Spatial and temporal patterns of wildfire ignitions in Canada from 1980 to 2006

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Abstract

A spatially explicit baseline measure of historic, current, and future wildfire ignition expectations is required to monitor and understand changes in fire occurrence, the distribution of which climate change is anticipated to modify. Using spatial-temporal patterns of fire in Canada, we present a method to identify baseline expectations and ignition trends between 1980 and 2006 across 1km spatial units. Kernel density estimates of wildfire ignitions and temporal trajectory metrics were calculated to describe expected ignition density, variability from expected density, and increasing or decreasing density trends. Baseline ignition expectations and trends were used to create unique fire ignition regimes and assess anthropogenic influence on ignitions. Fire ignition densities decreased exponentially as distance to road or populated places increased, and largest ignition trends occurred closest to both variables. Fire ignition regime delineation was more dependent on human transportation networks than human settlement. These findings provide a unique approach to quantifying ignition expectations. This research highlights the potential of this baseline approach for monitoring efforts and fire-environment interaction research and offers a preliminary spatially explicit model of wildfire occurrence expectations in Canada.

Summary

Spatial and temporal analysis of wildfire in Canada was completed to create baseline expectations of ignitions at 1 km spatial units. This baseline is used to delineate unique ignition regimes, explore anthropogenic influence on ignition expectation, variation and trend.

Introduction

Forests are subject to a range of natural and anthropogenic disturbances. Wildfire is considered to be the dominant natural disturbance in boreal forests due to the possibility of complete stand replacement (Johnson, 1992), and while variable approximately two million hectares of forest burn annually in Canada (Stocks *et al.* 2002). Fire is a driving factor for many ecological processes (Whelan, 1995), shapes landscape composition (Taylor and Skinner, 2003) and impacts carbon cycling (Kasischke *et al.* 1995).

Wildfire occurrence is influenced by four main factors: weather/climate (Flannigan and Harrington 1988), fuels (Romme 1982), ignition agents (Malamud *et al.* 2005), and humans (Rollins *et al.* 2001). Due to the spatially varying nature of factors influencing fire, fire ignition densities are also spatially heterogeneous. Spatial variability may be attributed to the vegetation heterogeneity (Larsen 1997), the temporal fire cycle (Parisien and Sirois 2003; Rollins *et al.* 2002), and/or vegetation and climate interactions (Bergeron *et al.* 2004). Spatial clustering has been found in both lightning caused fires (Podur *et al.* 2003; Diaz-Avalos *et al.* 2001) and in human caused fires (Yang *et al.* 2008; Cardille *et al.* 2001). Human activity can alter spatial pattern of wildfire in many anthropogenic regimes (Yang *et al.* 2007; Cardille *et al.* 2001), though the amount of impact may fluctuate with socioeconomic variables (Prestemon *et al.* 2002).

Temporal variations also occur in wildfire ignition densities. Ignitions per year can fluctuate in Canada with only 5,438 fires occurring in 2000 (Johnston 2000) to over 12,000 in 1989 (Stocks *et al.* 2002). Fire regimes are known to be extremely sensitive to climate (Flannigan and Harrington 1988), with Stocks *et al.* (2002) indicating that climate change impacts will be most significant in the boreal forest. Models have indicated expected increases in area burned (Flannigan *et al.* 2005), fire occurrence and severity (Flannigan *et al.* 2000; Stocks *et al.* 1998), fire season length (Wotton and Flannigan 1993), and lightning activity (Price and Rind 1994). Despite average trends localized climate impacts are spatially dependent; for instance, Bergeron *et al.* (2004) has found locations where projected fire frequency is lower than historical numbers under increased atmospheric CO_2 scenarios. It is therefore important to quantify temporal pattern of ignitions at local spatial scales.

Spatial studies of wildfire typically emphasize area burned, total number of fires, or fire season length summarized over study area (e.g., Westerling *et al.* 2006; Stocks *et al.* 2002; Bergeron *et al.* 2001; Niklasson and Granstrom 2000; Weber and Stocks 1998). Fire occurrence cannot be explained solely by aspatial measures (Flannigan *et al.* 2005; Weber and Flannigan 1997; Whelan 1995) and as fire datasets have become better developed and spatial data analysis is more accessible, spatial pattern characterization of fire occurrence has provided benefits (Tuia *et al.* 2008b; Yang *et al.* 2007; Parisien *et al.* 2006). However, these studies often summarize spatial pattern for a geographic region (e.g., an ecozone, province/state or country) or have a small spatial analysis extent. Conversely, a recent study by Krawchuk *et al.* (2009) examines forest fire distribution at global extents and a 100 km spatial resolution. There is a gap in fire research with few studies conducted at fine spatial scales, over larger areas, and through many time periods.

Fire managers in Canada utilize the outputs of the Canadian Forest Fire Danger Rating System (CFFDRS) for daily decision making on forest fire management (Stocks *et al.* 1989). Fire danger describes the overall static and dynamic factors in a fire environment that contribute to ignition ease, spread rate, difficultly of control, and fire impact (Wotton, 2009). The CFFDRS is comprised of four components: the Fire Weather Index System (FWI), the Fire Behavior Prediction System (FBP), the Accessory Fuel Moisture System (AFMS), and the Fire Occurrence Prediction System (FOP). The FWI system (Van Wagner 1987) is used to evaluate fire weather conditions in a standardized forest type, providing a daily index based on temperature, relative humidity, wind speed and rainfall. The FBP system (Forestry Canada Fire Danger Group 1992) uses FWI outputs and location specific information to provide quantitative assessments of fire behavior in major Canadian fuel types. The AFMS allows for more specific temporal models of fuel moisture based on stand specific measures. The FOP system represents the expected fire occurrence in an area. There is no single, unified system for assessing fire occurrence probability across Canada and much of the prediction is based on FWI output, lightning and potential human activity, and the manager's professional experience. For a more complete description of the CFFDRS and its constituent systems see Wotton (2009).

The FOP system does not currently have a standardized mechanism for assessing wildfire ignition probability across Canada (Wotton 2009). This CFFDRS component relies heavily on daily weather conditions, which are already reported in the FWI, and the manager's expertise. The development of an expected ignition baseline would assist fire managers in understanding the future fire activity potential in a management area. Many factors influence whether a fire will ignite but the realization of a fire pattern is susceptible to a certain amount of variation. In order to monitor change, it is important to know baseline spatial-temporal fire conditions at a fine spatial resolution and over a national spatial extent. Identifying and mapping unexpected fire pattern (that which is outside the acceptable variation) would allow managers to determine where change is occurring. Further, ecological studies can be informed through knowledge of disturbance rates, with unusual rates over a region such as an ecozone or a particular location informing on habitat and possible changes to the nature of a given ecosystem (Duro *et al.* 2005).

