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To be submitted to International Journal of Wildland Fire

Lightning-Landscape-Fire Relationships in Two Large Rocky Mountain Wilderness Landscapes

Matthew G. Rollins

USDA Forest Service
Fire Sciences Laboratory
5775 Hwy 10 West
Missoula, Montana 59807
(406) 329-4960

Introduction

Although detailed fire and lightning occurrence data have been compiled for federal lands in the United States in recent decades, little research has been conducted evaluating spatial and/or temporal associations that might be revealed by direct comparisons and spatial analyses of these data. Empirical research relating lightning distribution and characteristics to wildland fire ignition and landscape variables over broad scales increases the understanding of the spatial and temporal distribution of ignition probabilities. This information is particularly useful for 1) evaluating the effects of changing fire regimes, 2) parameterizing spatially explicit landscape-fire models, 3) for evaluating the risks and benefits of wildland fire, and 4) for strategically and tactically planning for wildland fire use, mechanical fuels treatments, and fire suppression.

Analyses of the spatial distribution of lightning-caused fire records at landscape scales illustrate important spatial aspects of local-to-regional fire regimes. Specifically, these comparisons identify areas where lightning-caused fires are dense and tend to get large. This information is particularly useful for supporting tactical decisions by fire managers faced with multiple ignitions across broad areas. Conversely, these analyses also show where lightning-caused fires are less dense or rare. This information may be used to strategically prioritize areas for alternative fuels management treatments (e.g. management ignited fires) in wilderness or roadless areas where wildland fire use may be the only method for restoring ecosystems to historical conditions.

We provide an easily repeatable, standardized process for evaluating ignition density over broad areas using relatively easily obtainable geospatial data representing lightning-location, landscape variables, and fire occurrence. We purposely excluded data representing daily weather or antecedent moisture conditions with the goal of simplifying our approach. This increased the likelihood that personnel without advanced geographic information system (GIS) or statistical modeling expertise could apply our methods using existing GIS databases. Daily, mapped weather data are difficult to compile, manipulate, and analyze; and can be quite expensive. These data do, however, exist (e.g. Thornton 1997; www.daymet.org). Comparing results from these two broad-scale, climatically distinct areas and analyzing the differences and similarities of results in the context of previous and on-going research in these areas yielded empirical evidence of the constraints and causal relationships that drive fire regimes in Rocky Mountain ecosystems and strengthened assertions that the lightning-caused fire maps that we present will be a useful tool for fire management strategies that involve both wildland fire use and fire suppression.

This paper describes an evaluation of spatial and temporal databases of fire and lightning occurrence in the 317,000 ha Gila/Aldo Leopold Wilderness Complex (GALWC) in New Mexico and the 547,000 ha Selway-Bitterroot Wilderness Complex (SBWC) in Idaho/Montana. Specific results include 1) summary descriptions of fire and lightning occurrence, 2) evaluation of the timing of lightning and fire occurrence, 3) development of ignition and lightning occurrence probability surfaces, 4) overlay analyses evaluating fire and lightning occurrence over a variety of landscape variables, and 5) comparison of fire rotation estimates based on separate databases describing recent fire history

Few studies of this type have been conducted (but see: Pickford et al. 1980, Flannigan and Wotton 1990; Granström 1993; Minnich et al. 1993; Nash and Johnson 1996; Vásquez and Moreno 1998). The research presented in this report encompasses the broadest temporal and spatial scales of lightning and fire relations yet investigated. Moreover, this research contributes to the overall understanding of interactions between the atmosphere and ecosystems. Rates of occurrence and spatial patterns of wildfires are key mechanisms by which climatic change, including changes in lightning processes, can drive ecological change (Overpeck et al. 1990; Ryan 1991; Price and Rind 1994). It is essential, therefore, that we begin to assess climate-fire patterns across a range of temporal and spatial scales (Schmoldt et al. 1999). Fire management has not taken full advantage of spatial databases for empirically evaluating relationships between lightning, vegetation and topography; the characteristics of lightning strikes that actually ignite wildfires; and the variability of lightning activity within and between years.

