Spatial Characteristics of Regional Wildfire Frequencies in Intermountain West Grass-Dominated Communities

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Abstract:
Understanding the environmental factors that influence spatial patterns of rangeland wildfires facilitates both fire and land management decisions. I used discriminant analysis to examine ignition frequency of lightning-initiated fires in grass-dominated communities in the Intermountain West between 1980 and 1994, then mapped regional fire frequencies to illustrate spatial patterns. Two canonical discriminant functions effectively separate groups of high, medium, and low ignition frequencies, based on climate conditions and fuel characteristics. Regions of highest frequency tend to have large elevational differences, more mesic climates, and less annual grass cover. Spatial patterns of ignition frequencies tend to reflect local topography, with higher frequencies west of 119° W. Expansion of exotic annual grasses throughout the region may be reducing differences in ignition frequency between regions of highest and lowest frequency.
Key Words: regional fire frequency, Intermountain West, lightning-initiated fires.

Article:
Alteration of wildfire regimes in Intermountain West rangelands (particularly the Great Basin) have become increasingly implicated in the disruption of native flora (Young et al. 1987; Billings 1994) and fauna (Groves and Steenhof 1988; Yensen et al. 1992), and often create problems for ranchers (Shinn 1980). Fire regimes in the Intermountain region are dynamic chiefly because of the combined effects of inadvertent plant introductions, domestic livestock grazing, and fire suppression activities (Mack 198 1; Pellant 1990; Knapp 1996). The accidental introduction of exotic annual grasses (whose distribution through the Intermountain region has been facilitated by domestic livestock) such as cheatgrass (Bromus tectorum) and medusahead (Taeniatherum medusae) has substantially altered fire regimes because they provide a continuous fuel bed necessary to carry fire (Young et al. 1987). Hence, both fire likelihood and fire season length increase when annual grasses dominate rangelands (Hull 1965).

Altered fire regimes have both ecologic and economic consequences. In the Great Basin Desert, Young et al. (1987) found that the presence of exotic annual grasses may support a fire regime that limits the reestablishment of native perennial shrubs (sometimes to the point of competitive exclusion). On the Snake River Birds of Prey Area of southwestern Idaho, cheatgrass establishment has led to changes in fire intensities and frequencies that have caused a decline in the population of Townsend's ground squirrels (Spermophilus townsendii idahoensis). Because the squirrels are a prey base for numerous animals, the population bases of these animals have likewise been affected (Groves and Steenhof 1988; Yensen et al. 1992). Rangeland damage caused by wild-fires is also costly. In an assessment of Bureau of Land Management (BLM) sagebrush-steppe communities of the Great Basin, Knapp (1996) found that the average annual cost associated with fires (i.e., resource damage, suppression costs, presuppression costs, rehabilitation, and fire management) was approximately $20 million between 1980 and 1992. Ranching has also been affected by changes in fire regimes, since those ranchers who rely on cheat-grass as a source of forage for cattle cannot be assured that it will not burn before it can be grazed (Knapp 1996).

In an effort to better understand the conditions conducive for rangeland fires, models have been designed (e.g., National Fire Danger Rating System, Lightning-Locating and Fire Forecasting System, and Fire Behavior Forecasting System) that predict the likelihood of fire for real-time (not beyond 2 days) and short to medium range (15–30 days) intervals (Bradshaw et al. 1983; Latham 1983; Rothermel et al. 1986). These models incorporate weather observations, fuel moisture levels, and some-times topographic data for their predictions. Longer range forecasts are also possible, and Knapp (1995) has demonstrated that areas burned by lightning-initiated fires in the Intermountain West can also be predicted with moderate success several months prior to the summer fire season (June 1–September 15) by relying solely on seasonal climatic variables.

Much of the success of fire prediction models is based on knowledge of site-specific fuel loadings (fuel bed density) and fuel moisture levels, although other factors, including vegetation type (fuel model), slope, and ignition probability also substantially influence fire likelihood (Albini 1993). While lightning fires account for approximately one-half of all fires in the western United States (Brown and Davis 1973), they may be correlated poorly with the number of lightning strikes. Instead, they may be more of a reflection of several factors working in concert, including vegetation type, climatic patterns, and landscape characteristics (Christensen 1993), features that vary spatially throughout the Intermountain region. Knapp (1995), for example, showed that the area burned by lightning-initiated fires in the Intermountain region was "distinctly regional," but did not attempt to link climatic parameters with regional fire frequencies. Additional insight on fire regimes could be gained by examining the spatial characteristics of fire (i.e., the environmental conditions) in the Intermountain region to assess whether pronounced regional variability exists in frequency, and to use this information to provide a statistical basis for long-range predictions of fire frequencies (McRae 1992).