The goal of this paper is to characterize the spatial and temporal pattern of wildfire ignition across Canada using ignition density estimates and temporal trajectories. We will demonstrate the potential of the ignition expectation baseline as a wildfire occurrence model and fire ecology research product by completing two objectives:

1. Regime Delineation: Summarize spatial and temporal wildfire occurrence patterns by ecozone and identify new regions with similar historical space-time ignition patterns in Canada.

2. Wildfire Ecology: Identify the relationship between fire ignition density and anthropogenic factors across Canada.

This study will focus on wildfire ignitions rather than area burned. While area burned is an important element of fire impact on forest systems, it greatly depends on human decision for suppression or non-suppression. This is exemplified by the often unsuppressed lightning fires in northern Canada which account for ~80% of national area burned (Stocks *et al.* 2002). Removing post-fire suppression from the analysis emphasizes the underlying ecological conditions leading to ignition.

Study Area and Data

Study area

The extent of this study is 6,897,200 km^2 of forested ecozones of Canada (Figure 1). Ecozones are ecological regions that consist of similar biotic and abiotic factors such as topography, vegetation, and climate (Ecological Stratification Working Group 1995). The Boreal Shield and Taiga Shield were divided into east and west constituents due to their large size and differences in climate and fire occurrence (Amiro *et al.* 2001; Stocks *et al.* 2002; Parisien *et al.* 2006).

Wildfire data

The National Fire Database (NFDB) is the most complete collection of Canadian wildfire data. The NFDB is compiled by the Canadian Forest Service from the 13 Canadian fire management agencies. For more information on the creation of the NFDB (previously referred to as the Large Fire Database) see Stocks (2002). The NFDB builds upon the LFDB as fires smaller than 200ha are now included when information is available. From the NFDB, fires were mapped as points in a Geographic Information System (GIS). Each fire point represents the presumed ignition location of the fire and has attribute information including: start date, fire size, and cause. Ignition cause, either human or lightning, may fluctuate spatially or through time (Figure 2). Both are included in this study to not assume underlying spatial conditions controlling susceptibility.

The NFDB data completeness varies between agencies and years and while some records date back to 1918, others were not mapped prior to 1980. Due to considerations of completeness and consistency, plus changes in detection with satellite and airborne technology, this study focuses on fires between 1980 and 2006. There are more than 280,000 fires in the database, with 190,338 fires occurring within the study time range. Even with the more limited temporal window, considerations remain: there is a lack of suitable contributions to the NFDB for Manitoba, Nova Scotia, Newfoundland for 2000-2006; Northwest Territories for 2006; and Quebec for 2001-2006. Additionally, fire detection varies across the landscape and ignitions may be unrecorded if they are remote and small enough to be unobserved by aerial technology.

Anthropogenic covariates

Two variables were used to assess anthropogenic influence on wildfire ignition: proximity to road and proximity to populated places. The proximity to roads provides, for each 1 km cell in the study area, Euclidean distance to nearest road of any size as specified by the 2008 road network file from Statistics Canada. The proximity to populated places coverage is similar but uses the distance to persistent night time light derived from the DMSP Operational Linescan System. This coverage represents 100% of populated places with a population above 5000, 96% of population above 500, and 65% of population 499 or less.

Methods

Kernel density estimation

The NFDB point data were converted to surfaces of ignition density using kernel density estimation. Kernel density estimators (KDE) allow continuous estimation of a spatial point process and allow the calculation of ignition density rather than ignition counts (Silverman 1986). The ignition density λ(**z**) at a particular location **z** in study area *A* can be estimated by

$$\lambda(z) = e(z)\sum_{i=1}^{n}\frac{1}{nh}k(\frac{z-z_i}{h}) \tag{1}$$

where *k* is a kernel function with unit variance and zero mean, *h* is the bandwidth, *n* is the number of events, and *e(z)* is the edge correction factor. A normal kernel was used. Cell size was chosen to be 1 km so it was large enough to include a homogenous area of landscape, yet small enough to conserve general landscape pattern. Edge correction was completed by dividing the intensity estimate by the convolution of the normal kernel within the observation window.

There are numerous methods for identifying bandwidths. Least squares cross-validation is commonly used (Brooks and Marron, 1991; Bowman 1984), though some criticize the result as under-smoothed in situations with large sample sizes (Hemson *et al.* 2005). A variable bandwidth KDE may make ecological sense since homogenous landscape patch sizes vary across Canada, but multiple bandwidths are a challenge for inter-cell comparison. We decided to use a value of 50 km based on the possible average daily spread rate of fire (Alexander and Cruz 2006) and for generalization of similar landscapes.

A KDE surface of ignition density is created for each year. The majority of fires occur within the summer months, from June until September, but early and late fires will also be a product of the annual climatic and environmental characteristics. The temporal resolution reflects the natural fire cycle.

Temporal trajectory

The yearly kernel density estimate surfaces provide an estimate of ignition density at each cell. Each cell has 27 years of ignition density information that may be examined as a temporal trajectory or time series. Each trajectory can be described by a number of metrics to summarize the ignition density temporal pattern (Figure 3), including: median, standardized inter-quartile range, and linear trend.

The median is the expected ignition density assuming no change in ignition trend. The median is a measure of central tendency and is preferred over the mean due to the left-skewed temporal trajectory distribution from high ignition density years. This is a simple yet effective measure of the expected ignition density for a cell.

The expected ignition density of a cell will be subject to natural variation from location specific climate, environmental, and anthropogenic changes. A normalized inter-quartile range was used to quantify this variation in a non-statistical manner. The inter-quartile range (IQR) is defined by

$$IQR = P_{0.75} - P_{0.25} \tag{3}$$

where $P_{0.75}$ and $P_{0.25}$ are the 75^{th} and 25^{th} percentiles of the time series, respectively. IQR is measure of variation that and is not influenced by outliers. A standardized IQR is created by

$$sIQR = \frac{IQR}{median} \tag{4}$$

Standardization allows for comparison between cells regardless of median amount since larger medians may inherently mean larger deviation.

The linear trend of the ignition density temporal trajectory was determined by ordinary least squares linear regression. Linear regression was used in an exploratory manner to determine whether magnitude of fire ignition trends are increasing, decreasing, or staying constant over the 27 year time period.

The resulting metrics will be analyzed using ecozones-specific frequency distributions to examine ecological differences in expected ignition densities, relative variation, or linear trend.

Cluster analysis

To delineate regions with similar temporal fire ignition patterns, k-means cluster analysis was applied to the three temporal metrics: median, sIQR and linear regression slope. As an unsupervised classification method, k-means clustering is beneficial since it requires no initial labeling of classes and is suitable for exploratory data analysis. Each metric was scaled to have unit variance and thus equal influence in each dimension.