The GALWC and SBWC were especially advantageous study areas because, in addition to existing databases related to previous and on-going research, the USDA Forest Service has actively managed fire in these areas for over a century, including nearly 30 years of wildland fire use for resource benefit (historically referred-to as prescribed natural fire management). The GALWC has the highest incidence of lightning-ignited wildfire in the United States, whereas lightning fire ignition rates in the SBWC are more typical of the rest of the North American Rocky Mountains (Schroeder and Buck 1970). These remote wilderness areas are especially at risk from lightning-caused wildfires because of inaccessibility and difficulty in detecting ignitions. The remoteness of lightning-caused fires in these areas necessitates aerial detection and suppression (including firefighter delivery and retardant application). This dramatically increases the cost of fire suppression in these large wilderness areas. Often, the time between fire detection and initial attack in these remote fires is quite long, contributing to the likelihood that these fires will be quite large before suppression action is possible. The products provided along with this report provide valuable information for fire managers in each wilderness to address spatial questions about both fire suppression and wildland fire use.

Study Areas

Gila Wilderness Complex

The Gila Aldo Leopold Wilderness Complex (GALWC) encompasses the headwaters of the Gila River in the Mogollon Mountains in central-western New Mexico (Figure 1). Elevations range from 1,300 m near the main stem of the Gila River to 3,300 m in the Mogollon Mountains. Parent material of the GALWC derives from volcanism in the late Cretaceous (USGS 1965). The Gila Conglomerate, a tertiary sedimentary formation, is exposed in tall, pinnacle-like rock formations along the middle and east forks of the Gila River.

Annual precipitation varies from 250 mm to 760 mm in the high mountain ranges of eastern Arizona and western New Mexico (Beschta 1976). Annual precipitation is bimodal, with a wet period between December and March and another occurring with the southwestern monsoon between July and September. Mean daily temperatures vary from below freezing in the winter to extremely hot in the middle of summer (30ºC). Thunderstorms are common in the summer months, resulting from the lifting of moist air masses moving north from the Gulf of Mexico. Fire season in the GALWC begins as early as April and may extend through September. Spring conditions are usually dry. Thunderstorm activity increases in early July.

Pre-EuroAmerican fire regimes in the in the GALWC were dominated by frequent, low-severity (i.e. low forest mortality) surface fires, with mixed surface and crown fires found at higher elevations (Swetnam and Dieterich 1985; Abolt 1996). During dry years of the 20th century, fire behavior has occasionally been extreme, with extensive crown fires across all elevations. The GALWC has the highest level of lightning-caused fire occurrence in the United States, with an average of 5 lightning-ignited fires per 100 ha per year (Barrows 1978).

Desert scrub (Ceanothus, Artemisia, and Yucca spp.) is found in broad valleys at the lowest elevations of the GALWC. As elevation increases, piñon/juniper woodlands (Pinus edulus, Juniperus deppeana, J. monosperma, and Quercus spp.) dominate. Forests convert to ponderosa pine (Pinus ponderosa) with a shift toward Douglas-fir (Pseudotsuga menziesii) as elevation increases. Piñon-juniper, ponderosa pine and Douglas-fir forests make up 88% of the land area of the GALWC. Forests at the highest elevations are comprised of mixed forests of Douglas-fir, southwestern white pine (Pinus strobiformis), Engelmann spruce (Picea engelmannii), subalpine fir (Abies lasiocarpa var. arizonica), white fir (Abies concolor), and aspen (Populus tremuloides).

Selway-Bitterroot Wilderness Complex

The Selway-Bitterroot Wilderness Complex (SBWC; Figure 1) in Idaho and Montana is the second largest designated wilderness in the conterminous United States. The largest is the adjacent Frank Church River-of-No-Return Wilderness in Idaho. The area is characterized by extremely rugged terrain, with broad topographic variation. Portions of the wilderness are found on the Bitterroot, Clearwater, Lolo and Nez Perce National Forests. The majority of the wilderness area is found within the Idaho batholith where parent material is characterized by 100 million year-old igneous compositions (Greenwood and Morrison 1973). Volcanic parent material in lower elevations along the Selway and Lochsa rivers was formed during the Mesozoic and Cenozoic periods (Habeck 1972). The canyons and valleys of the central Selway and Clearwater River drainages were dissected prior to the eruption of the Columbia River basalt.

Three main topographic regions exist within the wilderness area. The eastern portion of the wilderness consists of the north/south-oriented Bitterroot Range. These mountains begin in the northeastern corner of the wilderness and extend 70 k to the southeastern corner, and consist of large mountain peaks as high as 3,050 m. East/west-oriented glacial valleys dissect the mountains to valley bottoms as low as 1,000 m. The central/southern portion of the wilderness comprises the majority of the Selway River basin. This area consists of rugged terrain with complex high ridges (□2,500 m) dissected by steep canyons as low as 500 m. The northwestern portion of the wilderness, distinguished by an inland Pacific maritime climate, falls within the Lochsa River drainage, with high mountains (the Clearwater Mountains) and deep, forested valleys.

