate the precise mechanisms and, if possible, develop methods for mitigation.

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