Five classes were chosen based on an appropriate reduction in the sum-of-square-error for all metrics. Sum-of-square-error will decrease as each new class is added, but the rate of decrease will change at the acceptable number of classes (Duda *et al.* 2000). Five classes optimized sum-of-square-error while maximizing interpretability. Selection of number of classes can be a subjective endeavor that may change depending on the focus of the project.

Anthropogenic influence assessment

While ignition regimes depend on many non-anthropogenic factors like climate and vegetation type, the proximity of a location to human activity may help explain the spatial distribution of regimes (Brosofske *et al.* 2007; Syphard *et al.* 2007). Human activity may be concentrated as in human settlement (distance to populated places) or dispersed through transportation networks (distance to roads). It is important to assess how these two influential factors correlate to fire ignition patterns.

Ignition probability densities and anthropogenic covariate distances were compared between ignition causes at a national scale. Expected ignition density and temporal trend were plotted against anthropogenic covariate coverages and analyzed by regime. Frequency distributions of anthropogenic factors were developed for expected ignition density and ignition trend at both national and regime scales. Median and inter-quartile range were used to describe the distributions due to their robust nature. The national distribution of the proximity covariates was used as an expected value.

Results

Ignition regime delineation

Temporal trajectory metrics indicated that expected wildfire ignition density, relative density variation, and linear trend of ignition density varied across Canada (Figure 4). Expected ignition densities were highest in the south-central Montane Cordillera and north of Lake Huron in the central Boreal Shield. Ignition expectations were lowest in the northern, increasingly treeless, portions of Canada. Relative variation was highest in northern Canada and the Atlantic provinces, although reflecting opposed environmental and social conditions. The northern areas indicated have few trees or people, and the Atlantic locations with forests interspersed with roads and settlements. Ignition density trend varied across the country but tended to be neutral (no change) or slightly positive in more northern latitudes.

The broad, regional, expectations are driven by ecological and climatic conditions and can be observed when the temporal trajectory metrics were separated by ecozone (Figure 5). The Montane Cordillera experienced the highest median number of expected ignition densities, 2.68 $x10^{-3}$ ignitions per km^2, as well as the largest IQR and outlier range in expected density. The Boreal Plains, Boreal Shield, and Pacific Maritime ecozones were second, third and fourth for expected densities, respectively, with similar IQRs and outlier ranges about half as large as the Montane Cordillera. Atlantic Maritime ignitions were notable as well, with a slightly smaller expected density and outlier range than the previous ecozones, but a similar variance of the expected. All other ecozones experienced relatively low expected ignition densities.

Overall linear trends indicated that each ecozone has experienced a slight decrease in wildfire ignitions, similar to the annual ignition counts (Figure 2). Montane Cordillera has the lowest median trend with $-5.01x10^{-5}$ ignitions per km^2 per year, largest IQR and largest outlier range. The Boreal Plains and Boreal Shield ecozones have similar ignition trend distributions with a median slightly below zero and IQRs of $4.12x10^{-5}$ and $3.03x10^{-5}$ ignitions per km^2 per year. The trends of the Pacific Maritime ecozone are skewed high with few positive and many negative trend locations. The remaining ecozones have expected trends near zero and little to no variation from that.

The relative variance metric, sIQR, is inherently large for regions with very small ignition density expectations such as the Hudson Plains, Taiga Shield and Taiga Cordillera. The relative variation in ecozones with medium to high expected density are a preferred application of the statistic and more relevant to management considerations. Despite large differences in expected density, Montane Cordillera, Pacific Maritime and Boreal Shield have similar relative variance distributions. The Boreal Plains have a small and comparatively consistent relative variance. The east-west differentiation in the Montane Cordillera is of particular interest as neither expected density nor linear trend exhibit this pattern.

The k-means classification produced five distinct regimes distributed across Canada (Figure 6). Expected ignition density was the largest contributor to regime delineation with linear trend as a secondary influence. Regimes were labeled by their ignition risk: 1. *Very Low*, 2. *Low*, 3. *Medium (with increasing linear trend)* or *Medium+*, 4. *Medium*, and 5. *High*. Temporal trajectory metric distributions for each regime are described in Figure 7. All regimes, with the exception of *Medium+*, have an overall neutral or negative linear trend.

The *Very Low* regime was located mostly throughout the northern forested ecozones of Canada and the Atlantic provinces. *Low* regime occurred through most of the south-central latitudes, roughly following the boreal forest and buffering the higher-expectation regimes. *Medium* and *Medium +* regimes were similar in density expectation but were differentiated by the ignition trend of the contained cells. These tended to occur within the southern ecozones. The *High* regime was found mainly in the south-central Montane Cordillera as well as patches throughout the Pacific Maritime, Boreal Shield, and Boreal Plains; these are also the areas with the highest ignition densities in Canada.

Assessment of anthropogenic influence

The ignition probability densities for proximity to road or populated place for lightning vs. human caused fires are presented in Figure 8. Human caused ignitions occur slightly closer to roads than natural ignitions. Similarly, human caused ignitions occur closer to populated places with a maximum probability at 20km, whereas lightning ignitions have a maximum probability of 50km. Both are closer more likely to occur than expected at closer proximities to populated places when compared to the national distribution.

The distributions of temporal trajectory metrics by distance to road or distance to populated places are presented in Figure 9. The expected ignition density decreased exponentially as both distance to road and distance to populated places increased. The highest expected ignition densities were located in close proximity to roads and slightly further away from populated places. Locations furthest away from roads and populated places have very low expected number of ignitions. Maximum distance to roads were 80 km, 70 km, 62 km, and 36 km for the *Low*, *Med+*, *Med*, and *High* regimes, respectively. Maximum distances to populated places were 325 km, 194 km, 233 km, and 189 km, respectively. Linear trend of ignition density converged to zero as both covariates increased. Trends with the greatest magnitude occurred in locations close to roads and populated places.

Regime delineated covariate distribution characteristics (median and IQR) were compared to random using the national covariate distributions as expected. Median distance to road and median distance to light both decreased as ignition expectation increases (Table 1). *Very Low* areas occurred further away from both roads and light than the national expectation, though variation in distance to light was similar. All other regimes occurred closer to roads and light and have correspondingly smaller variance. Increasing ignition risk corresponded with increased proximity to covariate. Regime covariate distributions deviated from expected faster with distance to roads than populated places.