Mapping of regional fire frequencies (i.e., the number of fires per area per unit time) is one means of improving our understanding of fire regimes, particularly because regional fire frequency is not as directly affected by fire suppression activities as is the area burned (Barton 1994). Thus, examining regional fire frequencies (aka ignition frequencies) allows for a better assessment of natural patterns of fire because the confounding effects of human agency (e.g., fire suppression) are reduced (Barton 1994).

This paper focuses on the spatial characteristics of regional fire frequency in the Inter-mountain West grass-dominated communities between 1980 and 1994. The purpose is two-fold. First, I will illustrate the spatial patterns of ignition frequencies. Second, I will determine what environmental characteristics best delineate areas of high ignition frequency from areas of lower ignition frequency. This latter point is important because while topographic features are static, plant communities are dynamic over space and time: changes in composition and cover are likely to occur across regions, which in turn may influence fire frequencies. Thus, the results will allow for comparison with future studies to determine if the spatial representation of ignition frequencies in shrub-dominated communities and dry pine stands has changed significantly.

Study Area

The Intermountain West lies between the Cascade-Sierra Nevada Mountain Ranges on the west and the Rocky Mountains on the east. The region ranges from 38° to 47°N and occupies an area of about 700,000 km^2. The topography is basin and range, characterized by north-south oriented fault-block mountains often rising 1000–2000 m above typically wide (>75km) surrounding basins (Trimble 1989). Except in areas where mountains receive substantial orographic-induced precipitation, the climate is semiarid (25–50cm ppt/yr) north of 41°N and becomes increasingly arid (<25cm ppt/yr) farther south. Pacific-type frontal systems are the major source of precipitation throughout the region during autumn, winter, and spring (Houghton et al. 1975), while summer convective thunderstorms may also be a significant source of precipitation east of the 115th meridian (Knapp 1994). Temperature extremes vary substantially between January (− 40° C) and July (45° C) (Western Regional Climate Center 1993).

Excluding the more mesic (forested) montane vegetation, three distinct vegetation zones comprise approximately 80% of the Intermountain West (West 1983a, b, c; Trimble 1989). Shadscale (Atriplex confertifolia) occupies the arid, low-elevation areas of the Intermountain region, and is most common in the

Lahontan Trough in the west and the Bonneville Basin in the east (West 1983a). Cover in this association is sparse, often less than 20%. The dominant shrubs are shadscale, Bailey's grease-wood (Sarcobatus baileyi), and horsebrush (Tetradymia spp.), interspersed with the perennial Indian ricegrass (Oryzopsis hymenoides) (Tueller 1989). In many of the disturbed areas, the exotic annual grass cheatgrass (Bromus tectorum) is also found, particularly after wet years.

Two other vegetation zones in the Inter-mountain area are found in either wetter or less saline environments than the shadscale zone. North of approximately 41°N lies the sagebrush-steppe zone, where cover may range from 30% (Knapp 1992) to greater than 80% (West 1983b). The dominants here are big sagebrush; the perennial grasses Idaho fescue (Festuca idahoensis), bluebunch wheatgrass (Agropyron spicatum), western wheatgrass (A. smithii), thickspike wheatgrass (A. dasystachyum), and the needle grasses (Stipa spp.); and the annual exotic grasses cheatgrass and medusahead (Taeniatherum caput-medusae) (West 1983b; Whitson et al. 1992). In the absence of significant anthropogenic disturbance, equal proportions of sagebrush and grasses are typical (West 1983b), but exotic annual grasses may dominate (>60% biomass) in some disturbed areas (Pellant and Hall 1994).

Similar to the sagebrush-steppe zone in species composition, but generally lying south of 41°N, is the sagebrush-desert zone. Because of the progressively drier conditions found in the central and southern thirds of the Intermountain region, the relative abundance of big sage-brush (>70%) increases while grass cover (<30%) decreases (West 1983c). Total cover rarely exceeds 40% except where exotic annual grasses have invaded (West 1983c).

Grass-dominated communities may also extend above the higher (and wetter) sections of the sagebrush steppe zones and be interspersed with open stands of timber. The most common trees found are western juniper (Juniperus occidentalis), singleleaf pinyon (Pinus monophylla), ponderosa pine (P. ponderosa), and Jeffrey pine (P. jeffreyi). These communities are rare within the Intermountain region and are not to be equated with pinyon-juniper woodlands (lacking a significant grassy understory), a vegetation type not considered in this study.

Methods

Data

Seventeen Bureau of Land Management (BLM) districts were chosen because their boundaries fall largely within the Intermountain region. The selected districts were Susanville (California); Boise, Burley, Idaho Falls, and Shoshone (Idaho); Burns, Lakeview, Prineville, and Vale (Oregon); Battle Mountain, Carson City, Elko, Ely, and Winnemucca (Nevada); and Cedar City, Richfield, and Salt Lake (Utah). The data from each district extended from 1980 to 1994 and included the following information for each fire, based on the point of origin: BLM district, year, fire type, cause, latitude, longitude, vegetation type, acres burned, topography, aspect, slope, elevation, fuel model, slope class, grass type, and climate classification. Data were provided by the National Interagency Fire Center (NIFC) in Boise, Idaho.