Average precipitation in the SBWC is quite high. Along the main stems of the Lochsa and Selway Rivers, close to 1,000 mm of precipitation falls annually, with values as high as 1800 mm in the central and Bitterroot mountain ranges. Over 50% of this precipitation falls as snow (Finklin 1983). January is the wettest month, with normal monthly precipitation ranging from 75 mm to 250 mm (Finklin 1983). Late summer is the driest time of year with average monthly precipitation between 20 and 30 mm. Summertime precipitation varies widely; July-August values have ranged from 7 mm in 1969 to 160 mm in 1975 (Finklin 1983). Large thunderstorms are frequent in the SBWC, peaking in activity during the early summer. Monthly mean temperatures range from –10ºC in January and average daily temperatures as high as 30ºC in July and August. Fire season in the SBWC begins in the early summer and may extend through September. Fire regimes are mixed, with patchy stand replacement fire dominant in upper elevation forests (68% of the SBWC) and more frequent, lower severity fires at lower elevations (Brown et al. 1994). Historically, the moist forests of the lowest elevations along the Lochsa and Selway Rivers had fire return intervals between 300 and 450 yr (Shiplett and Neuenschwander

1994, Brown et al. 1994). Stand replacement fires are dominant across all elevations during extreme years (Brown et al 1994; Barrett and Arno 1991).

The lowest elevations (500-1500 m) in the wilderness (i.e. the lower Lochsa and Selway River basins) are distinct from surrounding areas. These inland Pacific maritime forests are characterized by mesic assemblages of western redcedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*), western white pine (*Pinus monticola*), grand fir (*Abies grandis*) and Douglas-fir. At elevations around 1000 m, forests of the SBWC are dominated by ponderosa pine, Douglas-fir and western larch (*Larix occidentalis*) forests. As elevation increases, these assemblages convert to mixed Douglas-fir/Engelmann spruce/grand fir forests followed by subalpine forests containing assemblages of Engelmann spruce, subalpine fir (*Abies lasiocarpa*), whitebark pine (*Pinus albicaulis*) and lodgepole pine (*Pinus contorta*). Many extensive stands of lodgepole pine resulted from large fires with homogenous stand structure and ages. The highest subalpine elevations are characterized by mixed whitebark pine/alpine larch (*Larix lyallii*) forests (Habeck 1972). Sixty percent of the area of the SBWC is comprised of subalpine forests.

Data and Methods

Topography

Elevation data were available from the USDA Fire Sciences Laboratory in Missoula, Montana. Digital elevation data were developed as two compiled sets of USGS 7.5 minute digital elevation models (DEMs, 30 m cells) for the GALWC and SBWC by Keane et al. (1998; 2000). For both areas, a combination of level 1 and level 2 DEMs was used to obtain complete coverage of the study area. Level 1 DEMs sometimes show a horizontal banding pattern, and this was the case in some of the DEMs used. An equal weight, directional filter 7 cells high and 1 cell wide was applied to the level 1 DEMs to smooth areas where horizontal banding was most apparent. The DEMs were then tiled together, and edges between Level 1 and Level 2 DEMs were filtered to smooth transitions between adjoining datasets by Keane et al. (1998). Each DEM was ‘clipped’ to the 5-km study area boundary. Slope and aspect surfaces were derived from the final DEMs using the Arc/GRID commands ‘slope’ and ‘aspect’ (ESRI 1998).

Potential Vegetation

Potential vegetation type (PVT) is used to describe biophysical characteristics of a site. This method is rooted in succession theory (Clements 1936), and is based on logic developed by Daubenmire (1968) and Pfister (1980) for describing the distribution of plant habitat across landscapes. PVTs are named for the plant association presumed to exist in the absence of disturbance (Cooper et al. 1991). PVTs uniquely describe a biophysical setting, and provide a direct method for classifying biophysical settings across landscapes (Keane et al. 1998). Though originally based on single-pathway succession, the concept remains valid for multiple pathway succession models. Potential vegetation is well suited to time series analyses because it integrates biophysical factors that are important to plant distribution and is based on well-founded classification schemes. Existing vegetation maps represent a single moment in time, and classification schemes for mapping differ dramatically between agencies, areas, and individuals.