Discussion

Wildfire ignition in Canada is a spatially and temporally variable process. Summarization by ecozone is a useful way to examine the ecological impact on ignition expectation, variation, and trend. The likelihood of a fire igniting was highest in regions such as the south-central Montane Cordillera with a maximum of one ignition every 89.3 km^2 each year. Variability in ignition density may be dependent on elevation or terrain complexity as the eastern, higher elevation region of the ecozone exhibits higher relative variance. The interior plateau, a flat region within the western Montane Cordillera, had a smaller relative variance and therefore more consistent ignition expectation. The dry summers, fire-dependent conifers, and reduced fuel contiguity due to rugged topography (Parisien *et al.* 2006) may constitute the ecological risks for high ignition expectation under consistent external influences. Fire suppression and prevention have been effective in most of the Montane Cordillera as observed with the negative trends in ignition density. Unfortunately, this suppression has also been recognized as a cause for the increased homogeneity in forest structure and increased fuel loading in traditionally surface-fire dominated regimes (Brown 1983), effectively increasing the risk of a stand replacing fire. Anthropogenic risk for this ecozone can be explained by proximity to roads or populated places as fire ignition densities increased with proximity to both human covariates. This is consistent with results from Portugal (Catry *et al.* 2009), Spain (Romero-Calcerrada *et al.* 2008), Florida (Mercer and Presemon 2005), and the upper Midwest of United States (Cardille *et al.* 2001).

The Boreal Plains, Boreal Shield, and Pacific Maritime ecozones all experienced similar ignition density frequency distributions. Contrary to evidence that large fires with a short fire cycle occur in coniferous boreal forest (Payette *et al.* 1989) and smaller fires with a longer fire cycle occur in deciduous or mixedwood stands (Bergeron *et al.* 2001), no evident bias exists at this scale for the likelihood of ignition in conifer versus mixedwood stands, both which are interspersed throughout these ecozones. The heterogeneous deciduous and conifer dominated south eastern Boreal Shield experienced similar ignition density expectations as the coniferous south western Boreal Shield and eastern Boreal Plains. The Boreal Plains and Boreal Shield had high ignition rates surrounding the easily accessible lakes, likely indicating ignitions caused by human recreation. Similarly, the Pacific Maritime experienced high ignition density in south eastern Vancouver Island, exemplifying the impact of human presence on ignition density. Relative variance in expected density is low for all medium to high ignition density areas, indicating fairly consistent ignition rates in these ecozones.

Lowest ignition densities occurred in the northern ecozones where some areas have never experienced an ignition. Relative variation is high due to the low expected ignition density and linear trend is mostly zero. The cold climate and low levels of recreational activity partially explain the low number of ignitions, as does the more natural fire regime allowed in the area. The few fires in these remote locations pose little danger to communities and are rarely suppressed, resulting in 50% of the area burned in Canada (Stocks *et al.* 2002), further timber harvest operation are not present in this area. This unaltered, natural fire regime allows for large fires to remove built up fuel and undergrowth, reducing the ignition susceptibility in the region and promoting a longer and more stable fire cycle. This is consistent with the modeled relationship between fire frequency and fire size in a natural regime, or “let burn” scenario, examined by Li and colleagues (1999). This stable fire cycle may be observed from the lack of trend in ignition density throughout these ecozones. As indicated from land cover (Wulder *et al.* 2008a) and related derived information on forest composition (amount of forest over a given unit area) (Wulder *et al.* 2008b), these areas are characterized by sparse forest cover, low vegetation ground cover, wetlands, and lakes.

An interesting relationship can observed between ignition density expectation and linear trend of ignition density. In most locations a high ignition density was coupled with a negative trend in fire ignitions through time, possibly indicating the effectiveness of fire suppression or prevention efforts in ignition-prone areas. The locations with greatest positive ignition trends through time in the Boreal Plains and Boreal Shield occurred adjacent to regions with high ignitions and negative trend. While these areas often had less intensive ignitions, the positive trend indicates changing environmental or anthropogenic influence which may change the fire regime, and thus the ecology, of the region. These may be the most important areas to focus risk rating and monitoring efforts.

The delineation of wildfire regimes based on ignition expectations allows for identification of similar regions of space-time fire pattern across Canada. The five resultant groups are spatially distributed across the country. The *Very Low* ignition class is identified in northern Canada, immediately bordering the prairies, and Pacific and Atlantic coastlines with little fuel or human activity. Driving factors in these regions may vary between high moisture (maritime coasts), low fuel availability (prairies), and low human activity (northern Canada). The *Low* regime roughly follows the July minimum temperature isoline of 10ºC throughout the Boreal Plains and Boreal Shield and up into the Taiga Plains. The Montane Cordillera, despite being outside this isoline, has a higher predisposition to ignitions due to its dry summers and coniferous stands. An isolated patch designated *Low* is located in the Boreal Cordillera near Whitehorse, Yukon Territory, and is best attributed to higher local levels of anthropogenic activity.

It is evident that the regime with fewest wildfire ignitions is occurring at the furthest distances from roads and populated places. These locations would be considered to be the most natural and have the least human influence. The *Very Low* regime may still occur near roads or human settlement, but climate, ecology, or human prevention ensures a negligible ignition risk. The *Low* regime also occurs at greater distances to road or populated places relative to the three highest regimes, though is absent at distances beyond 80 km from road and 325 km from populated places.

The higher ignition probability densities found in the *Medium*, *Medium+*, and *High* regimes are indicative of important areas to focus research and management attention. Again, these regimes encompass lakes with high human activity in accessible regions. *Medium* and *High* ignition regimes occurred in many of the same areas with *Medium* often encircling the *High* regime. Both regimes occurred much closer to roads and populated places than the two lowest regimes, making it evident that greater numbers of ignitions occur in locations close to human activity. The Montane Cordillera contains the largest portion of contiguous *High* regime cells due to the conditions mentioned earlier, yet this regime exists in multiple ecozones despite the difference in underlying ecological composition. Factors impacting ignition may be different here, with ecology/management having greater influence in the Montane Cordillera while human activity or seasonal moisture levels are the main drivers elsewhere. The *Medium* regime follows the same premise although expected ignitions are reduced.

The Linear trend of the ignition density also increases in magnitude, either positive or negative, as proximity to humans increases. The decrease in ignitions, possibly due to prevention or environmental change, is likely to occur close to humans given that distant locations are allowed to experience a more natural fire regime. Fire suppression and prevention efforts are most prevalent where civilian or corporate investments are at stake (Ward *et al.* 2001). Conversely, areas of increased ignitions are also occurring close to humans. The *Medium+* regime, similar in ignition expectation to the *Medium* or *Low* regime, spatially delineates this increasing ignition trend. While these locations do not have the immediate ignition susceptibility of the *High* regime, the increasing trend is indicative of changing ecological or anthropogenic conditions and should be considered for future forest management. This regime occurs closer to roads and populated places than would be implied from its ignition density, signifying the impact of human presence on not only expected ignition density but ignition density trend as well.