Some data from the original dataset were eliminated prior to statistical analyses. I removed all non-lightning-initiated fires because I wanted to reduce the influence of human agency. Further, without the elimination of non-lightning-initiated fires, it would have been difficult to compare spatial patterns between more densely populated (e.g., around Salt Lake City) and sparsely populated areas (e.g., rural Nevada). Lightning-initiated fires represented 60.1% of all fires in the Intermountain West between 1980 and 1994, while no other *defined* fire cause was greater than 6.1 %. Thus, this selection criteria allowed me to minimize the effects of human activities (as a function of population density), yet retain over half of the original data.

I used only data for fires classified as "grass-dominated," based on fuel model criteria outlined by Anderson (1982). Grass-dominated fuel models are: (1) "A"—western annual grasses (trees and shrubs sparse, cheatgrass and medusahead common with >50% of herbaceous species being annuals; cover varies with annual rainfall); (2) "L"—western perennial grasses (trees and shrubs sparse, perennial grasses dominant); (3) "T"— sagebrush-grass (shrubs occupy at least 3 3 % of site, annual and perennial grasses common); and (4) "C"—open timber with grass (perennial grasses dominate understory; stands of ponderosa, Jeffrey, and sugar pines, and sometimes pinyon-juniper).

To determine which areas had the highest annual mean number of lightning-initiated fires, the modified data file was used to pro-duce a rasterized data file in IDRISI. The area between 36°–46°N and 110°–123°W was divided into 885 25 km × 25 km cells. Because the length of both a degree of latitude and longitude vary latitudinally, and it was important to have all cells approximately the same size, an average length for both was based on the 41st parallel. Ultimately, this compromise allowed for the cell size to be 25 km × 2 5 km along 41°N and only slightly smaller on the northern (46°N) and slightly larger on the southern (36°N) boundaries. Regional fire frequency based on the average number of fires per year per cell was calculated, mapped, and overlaid onto a base map of the study area.

Two additional statistics were mapped. First, I mapped mean annual lightning strike density between 1985 and 1994. The lightning strike data, provided by the National Interagency Fire Center for these years, represented all cloud-to-ground strikes recorded by the BLM's Automatic Lightning Detection System, which has an 85% detection efficiency. Locational accuracy is a ±1852m error per 111,120m from the detection finder. Mapped cells were based on 1° latitude × 1° longitude dimensions (the resolution provided by the data). Second, to illustrate ignition success, I mapped Spearman correlation values between lightning fires and lightning strike densities between 1985 and 1994 also based on a 1° latitude × 1° longitude grid (83 correlations). Caution is necessary, however, when interpreting correlation values based on only 10 samples. Even when correlation values are statistically insignificant, however, it is meaningful to map them in an effort to discern broad-scale patterns of ignition success.

Canonical Discriminant Analysis

In order to examine factors that influence ignition frequency, statistical analyses were performed using canonical discriminant analysis (CDA) (SAS 1988). CDA classifies data by deriving linear combinations of variables that summarize variation between groups of sites based on individual "cases" (samples) selected from those groups (Klecka 1980). CDA has been widely applied in geographical and ecological studies (Williams 1983) and is useful when the research goal is both classification (seeking maximum group separation) and interpretation (analyzing how groups differ) (Klecka 1980). Further, CDA often reduces the dimensionality of multivariate analysis (Williams 1983) by allowing the "naming" of canonical discriminate functions based on variables that have large structure coefficients for that function. Thus, interpretation may be simplified.

I chose four sites for each of three groups based on high, medium, or low regional fire frequencies (Fig. 1). Data reduction into three groups was performed to determine if the included data could effectively separate environmental characteristics that promote a particular fire regime. I identified groups based on ignition frequency by plotting the 20 cells with the highest and lowest frequencies, and 20 cells in between, on a 1° × 1° grid. When multiple cells occupied the same grid square, I used the cell with the highest value. This technique insured that I did not pick a 25 km × 25 km cell that was anomalous (i.e., no other comparable values were close) compared to the rest of the data, and allowed for greater confidence that the ignition frequency value represented was consistent within the region.

Independent variables included were NFDRS climate classification (based on Thornthwaite's (1931) humidity provinces), slope, percentage annual grass, percentage of fuel groups, "T" (sagebrush-grass) and "C" (open timber with grass), and elevational difference, which was the difference between highest and lowest altitude of recorded fires (Table 1). Although other data may have been useful for interpreting differences between groups (e.g., climatic data), my goal was to use only data that were collected by the BLM/NIFC; hence, future analyses would re-quire no additional data collection.

