

## Geomatics for informed decisions (GEOIDE): A case study of forest fire boundaries under a low severity fire regime

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### ABSTRACT

The natural disturbances paradigm in forestry management emphasizes understanding and emulating natural variation in forest ecosystems processes and patterns. Using dendrochronological data in two study areas in the Stein River valley, British Columbia, we provide empirical models of the spatial-temporal variation in boundaries of low-severity fires. With geographic information systems, database management tools and local statistics, we analyze the fire scar data to extract information of fire boundary persistence and local "hot spots". When coupling this information with topographic variables, a clear influence of the physical landscape on the local fire regime emerges. We found that the fire regime in the Stein Valley is characterized by fire boundary persistence, showing significant relationships to fluvial breaks in both the middle and lower valley study areas. By extracting such boundary information from spatio-temporal fire evidence databases, we are able to make more informed forestry management recommendations for fuel load treatment with respect to low severity fires under the natural disturbance paradigm.

Natural disturbance; boundary; spatial analysis

### 1. Introduction

The natural disturbance paradigm is commended as an approach to forest management which emulates the variability of frequency, size, distribution, and biological legacies of natural disturbances (Hunter, 1993; Swanson et al., 1993; Galindo-Leal and Bunnell, 1995; Bergeron et al., 1999; Niemala, 1999). While clear-cut timber harvesting may be able to mimic certain characteristics of a stand-replacing fire, such as size and shape, and thus initiating secondary succession (Niemala, 1999), the same approach of natural disturbances can be used to time and control let-burn wildfires or prescribed burns in non-commercial forests, such as in parks. Maintaining a fire regime, rather than suppressing fire, as has been done in the recent centennial past, allows regular removal of fuels, thus precluding fuel build-up and the risk of a catastrophic fire (Agee, 1997). Pyne (2001) reviewed historical narratives of fire management and stated: "With fire there is no neutral position, because fire may be as ecologically powerful when it is withheld as when it is applied." To make recommendations for management, based on the natural disturbance paradigm, we investigate, using geographic information systems, database management and spatial statistics, the boundary characteristics of natural fire disturbance at the landscape scale.

A landscape patterned by a fire regime is spatially controlled by fire severity, size and shape. Fire severity is characterized by the extent to which growing space is created on the landscape and the degree to which the successional pattern is altered (DeBano et al., 1998). A key question within the spatial context of the natural disturbance paradigm refers not only to number, size and shape of an anthropogenic disturbance would mimic nature, but, where forest fire boundaries have occurred, i.e. where the fire stopped. While streams are often considered fuel breaks, McCleary and Andison (2001) reported that fires in the Alberta Foothills tended to burn through lower order streams. Higher order streams, as well as ridges (Agee et al., 2000) and avalanche tracks (Suffling, 1993) are probable natural fuelbreaks in a fire maintained forest ecosystem. Fuelbreaks are used to change fire behaviour and as anchor points for controlling wild or prescribed fire (Agee et al., 2000; Finney, 2001). Agee et al. (2000) stated that when reducing fuel loads in wild or prescribed fire management, a knowledge of historic conditions contributes to a "light-on-the-landscape" approach. We are unaware of any study which takes into long historical records to determine spatial distribution of past historical fire boundaries and compares these with the location of natural fuel breaks. A knowledge of long temporal histories of natural fire boundaries will contribute to the location component in the spatial context of natural disturbance paradigm. By extension, such knowledge also provides a practical approach for management to know where persistent fire boundaries have occurred on the landscape in order to allocate fire prevention resources wisely in a given watershed.

Fundamental difficulties in identification of landscape boundary characteristics include the subjective nature of boundary delineation, scale-dependencies such as those related to data type, extrapolation and predictability (Gosz, 1991). Here, we

show that a better understanding of forest fire boundary description and delineation can be achieved by using spatial analyses using randomizations of the spatial attribute database, spatial autocorrelation measures (Legendre and Fortin, 1989), and overlap statistics (Fortin, 1992; Jacquez, 1995). Our methods include defining boundary occurrence and assessing the frequency of fire boundaries. From these, we generate our null hypotheses on the premise that fire boundaries are located randomly. Our null hypotheses are that (1) there are no significantly persistent fire boundaries, (2) the frequencies of boundaries are randomly located through space and are not influenced by nearby boundaries, and (3) that overlap between fire boundary frequency and river breaks occurs randomly. Rejection of the null hypotheses will indicate that boundary occurrence is not a random event on the landscape and that certain boundary properties are significant.