Both lighting and human caused fires occur with greater probability when closer to roads and populated places. While the importance of both proximity to road and populated places on ignition density is evident, proximity to roads has greater relative change from the expected distribution in all regimes. This indicates that proximity to roads has a larger impact on regime delineation than proximity to populated places. The influence of human transportation network on ignitions has been discussed in the literature (Syphard *et al.* 2008; Stephens 2005) and is not surprising, considering humans disperse along transportation networks before accidentally igniting a fire. The relationship between lightning ignitions near roads and populated places may be attributed to increased flammable fuels, increased metal infrastructure, topographic characteristics of preferable road locations, or increased observance of a fire (Arienti et al. 2009). This provides further emphasis to include anthropogenic covariates, namely road proximity, into fire ignition models to compliment the ecologically established risk.

The ignition occurrence regimes created in this exploratory analysis are best used to describe spatially explicit, long term expectations at a national scale. The few occurrence modeling studies in the literature often examined smaller extents with more responsive models. Regardless of ignition cause, fine temporal scale weather and moisture information were the ideal predictors of when and where ignitions would occur (Wotton and Martell 2005; Wotton *et al.* 2003, Martell *et al.* 1989, Martell *et al.* 1987). Moisture was best modeled using the Fine Fuels Moisture Code (FFMC; the moisture content of the fine litter on the forest floor; Wotton *et al.* 2003), or the Sheltered Duff Moisture Code (SDMC; the moisture content of the upper part of the organic layer near boles of sheltered overstory trees; Wotton *et al.* 2005). Increased rain in subsequent days following ignition and high wind speeds were demonstrated to reduce the change of an ignition smoldering to a fire (Wotton and Martell 2005), while type of lightning strike and likelihood or duration of smoldering (Anderson 2002) and time of season (Martell *et al.* 1989) would also matter. The annual temporal grain and national extent of this analysis prevents the inclusion of such fine scale measures such as SDMC, weather, or season. However, many of these general climatic characteristics, such as very dry moisture indices, can be observed through spatial representation in the High and Medium regimes. The developed ignition regimes would be best used in conjunction with finer scale models, or when regions need to be compared nationally.

The ignition expectation baseline is a robust starting point for assessing wildfire occurrence at a national scale. Ignition influencing factors that change gradually or through multi-year cycles may be accounted for with inter-year ignition density variation or trend analysis. These underlying factors would include changing climatic conditions, periodic climatic patterns like El Niño, or the long term effects of increased or decreased management or landscape disturbance. This baseline cannot account for abrupt changes influencing ignition likelihood including increased commercial or recreational use, expansion of roads or railways, or extreme weather events. Effective prediction of occurrence will require keeping this baseline concurrent with anthropogenic development in addition to its use with local fire weather and fire behavior systems.

Conclusions

The objective of this study was to quantify the spatial and temporal patterns of wildfire in Canada by identifying baseline ignition expectations and ignition trends. Distinct ignition-based regimes were spatially delineated and emphasize the variation in ignition density through space and time. Ignition density and ignition trend magnitude, both positive and negative, were positively influenced by increased proximity to human transportation network and human settlement. As a preliminary attempt to create a spatially explicit national measure of ignition expectation, this project has successfully quantified the space-time pattern of fire across Canada.

The ignition density and temporal trajectory metric approach provides spatially explicit, applicable information on ignition expectation baseline and forecasting using historic data. Future improvements to this model are easily implemented due to the flexibility of adding additional temporal trajectory metrics. Additionally, this method can be applied to any large point dataset to create a spatially continuous and temporally comparable measure. The results of this project address the necessity for a nation-wide fire ignition expectation model in Canada (Wotton, 2009) and demonstrate potential uses of the product.

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Table 1 Anthropogenic covariate proximity distributions by ignition regime.

The expected distribution is from the complete national dataset. Regimes are compared to expected distances from covariates using median and inter-quartile range as descriptors.

	Road Median		Road IQR		Pop. Place Median		Pop. Place IQR	
	(m)	(% exp)	(m)	(% exp)	(m)	(% exp)	(m)	(% exp)
Expected	12040	(100%)	36044	(100%)	133300	(100%)	215830	(100%)
Very Low	27510	(228.4%)	52676	(146.1%)	245600	(184.2%)	226500	(104.9%)
Low	7000	(58.1%)	16046	(44.5%)	80230	(60.2%)	79730	(36.9%)
Medium+	1000	(8.3%)	4123	(11.4%)	46240	(34.7%)	47290	(21.9%)
Medium	2000	(16.6%)	6083	(16.9%)	57070	(42.8%)	51920	(24.1%)
High	1000	(8.3%)	2000	(5.5%)	39620	(29.7%)	32660	(15.1%)

Figure 1 Canadian forested ecozones (green) and fire ignition locations (black) from 1980 to 2006.

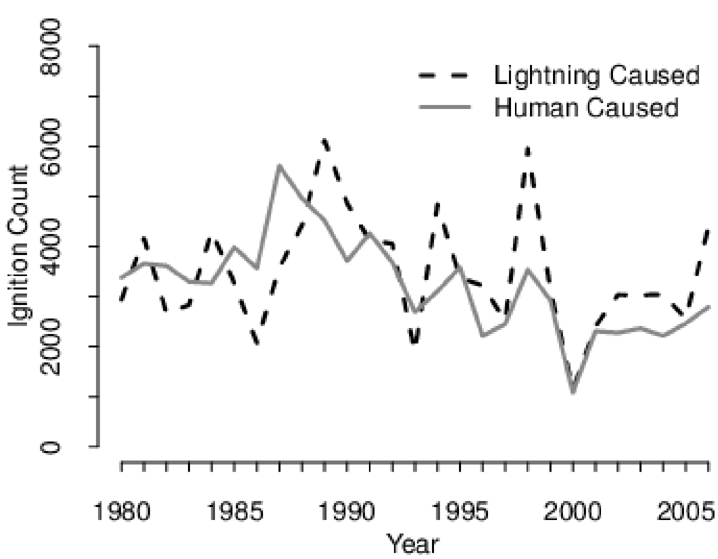

Figure 2 Number of human and lightning caused wildfire ignitions in Canada by year from 1980 to 2006.

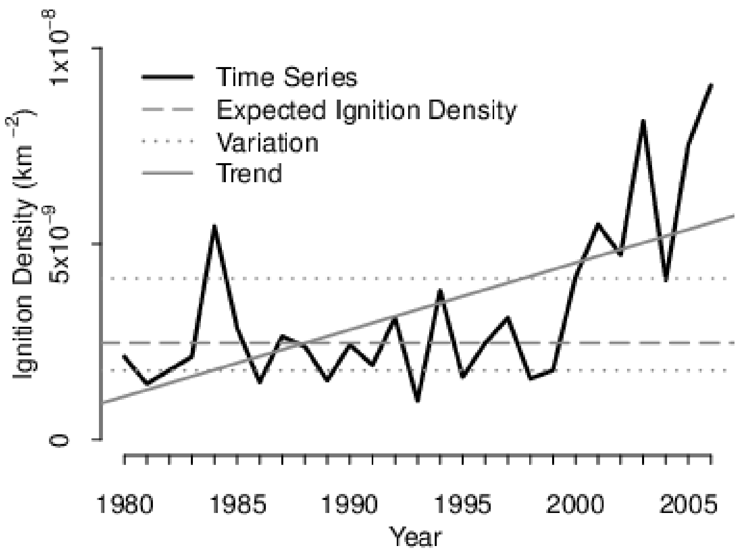

Figure 3 Ignition density temporal trajectory example with expected ignition density (median), amount of variation (inter-quartile range), and trajectory trend (ordinary least squares linear regression slope).