Fuel model data were presented nominally, but were converted to dummy variables for inclusion in the models. None of the independent variables were highly correlated (all $r < 0.8$). While the group covariance matrices were unequal and group populations were not multivariate normally distributed, the large data set (805 observations) and high combined squared canonical correlation (0.70) indicated that CDA remained a robust technique and that violations may have decreased classification precision but did not invalidate their interpretation (Klecka 1980).

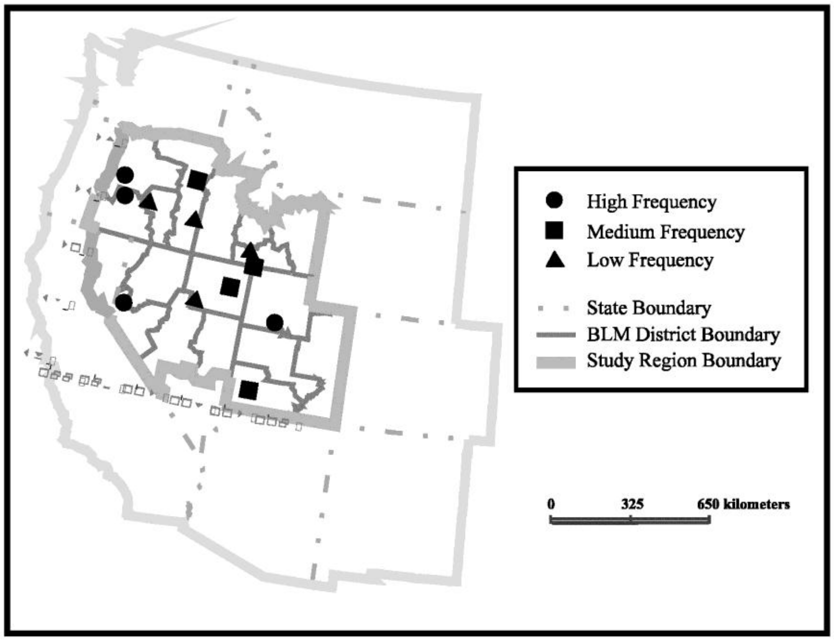

Figure 1: *Locations of selected sample sites used in canonical discriminant analysis based on regional fire frequencies (1980–1994).*

Results

The annual number of fires ranged from 0.93 to 12.73 in the 25 km x 25 km cells chosen for CDA analysis (Table 1). Elevational differences varied from 610 to 1830m, and NFDRS climate classifications from 1.00 (arid to semiarid) to 2.00 (subhumid). In both instances, higher ignition frequencies were associated with larger values (Table 1). Slope values, which represented the average of all observations for each case, ranged from 4.2% to 32.8%, and fuel type coverage (again, an average of all observations per case) ranged from 4.9% to 100% for coverage of sagebrush-grass (T) and from 0 to 60% for coverage of open timber with grass (C). Annual grass coverage ranged from 0 to 90.9% for each cell and was typically higher at sites with lower ignition frequencies (Table 1).

Table 1 *General Characteristics of Selected Sites*

Fire Frequency Class	Annual # Fires/ ($625 km^2$)	Location		NFDRS[a] Climate Class	Slope (%)	Fuel Model		Annual Grass (%)	Elevational Difference (m)
		Lat. (°N)	Long. (°W)			T[b] (%)	C[c] (%)		
High	12.73	43.39	120.78	1.27	4.2	37.4	60.4	39.6	1220
High	6.80	40.20	112.51	1.00	18.4	4.9	33.3	60.7	1524
High	9.73	39.75	119.60	2.00	32.1	100.0	0.0	0.0	1830
High	8.33	44.07	121.08	1.99	19.3	82.1	14.9	4.5	1220
Medium	2.67	44.52	117.53	1.17	32.8	92.9	7.1	7.1	1830
Medium	3.00	41.11	114.88	1.02	25.6	53.3	46.7	0.0	915
Medium	3.40	37.70	113.10	1.17	21.1	80.8	19.2	0.0	915
Medium	2.93	42.02	113.99	1.13	24.7	71.1	13.3	28.9	915
Low	0.93	43.39	119.60	1.00	2.3	36.3	9.1	90.9	610
Low	0.93	43.16	117.24	1.00	19.8	80.0	0.0	26.7	915
Low	0.93	42.48	114.28	1.12	29.1	88.2	0.0	58.8	610
Low	0.93	42.93	118.42	1.00	28.82	42.9	28.6	92.9	915

[a] *NFDRS climate classification based on Thornthwaite (1931).*
[b] *Sagebrush-grass fuel model.*
[c] *Open timber with grass fuel model.*

Several regional fire patterns are apparent (Fig. 2). In the western third of the region, fire frequencies peak along the eastern foothills of the Oregon Cascades and the Sierra Nevada/Carson Range foothills of Nevada/ California. Fully 15 of the 20 cells with the highest fire frequency are west of 119° W. In the east, a peak occurs near the Stansbury Mountains in Utah. Smaller peaks occur along the Snake River Plains of Idaho and Ruby Mountains of Nevada. Low ignition frequencies are particularly pronounced in the Lahontan (Oregon-Nevada) and Bonneville (Utah) Basins.