## 2. Study area

The Stein River Valley, British Columbia, Canada, is located to the west of the Fraser River and within the Stein Valley Nlaka'pamux Heritage Provincial Park (MELP, 2001). Fire management within this landscape has been limited. Most of the fire regime (i.e., pre-20<sup>th</sup> century) can be considered natural, whether ignited by lightning or First Nations traditional ways of living (S. Newton, pers. comm. 2001). The Stein is therefore a unique region where natural low-severity fire can be reconstructed using dendrochronology.

The Stein Valley drainage basin is located near the northern extremity of the western North American Ponderosa Pine (*Pinus ponderosa*). The area is a transitional zone between the dry rain shadow interior and the wet climate of the Coast Mountains (MELP 2001). The forests in the park area range from dry Ponderosa Pine in the lower valley to through Douglas Fir (*Pseudotsuga menziesii*) zones to upper elevations in the western part of the valley of hemlock, spruce and fir. The valley is situated in mountainous terrain comprising two major canyons and a change in elevation from 220 to 2954 m. The topography has been heavily impacted by glacial events, resulting in sculpted U-shaped valleys. The Stein River extends approximately 60 km from Stein Lake in the west to the Fraser River in the east (MELP 2001).

A spatially-explicit sampling design was used to collect data in two different areas along the Stein River, one in the middle valley and the other in the lower. In the middle valley, 44 plots of approximately 1 ha in size were sampled on a three-plot transect grid upslope of north side of the Stein River (resulting in an elongated study area extent, ~1512 ha). At each plot, sections from an average of five trees were collected from Ponderosa Pine or Douglas Fir. Cross-dating of tree ring widths assigned calendar year to the rings (E. Heyerdahl, pers. comm. 2000). The tree ring records extend from 1562 to 1937. In the lower valley, 36 plots were sampled on a grid of approximately 1 ha in size, on upslopes both north and south of the Stein (total extent ~ 412 ha). The lower Stein tree ring records extend from 1669 to 1947 (E. Heyerdahl, pers. comm. 2000).

For our study, we used a subset of both study area data sets, in order to capture as many continuously recording plots as possible. This selection procedure shortened the data sets temporally and reduced the number of sampled plots. For the middle Stein valley we used a subset of 33 plots, for which 48 fire years have been compiled between 1785 and 1937. In the lower Stein, 35 plots of data are used, for which 22 fire years have been compiled between 1879 and 1947.

## 3. Methods

The framework of our methods is based on our boundary persistence definition from which we explored the frequency of boundary persistence in the data sets. Under the assumption that forest fire pattern is generated by spatially contiguous fire process, we tested the persistence of boundaries using restricted spatial randomization. To assess whether the boundary frequency values are randomly located through the extent of the data set or whether they show spatial associations, we computed local spatial measures to detect subareas where boundaries may exhibit significant association with neighbours (Boots, 2002). We also tested spatial relationships between data sets, i.e. variable layers, which may reveal significant overlaps. We tested overlaps for fire boundary and riparian zones.

### 3.1 Definition and computation of boundary frequency

The set of link between nearest-neighbours which is created from the set of plots is termed a Delaunay network (Legendre and Fortin, 1989). The bisectors of each link create the network of Voronoi polygons (Okabe et al., 1992; Okabe et al., 2000). We define the bisector between two nearest-neighbour plots a candidate Boundary Element (cBE) after Jacquez et al. (2000). If, for any given year, fire evidence was observed at one plot, but not the other, the cBE is classified as a

boundary between two plots. We consider this a dissimilarity, that is, a match-mismatch, of categories in the same way which Oden et al. (1993) defined categorical wombling. We assumed boundary frequency to be the number of dissimilarities, i.e. boundaries at each bisector, formed between two neighbouring plots. To calculate the observed boundary frequency, we computed a summation of boundaries (Oden et al., 1993; Boots, 2002) in the GIS attribute database.