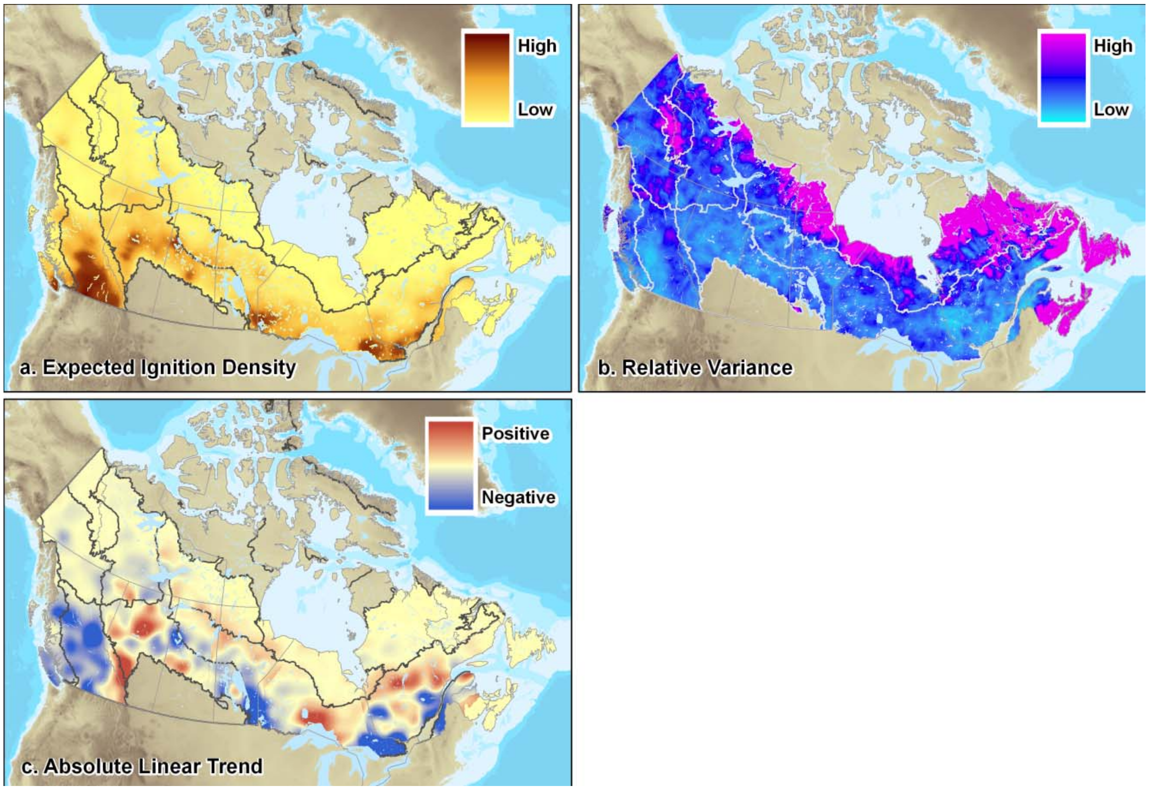

Figure 4 Temporal trajectory metrics of wildfire ignition density (a. expected ignition density - median; b. relative trajectory variation – standardized inter-quartile range; c. trajectory trend – ordinary least squares linear regression slope) across Canada.