The USDA Forest Service Fire Sciences Laboratory in Missoula, Montana provided maps of PVTs for both wilderness complexes. These classifications represented aggregated habitat types and were based on geographic and topographic settings using a heuristic, rule-based approach (Keane et al. 1998; 2000). Rules for mapping habitat types in each wilderness were based on five GIS layers—geographic zone, existing vegetation, elevation, slope, and aspect. Using these layers, area ecologists and scientists formulated series of rules to assign PVT to different groups of habitat types represented by permutations of location and topography. These rules were incorporated into a classification model within a GIS to create raster maps of PVTs for each wilderness with a 30-m grid cell resolution. Thematic accuracy of these layers was determined by comparison with field data. Accuracies of PVT maps were 57% in the SBWC and 89% in the GALWC (Keane et al. 1998; 2000). Extensive fieldwork for other research projects showed that, qualitatively, the PVT classes correctly represented the range of plant habitat and site conditions across each wilderness complex.

Our only modifications of the provided data were to group the subalpine classes for the SBWC to form two new classes: lower subalpine and upper subalpine, and to subset PVT data to the extent of the each wilderness complex. Ponderosa pine occurs as a PVT in the GALWC, but not in the SBWC; however ponderosa pine may occur as a dominant seral tree in the Douglas-fir PVT in either study area. We excluded areas of development and water bodies from our analyses; these were insignificant portions of each study area (less than 1%).

Digital Fire Atlases

Twentieth-century fire perimeters were obtained in digital form (or digitized) from archival fire data at the Gila National Forest Supervisor's Office for the GALWC and from the Bitterroot, Clearwater, and Nez Perce National Forest Supervisor's Offices for the SBWC (Figures 2 and 3). Archives were compiled from old fire reports or operational fire perimeter maps. Although it is impossible to assess the map accuracy of these data completely, it is safe to assume that mapped fire perimeters are based on information intended to spatially represent the location, size, and shape of fire events. Fires that are the most important financially, ecologically and socially are the most likely to be mapped (McKelvey and Busse 1996). This may bias the data toward large, high severity events; however, the large fires usually comprise a very large proportion of the area actually burned (Strauss et al. 1989).

Fire perimeters were compiled using the Arc/INFO ‘regions’ database architecture (ESRI 1998). A 5-km buffer around each wilderness boundary was used to define the extent of the fire atlases for each study area. This insured inclusion of the majority of fires that burned over the boundaries of the wilderness areas. Most of the area included in the 5-km boundary was not densely roaded or harvested. Arc/INFO regions maximize the possibilities for manipulating fire atlas data, because the overlapping fire perimeters may be stored in a single database, while analyses involving reburned areas or individual fires are still possible. Previous research in the GALWC and SBWC has reconstructed fire patterns (e.g., fire size, shape, severity, and frequency) for the 20th-century based on these compiled Forest Service fire atlases (Rollins 2000; Rollins et al 2001).

National Interagency Fire Management Integrated Database

USDA Forest Service historical wildfire data (1970-present) are stored in the National Interagency Fire Management Integrated Database (NIFMID), an Oracle database at the USDA National Computer Center in Kansas City (USDA Forest Service 1993; Duce et al. 1997). The NIFMID data from 1986-1997 were acquired from the National Interagency Fire Center, Boise, Idaho. Of the information included for each fire, only the following was used in this research: location (latitude/longitude), discovery date (month/day/year), statistical cause (lightning or human), and final fire size (acres). Fires are originally reported in public land survey (PLS) coordinates (sections), so the actual spatial resolution of the database is affected by the local accuracy of the public land survey and the degree to which coordinates are truncated prior to storage as geographic coordinates in NIFMID. This degree of truncation differs between states, and was approximately 1 section for each study area. These fire occurrence data were compiled as two Arc/INFO point coverages, one for each study area (Figure 4). The data were projected to the UTM map projection (zone 11 for the SBWC and zone 12 for the GALWC; NAD27) and subset to the boundaries of each study area. To assess the spatial distribution of fires of different sizes we created 'spot' maps where a circle, the area of which was determined by the area burned represented each fire in the study area. These spot maps were used to determine fire rotations by potential vegetation type for the period of record. Tabular data were exported as a SAS database (SAS Institute 1989) for analysis.