In order to determine whether the frequency of boundary occurrences is significant, we created a reference distribution from the observed values. Since fire is generally considered a spatially contiguous process, we developed a method to test for significant boundaries using spatially restricted randomization (Manly, 1997; Fortin and Jacquez, 2000). We first displayed all fire year maps using a GIS and examined, in turn, the fire evidence in each year to determine the degree of contiguity of fire scar evidence between plots. We counted the number of fire evidence groups connected by at least one nearest neighbour plot for each fire year. Having determined the most frequently occurring number of connected fire groups per fire year, we used the results to justify restricted randomization. For the restricted randomization, we shuffled the fire scar data within each year in the original fire evidence database, with the constraint that the randomized data would be spatially contiguous. For each shuffle of the database attributes, which were randomly, but restrictively, assigned to new locations, we recomputed the frequency of boundary occurrence at each cBE, and calculated the mean and standard deviation of 1000 shuffles. We compared the observed frequency with the expected frequencies for each cBE.

### **3.2 Spatial autocorrelation of boundaries**

Local spatial autocorrelation (SA) measures (Anselin, 1995) are able to determine significant similarities or differences from the neighbourhood of an entity. These measures can identify location and scale of SA and create a mappable surface to identify the scale of processes responsible for spatial pattern (Boots 2002). To locate significantly spatially autocorrelated subareas within the data sets, we computed the local Moran's I (Anselin, 1995) for each boundary using *CrimeStat* (Levine et al., 1999). We used an inverse distance weighting function and adjusted for small distances.

### **3.3 Spatial overlap of boundary types**

Overlap statistics (OS) compute the spatial association of boundaries (Jacquez et al 2000). There are two types of OS: (1) direct overlap assessing the number of boundaries at the same location, and (2) the mean distance between nearest neighbours (Fortin, 1992; Jacquez, 1995). Examples of overlap statistic applications of include medical and environmental boundary overlap (Jacquez, 1996) and soil-vegetation boundary overlap (Fortin et al., 1996). Overlap statistics (Fortin, 1992; Jacquez, 1995) were performed for all paired combinations of fire boundaries and riparian breaks. Fire boundaries were randomized (runs = 999) and the independent data of river boundaries were not.

## **4. Results**

### **4.1 Definition and computation of boundary frequency**

In the middle Stein data set, 65 pairs of nearest plot neighbours (i.e. 65 Delaunay links with the same number of corresponding cBEs) were detected from the 33 plots. In the lower Stein, 86 cBEs were detected from the 35 plots. We inspected the maps of the fire years for spatial contiguity of sample plot fire evidence. For the middle Stein, this visual inspection of the fire events revealed that the most frequently occurring spatial arrangement is indeed contiguous for any given fire year: i.e. 30 out of the 48 fire years show connected fire evidence by at least one Delaunay link. Similarly, for the lower Stein, the visual inspection showed that the most frequently occurring arrangement had one contiguous event, i.e. 14 of 22 fire events. Since this inspection showed that fire events were frequently contiguous, we felt confident in using spatially restricted randomization to test for significance of boundary persistence. We compared our expected boundary frequency value at each cBE with the observed frequency. Significant persistence of boundaries, i.e. high frequency, was found ( $p < 0.025$ ), as well as significant rarity of boundary occurrence ( $p < 0.025$ ). For the middle Stein, twelve cBEs were found significantly persistent and five cBEs were found to have significantly rare boundary occurrence. All except one of the persistent boundaries are located between plots which also have a riparian zone between them. For the lower Stein, there are 8 significantly rare boundaries and 8 significantly persistent ones. Five of the persistent boundaries are located between plots which also span the main stem of the Stein. The three others are located in the northwest of the study area. These boundaries are likely associated with a fuel-poor area. The rarest boundaries are near the south side of the main Stein stem. Visually, the boundaries in generally show spatial aggregation amongst themselves and a certain amount of connectivity.

## 4.2 Spatial autocorrelation of boundaries

The results from the local Moran show “hot spots” and “cold spots” of boundary frequency values. In the middle Stein, significant negative local SA is found along a riparian zone. This corroborates the findings from our persistence analysis: this particular riparian zone has three high frequency boundaries along it, flanked by two very low frequency boundaries. This type of association between boundary values may be indicative of the spatial scale of a process. “Hot spots” of positive SA are found in the region between two riparian zones where boundary frequency is moderate to low, and fire frequency is also moderate.