Two canonical discriminant functions (CDFI, CDFII) had squared canonical correlations of 0.56 (CDFI) and 0.14 (CDFII). The combined squared canonical correlation of 0.70 suggests that the two discriminant functions effectively separated high, medium, and low regional fire frequency by groups. CDFI accounted for 89% of the total discriminating power, while CDFII accounted for 11%. Wilk's Lambda values were 0.38 and 0.86 ($p < 0.0001$) for CDFI and CDFII, respectively. These values indicate that inclusion of both CDFs is necessary to represent observed differences between groups (Klecka 1980).

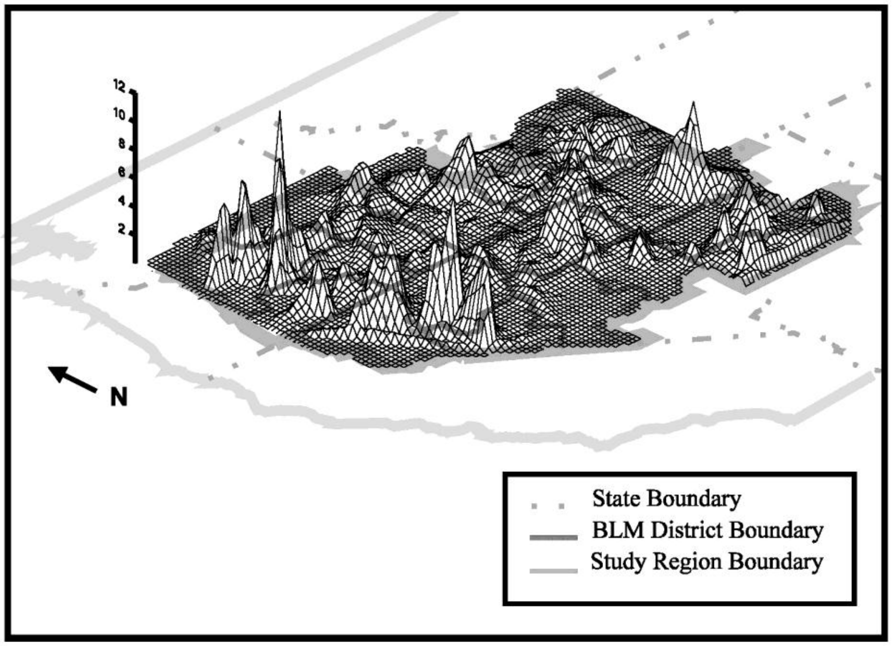

Figure 2: *Mean annual frequency of lightning-initiated fires in the Intermountain West, 1980–1994.*

Standardized canonical coefficients show the relative importance of a variable in relation to its function score. For CDFI, elevational difference and percentage slope made the largest contribution to the function scores, while climate classification had an intermediate contribution, and percentage sagebrush-grass, open timber with grass, and annual grass had minor contributions (Table 2). Percentage annual grass made the largest contribution to CDFII, followed by intermediate contributions by climate classification, relief, and the two fuel models (Table 2). Slope made little contribution to CDFII. Values for structure coefficients, indicating how closely a variable and function are related (Klecka 1980), show that CDFI is closely related to elevational difference and NFDRS climate classification, suggesting that this function is largely a "climate" dimension (Table 2). CDFII is dominated by percentage of annual grass, and suggests that this function is a measure of "fuel characteristics" (Table 2). Combined, CDFI and CDFII show that sites with a large elevational difference, a more mesic climate, and less annual grass cover are more likely to experience higher ignition frequencies.

Table 2 *Total and Standardized Canonical Coefficients for CDFI and CDFII*

	Total Canonical Structure Coefficients		Standardized Canonical Coefficients	
Variables	Function 1	Function 2	Function 1	Function 2
Climate classification	0.52	−0.10	0.57	−0.65
Slope	−0.33	0.27	−0.76	0.08
Sagebrush–grass (T) fuel model	−0.14	0.16	−0.20	0.40
Open timber with grass (C) fuel model	0.15	0.14	0.29	0.33
Annual grass	−0.05	−0.79	0.26	−0.90
Elevational difference	0.73	0.37	1.24	0.45

Group differences were further interpreted by predicting fire frequency group membership based on CDFI and CDFII, and by comparing this classification to actual group membership. 88.5% of all the observations were correctly classified in their respective fire frequency groups (Table 3). The highest correct classification (98.6%) occurred for the high fire frequency group, while both the medium (62.3 %) and low fire frequency groups (66.7%) had lower classification accuracy. The majority of misclassified low fire frequency observations were placed in the medium fire frequency group, while the majority of misclassified medium fire frequency observations were placed in the high fire frequency group (Table 3). A distinct pattern for lightning strike densities is seen for the study area (Fig. 3). In general, density increases from west to east and from north to south. Patterns showing ignition success, however, are less distinct (Fig. 4). No statistically significant correlations (α = 0.01) between lightning-initiated fires and lightning strike densities occurred in the study area. The highest positive correlations (>0.65) occurred along the 120th meridian between 40° and 43°N, while the most negative correlations (<−0.60) occurred along the 112th meridian between 39 and 41°N.