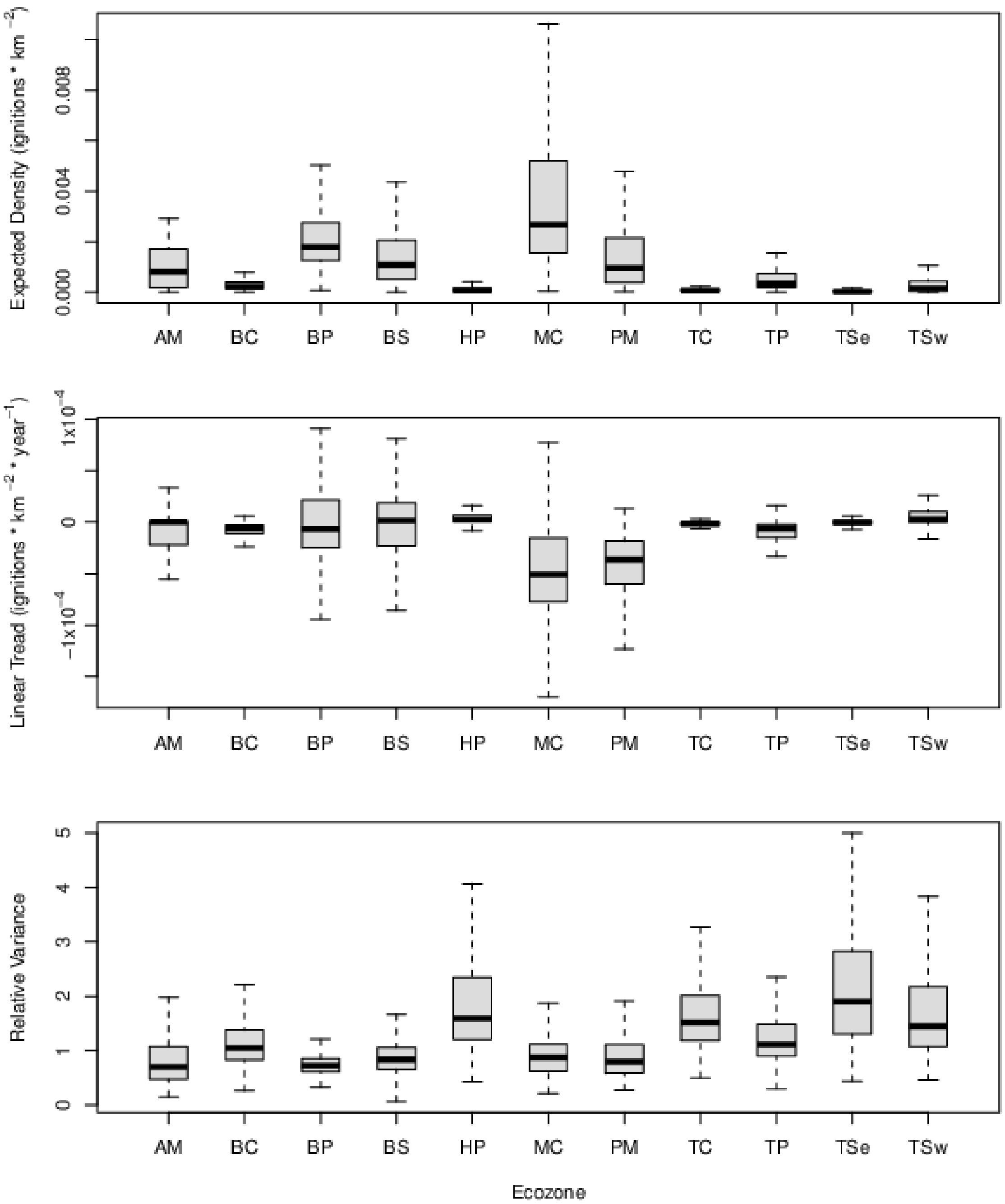

Figure 5 Ecozone separated box-and-whisker plot of temporal trajectory metric distributions. Median, 25th and 75th percentiles are represented in the box. The whisker denotes 1.5 * inter-quartile range or maximum/minimum data value, whichever is closer to the media.

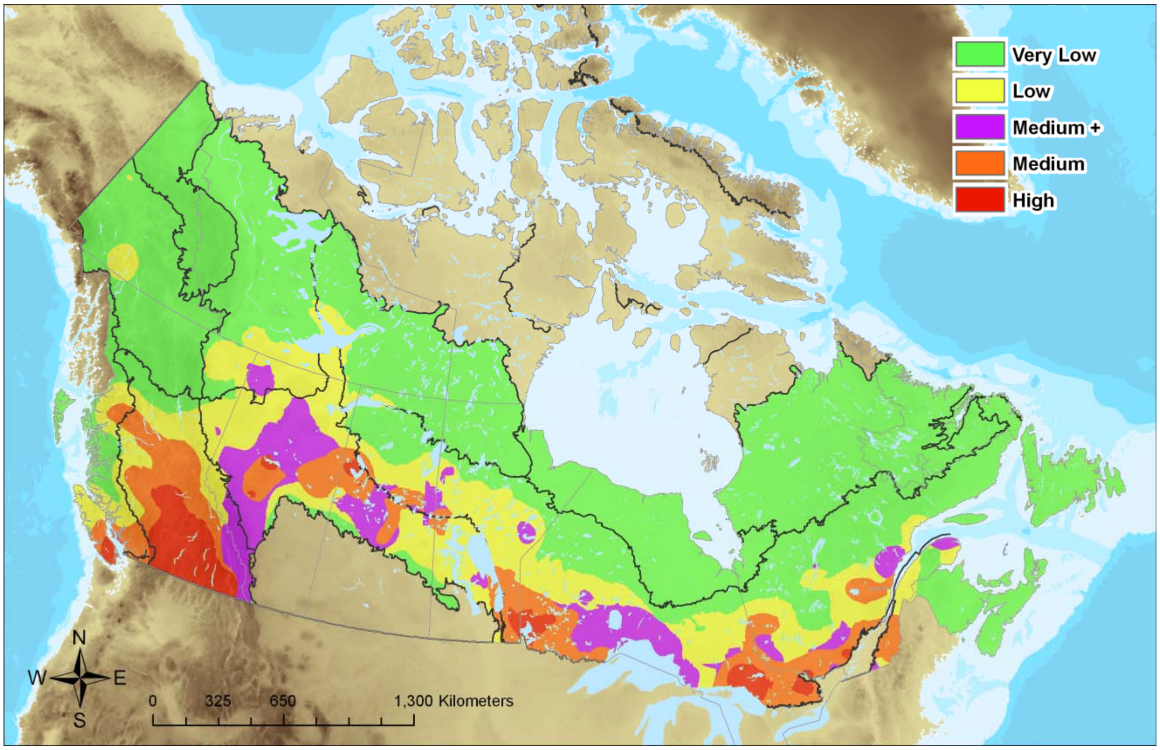

Figure 6 K-means delineated fire ignition regimes in the forested ecozones of Canada.