In the lower Stein, significant negative autocorrelation is found along the main stem of the Stein. Results show positive SA along the western portion of the study area, along the Stein. This may be explained by edge effects of the study area, coupled with the way we computed locations for the boundaries (i.e. the mid point of each boundary as its “point” location). Other “hot spots” include the southeastern portion of the study area where 11 boundaries show significantly positive SA. These are extremely low boundary frequencies, a result of the fact that the fire evidence is low.

## 4.3 Spatial overlap of boundary types

The overlap statistics in the middle Stein reveal that fire and river boundaries have significant direct overlap ( $O_S = 2.893$ ,  $p = 0.008$ ). The overlap of fire boundaries on river boundaries is also significant ( $OF = -2.13$ , lower  $p = 0.006$ ). This supports the alternate hypothesis that fire boundary distribution is not random, but associated with the spatial distribution of river boundaries. This is also confirmed by a Mann-Whitney U test which simply examined the persistence values of each boundary according to whether they were associated with a river boundary or not ( $z = -5.170$ ,  $p \leq 0.000$ ).

The overlap statistics for the lower valley area show that direct overlap of fire boundaries on river boundaries is significant ( $O_S = 2.157$ , upper  $p = 0.039$ ). Directional overlap of fire boundaries on the river boundaries is low (that is, the fire boundaries do not “avoid” the river boundaries), but it is not significant ( $OF = -1.16$ , lower  $p = 0.114$ ). This can be explained by three cBEs which present a bit of an anomaly and are likely associated with the fuel-bare patch rather than a fluvial form. An improved analysis would consider both river and other fuel-impoverished zones coupled as “topographic boundaries”. A Mann-Whitney U test, however, showed significant relationship between the most persistent boundaries and the fluvial boundaries ( $z = -5.232$ ,  $p \leq 0.000$ ).

## 5. Discussion

In general, boundaries can be detected by delimiting homogenous areas or by determining significant changes in spatial variables (Fortin and Drapeau, 1995). The forest patch boundary’s complex structural arrangement and orientation control its width and microclimatic conditions (Forman, 1995; Oliver and Larson, 1996; Matlack and Litvaitis, 1999), permeability of biotic and abiotic fluxes (Weins et al., 1985; Gosz, 1991; Hunter, 1997) and contribute to biodiversity (Matlack and Litvaitis, 1999) and is of importance in management of forest landscape.

Using spatially-explicit statistical methods, we have shown that persistent and rare natural disturbance boundary patterns occur in the Stein river valley. We have used a novel approach to analyze the spatial structure of forest fire boundary by developing a spatially restricted randomization procedure to demonstrate boundary persistence. We have shown, using local Moran’s I, that there are “hot spots” of boundary persistence. Using overlap statistics, fire boundary frequency has been shown to be related to riparian fuel breaks. These analyses contribute to the understanding the spatial nature of fire disturbance on a landscape. We can summarize our findings as follows:

- Fire boundaries may persist. Significantly persistent boundaries can be extracted from point data using the spatial topological relationships between neighbours and spatially restricted randomization tests.
- Fire boundaries show spatial relationships with each other, that is, high frequency boundaries, such as those along riparian zones may be flanked by lower frequency boundaries, resulting in negative autocorrelation “cold spots”. Positive autocorrelation, indicating “hot spots” of similar values may be found where lower frequency boundaries are located near other lower-value ones.

- Fire boundaries show relationship with riparian fuel breaks. From a management perspective of low-severity fires, understanding the spatial distribution of historically persistent boundaries can be useful in present day management of prescribed fires or let-burn wildfires.

## 6. Conclusion

Our study shows natural topographic fuel break control on fire boundaries, contributing new knowledge to the natural disturbance paradigm. While Anderson and Marshall (1999) caution that site specificity must always be considered, we suggest that our approach to analyzing fire boundaries can be applied generally and help forest fire management. That is, at any site under study, low severity fire regime boundary information can be extracted using spatially-explicit analyses provided appropriate dendrochronological records are available. We have shown that within a landscape context, fire boundaries exhibit persistence, spatial association and have statistically significant overlap with watershed corridors, i.e. riparian zones. Visual displays in GIS, database randomization and spatial analyses for detecting fire boundaries contribute to transformation of spatial data into spatial information for improved decisions under the natural disturbance paradigm.

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