Table 3 *Predicted Category Membership for Each Observation Based on Group*

	Predicted Category Membership		
Actual category	High	Medium	Low
High	565 (98.6)	7 (1.2)	1 (0.2)
Medium	55 (31.4)	109 (62.3)	11 (6.3)
Low	3 (5.3)	16 (28.1)	38 (66.7)
Percentage of sites classified correctly: 88.5%			

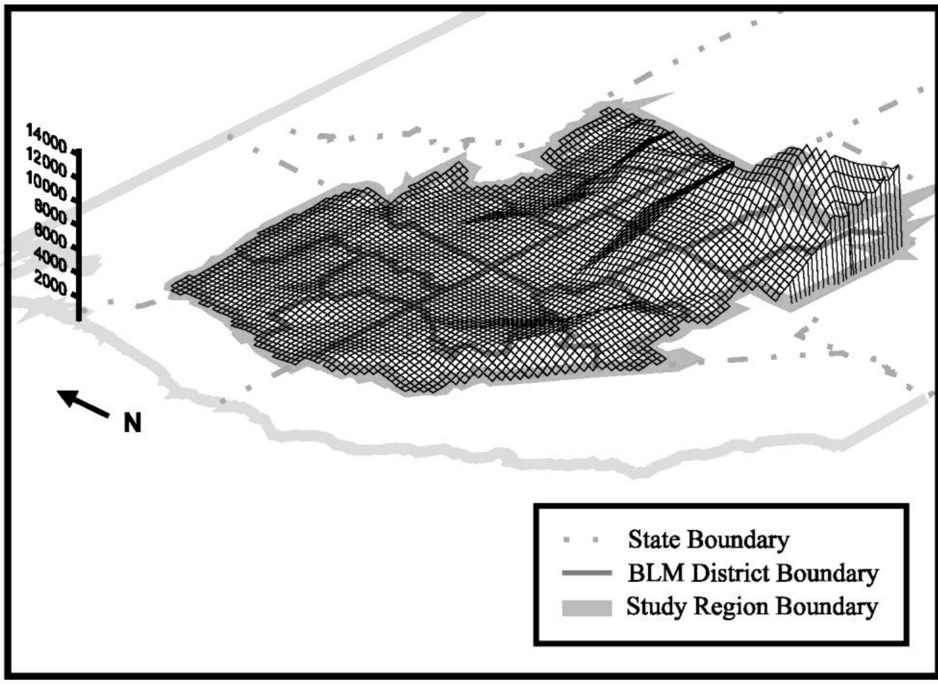

Figure 3: *Mean annual frequency of lightning strikes in the Intermountain West, 1985–1994.*

Discussion

Canonical Discriminant Function I

Elevational difference and NFDRS climate classification provided the majority of the discriminating power for delineating regional fire frequency. In general, when there is greater elevational difference and greater effective precipitation (i.e., higher NFDRS climate classification values), ignition frequency increases. Elevation itself did not contribute significantly enough to be incorporated in the discriminant analysis. Instead, elevational difference is indicative of a site that has varied topography conducive to orographic enhancement of both frontal and convective-initiated systems that substantially increase the magnitude of precipitation events. Orographic precipitation gradients in the Great Basin are steep, and in some instances (e.g., the Ruby Mountains of Nevada) precipitation on higher slopes may increase by more than 50 cm/year over surrounding basins (Houghton 1969). This enhancement of precipitation is probably associated with greater fuel production, which in turn increases ignition probabilities provided that fuel moisture levels do not exceed ignition thresholds. Thus, these regions of higher NFDRS climate classification and greater elevational difference likely represent regions where the optimal conditions of abundant fuel accumulation and low fuel moisture content are found. The data support this contention. Mesic environments *consistently* have greater plant cover (hence, available biomass) when compared to xeric environments. This component is seen through the positive association with the open timber with grass community (C), a plant community common in more mesic environments, as opposed to negative associations with sagebrush with grass (T), and annual grass cover, communities that are found in more xeric environments.