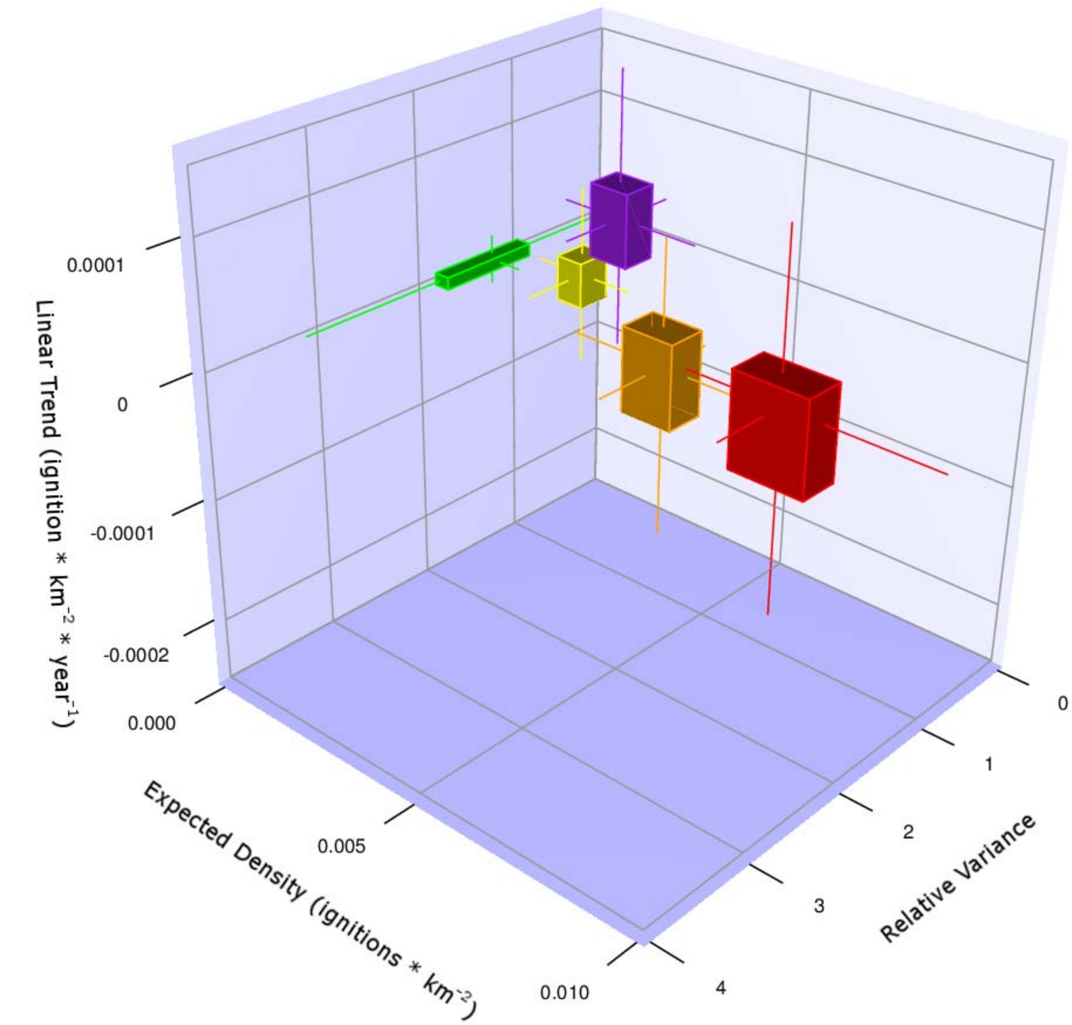

Figure 7 Three dimensional box-plot of the five delineated ignition regimes: green is very low, yellow is low, purple is medium with increasing trend, orange is medium, and red is high.

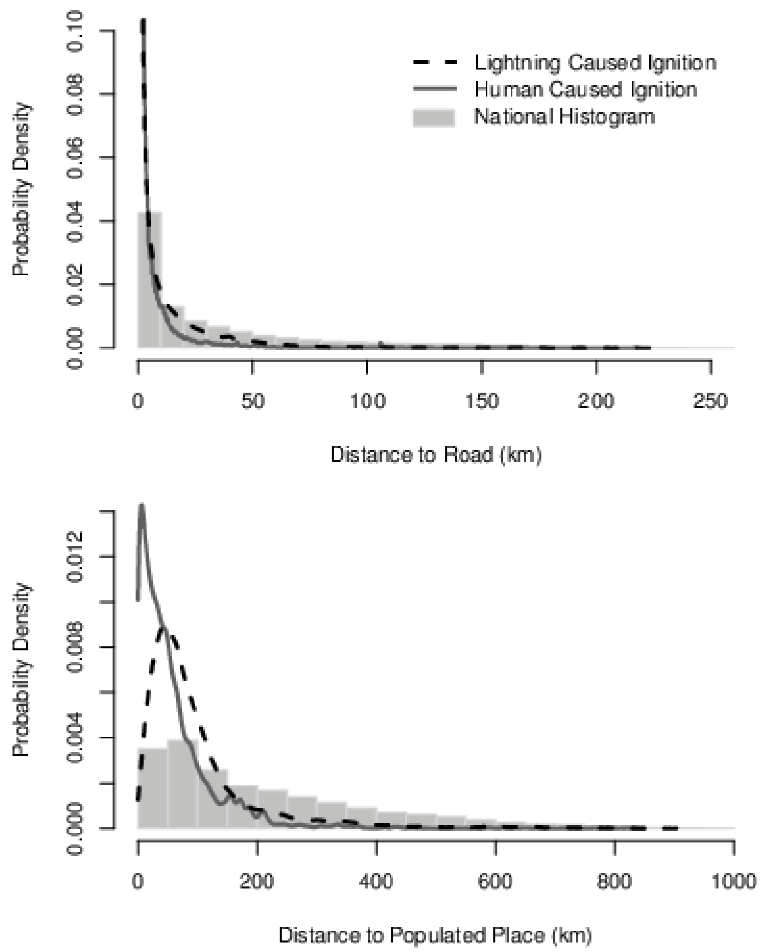

Figure 8 Probability density distribution of human or lightning caused wildfire ignitions compared with two anthropogenic covariates: distance to road and distance to populated place. The national distribution (all cells within the forested ecozone study area) is presented for comparison.

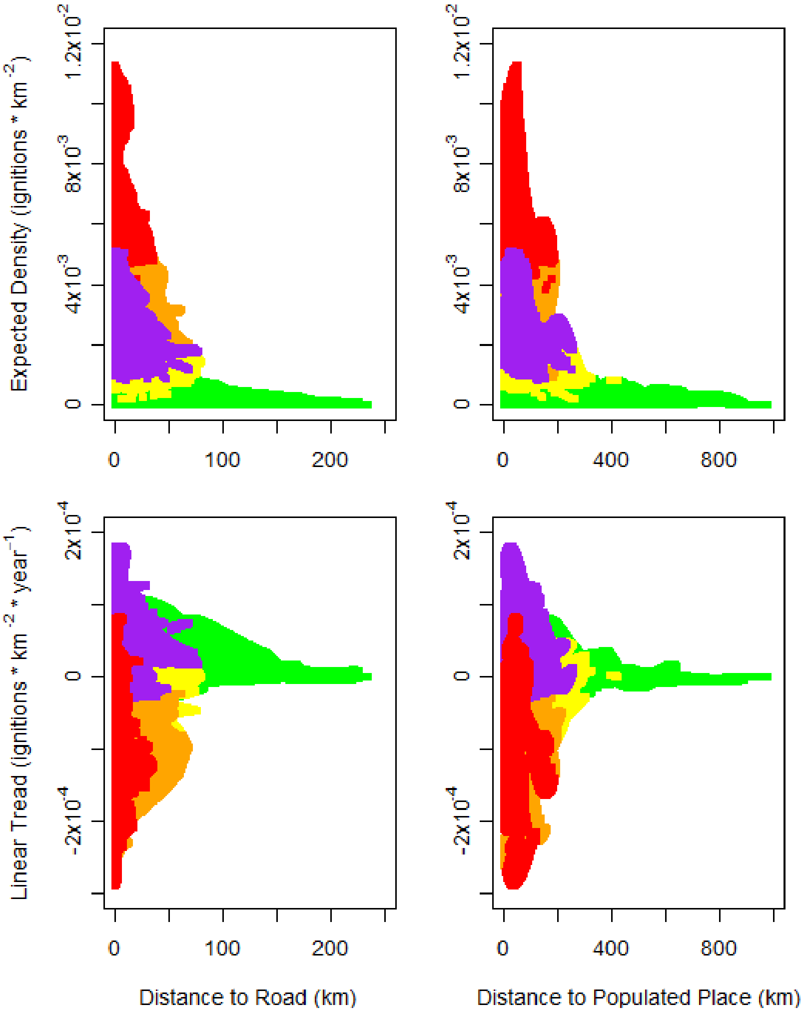

Figure 9 Temporal trajectory expected ignition density and linear trend plotted with two anthropogenic covariates: distance to road and distance to populated place. Points are color coded by the regime they belong to: green is very low, yellow is low, purple is medium with increasing trend, orange is medium, and red is high.