While elevation was not an important factor within the Intermountain West grass communities, other studies conducted in the mountains of the western United States have shown that ignition frequency is correlated with elevation (Romme and Knight 1981; Vankat 1985; Allen and Peet 1990; Baisan and Swetnam 1990; Agee

1991; Barton 1994). Martin (1982) addressed this variability by illustrating the relationship between fire frequency and site conditions. He found that plotting fire frequencies based on temperature/moisture conditions produced a U-shaped distribution that linked highest frequencies (bottom of the U) in environments such as mesic rangelands where high fuel loadings and low fuel moisture content were optimal for frequent ignition. Low ignition frequencies (upper portions of the U) occurred in regions of either insufficient fuel loadings (desert) or excessive fuel moisture content (subalpine). Thus, in environments where fuel moisture content is initially high, increasing elevation (and precipitation) creates excessive fuel moisture conditions that decrease the likelihood of fire. Agee (1991), for example, found this relationship in the Siskiyou Mountains of southern Oregon. Conversely, several studies in Arizona and Colorado (e.g., Allen and Peet 1990; Barton 1994) have shown that ignition frequency increased with elevation because fuel loadings were insufficient to carry fire. It is noteworthy that the relationship between elevation and ignition frequency in the Intermountain West also may exist, but is confounded because base elevations of mountains (where the most xeric conditions typically are found) generally increase from the western to eastern portions of the region. Hence, two areas of comparable climate, vegetation, and ignition frequencies may exist at substantially different elevations.

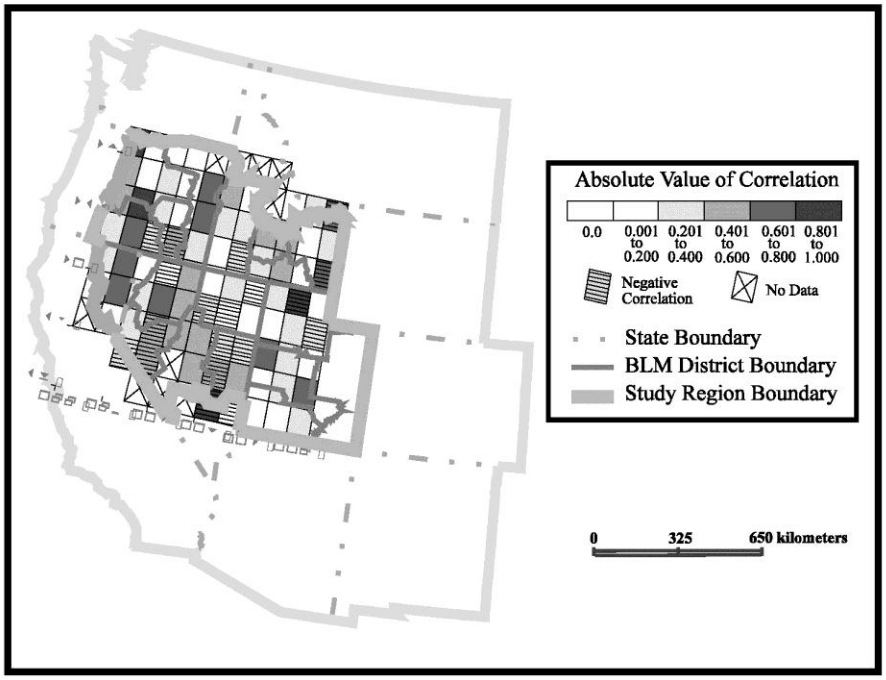

Figure 4: *Ignition success for the Intermountain West, 1985–1994.*

Large mountain barriers (indicated in this study as elevational difference) may also promote localized increases in lightning frequency. This effect, however, is expressed poorly. First, lightning strikes in the Intermountain West have two distinct spatial characteristics: they are most frequent in the southeast and steadily decline towards the northwest. Second, there is little variability to this pattern, with the exception of a slight increase towards the east side of the Sierra Nevada (Fig. 3). In fact, the region with the highest regional fire frequency receives among the fewest number of lightning strikes throughout the Intermountain West.

The relationship between fire frequency and lightning strikes is often weak because land-scape and fuel conditions have the largest influence on ignition probability (van Wagtendonk 1986; Christensen 1993). Latham (personal communication, 11/3/95) has noted that lightning frequency is not the limiting factor for fire frequency in the Intermountain West; rather, fire probabilities are chiefly associated with fuel loadings, fuel moisture levels, and arc duration. This concept is illustrated by the generally random pattern of correlation be-tween lighting-initiated fires and lightning density throughout most of the study region (Fig. 4). It is noteworthy that the most positive correlations typically exist in areas where strike density is low as opposed to only in areas where ignition frequencies are high, supporting the notion that strike density is not the limiting factor (Figs. 3 and 4). Further complicating this relationship is prior fire history and fuel buildup. Thus, equally sized areas with comparable fire probabilities could have different frequencies based on fire size, since a large fire would temporarily eliminate additional fires until sufficient fuel buildup occurred. Conversely, higher ignition frequencies are possible when fire size is limited, since additional lightning strikes could ignite non-burned sites. Interpretation of CDFII shows a possible effect of scale-based dependence.

Higher ignition frequency in the western side of the Intermountain West than in areas farther east (Fig. 2) may also be related to general synoptic patterns that favor greater summer precipitation east of 115° E. This location is the approximate boundary between infrequent and frequent moist air flow from the Gulf of Mexico during the summer (Houghton 1969). Between 1980 and 1992, for example, the southwestern portion of the Great Basin received approximately 46% as much summer rainfall (2.94 cm) as did the southeastern portion (6.22 cm) (Knapp 1995). While the absolute differences are modest, Knapp (1995) illustrated that summer precipitation during the same period was correlated negatively with area burned in the Great Basin.

Canonical Discriminant Function II

Percentage cover of annual grasses also helped to discriminate between regions with different ignition frequencies. Regions with high fire frequencies typically had less annual grass cover than did areas with lower fire frequencies. Many studies (e.g, Whisenant 1990, Billings 1994, Peters and Bunting 1994) have discussed the effects of the cheatgrass-wildfire cycle in the Intermountain Region, and have shown that fire-return intervals have decreased as annual grass cover has expanded. Along the Snake River Plains, where cheatgrass has replaced sagebrush-steppe communities, fire-return intervals have decreased from nearly centennial to once in five-year periods (Whisenant 1990). A shift toward annual grass dominance leads to fuel bed conditions that are conducive to “large and continuous fires” (Peters and Bunting 1994) as opposed to small and discontinuous ones.

Greater ignition frequency in areas of lower annual grass cover is likely a function of two causes. First, annual grass cover tends to be temporally inconsistent, reflecting great inter-annual precipitation variability throughout the Intermountain West. In the absence of favorable growing conditions, fuel availability at more xeric sites is limited by the sparse perennial vegetation that is insufficient for frequent ignitions; hence, many years occur with few fires. Second, because fires in annual grass tend to be large and continuous, these fires should decrease the likelihood of additional fires in that region because the ignition source has been eliminated (illustrating the importance of scale-based dependence of ignition frequency). Thus, while fires in areas dominated by annual grasses may be large, they are less likely to be as frequent. Conversely, as annual grass cover decreases, there is a tendency toward more but smaller fires. This contention is supported by area burned for the three groups. Only 27% of all fires in the low frequency group were less than 0.4 ha, while 79% and 90% of all fires were less than 0.4 ha for medium and high fire frequency groups, respectively. Ironically, the presence of annual grasses has probably decreased the difference in regional fire frequencies between high and low frequency groups. Ignition frequencies were rare in the low elevation sites prior to invasion of exotic annuals, while the presence of annuals in more mesic environments has likely decreased ignition frequencies because of increased fire size.

Conclusions

These results emphasize distinct patterns regarding regional fire frequencies in the Intermountain West. First, fire frequency patterns tend to reflect the local topography, with mountainous areas experiencing higher ignition frequencies than non-mountainous areas. Additionally, the western region of the Intermountain West experiences more fires than the central and eastern portions of the region, most likely a function of minimal summer precipitation on the western side. Second, at the scale examined, the influence of lightning frequency on ignition probabilities is minimal. There is little relationship between fire frequency and lightning density throughout most of the Intermountain region because fire probability is fuel limited. Third, the role of vegetation composition and cover is important. In particular, exotic annual grass cover is negatively correlated with ignition frequencies.

Fourth, changes in vegetation composition (i.e., a shift toward more annual grass cover) may substantially alter regional fire frequencies. Several authors have noted that during the last several decades, exotic annual grasses in the Intermountain West appear to have expanded their ranges, invading the lowest (most arid) regions (e.g., Young and Tipton 1990; Hunter 1991) and becoming more prevalent at higher (more mesic) elevations (e.g., Billings 1994). In the arid Lahontan Basin, for example, cheatgrass cover provides sufficient fuel for fire and increases regional fire frequencies, since prior to cheatgrass establishment, this area was considered "fireproof" (Young and Tipton 1990). Conversely, in more mesic environments where biomass production was already sufficient for fire, expansion of the annual grasses has led to likely decreases in regional fire frequency, since fires would be large and spatially continuous as opposed to small and spatially discontinuous.

This study provides a reference for analyzing spatial variability in regional fire frequencies in the Intermountain West. Higgins (1984) has reported that for the northern Great Plains, lightning fire characteristics have been altered by human factors (e.g., fire suppression and agriculture), and that fire frequencies likely have declined in the last century. Similarly, given the dynamic nature of vegetation change within the Intermountain West, particularly because of the influence of exotic annual grasses, the presented spatial patterns could be mapped again in future decades, noting whether distinct shifts in ignition frequency had occurred, thus helping land management agencies make more informed fire management decisions.

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