National Lightning Detection Network™ Database

Lightning occurrence data were acquired for each study area from the National Lightning Detection Network™ (NLDN) maintained by Global Atmospherics Incorporated in Tucson, Arizona for the period 1989 to 1999. Global Atmospherics Incorporated maintains a large network of gated, wideband lightning detectors, which triangulate the geographic location of every lightning strike in the conterminous United States (Krider et al. 1976; Noggle et al. 1976; Krider et al. 1980; Cummins et al. 1998a; 1998b). For each lightning strike the NLDN contains data for date (mm/dd/yy), time (hh/ss), polarity (+/-), strength (kA), and multiplicity (#strokes). The spatial accuracy of lightning locations changes over time within the database; with more recent data have higher spatial precision due to improving detection and location technologies (Cummins et al. 1998b). Estimated spatial resolution of the lightning occurrence data for the period of record in each wilderness was ±10 km (Krider and Cummins personal communication).

The NLDN data were converted into Arc/INFO point coverages and SAS databases in the same manner as the NIFMID data.

Analyses

Creating Raster Grids from Point data

All geospatial data were analyzed using the Arc/INFO GIS software (ESRI 1998) on a UNIX platform. In order to evaluate distributions of lightning-caused fires and lightning strikes, the NIFMID and NLDN point databases were tessellated or converted to raster surface models (compiled as Arc/INFO 'grids') using the following two methods. First, grids were created for each point database using the Arc/INFO 'pointstats' command to assign the number of lightning strikes and fires to 1,000 grid cells (100 ha) for each study area (Figures 5 and 6). This process simply divided the landscape into 1,000 m grid cells, then tallied the number of lightning strikes and fires for each cell. The second method for developing raster data layers from point data was based on the Arc/INFO 'pointdensity' command. This process calculated the density of points for a neighborhood around each grid cell. In this case, the number of lightning strikes and fires was calculated for a circle with radius 5,542 m (10,000 ha) around each grid cell. This value was divided by the area of the neighborhood, and then assigned to the center grid cell. This process resulted in a smoothed surface that both considered the low spatial precision of the point data and effectively resulted in a spatially continuous probability surface of lightning or fire occurrence (Figures 7 and 8). Units of each of the grids are the number of lightning strikes or lightning-caused fires per 100 ha. These spatial data layers were used directly in analyses of relationships between lightning, lightning-caused fires, topography, and vegetation and evaluating the variability of lightning and lightning-caused fires over time. Subsets of the raw data were compiled as grids using the methods described above were used to develop raster grid layers created surfaces of human vs. lightning-caused fires (Figure 9), and positive and negative lightning strikes of a particular strength (Figures 10 and 11).

Spatial Analyses

Tabular, graphical, and statistical analyses were based on overlaying areas of different levels of lightning occurrence with areas of different fire patterns (e.g., burned vs. unburned areas, 20th-century fire frequency), topography, and vegetation. The number of lightning-caused fires and lightning strikes were plotted along gradients of elevation, aspect, and potential vegetation to investigate potential relationships between lightning, lightning-caused fires, and different landscape characteristics. Proportions of lightning caused fires and lightning strikes were compared with the proportions of the study areas in different elevation, aspect, and potential vegetation classes. Maximum likelihood analysis was used to assess statistical significance of potential relationships. Plotting lightning frequency against fire occurrence over time permitted analyses of the temporal variability of lightning and area burned in both wilderness areas. Daily number of fires was plotted against daily number of lightning strikes to evaluate the assertion that negative lightning strikes cause more fires than positive strikes (see Flannigan and Wotton 1990) and the alternative assertion that positive strikes are the fire starters (see Fuquay 1972).

The distribution of lightning strikes was analyzed for complete spatial randomness (CSR) by comparing the frequency distribution of lightning strikes per grid cell to a Poisson distribution of using a Pearson X^2 goodness-of-fit test. Next, departure from CSR was measured with the point-to-point nearest neighborhood statistic, $\hat{G}$, which describes small-scale interactions between points. Topography and vegetation data were then used to determine is they were contributing to the non-random spatial distribution of lightning strikes. For these analyses, elevation was classified into 1,000 ft classes, aspect was classified to 9 classes, and slope was classified into 5 classes. For this spatial analysis existing vegetation data were obtained from Keane et al. (1998; 2000). These data were based on LANDSAT-Thematic Mapper 5 satellite imagery, and were preliminary products for developing the potential vegetation data described above.

Results and Discussion

During the period 1986-1997 there were 1,336 wildland fires in the GALWC and 1,657 wildland fires in the SBWC (Table 1). In the GALWC, 1993 was the year with the largest extent burned; 1988 was the largest fire year in the SBWC (Table 2). Of the total number of fires, 75 in the GALWC and 167 in the SBWC were human caused (Table 1). During the period of record, more fires occurred in the SBWC, and more of these fires were large; however, wildland fires burned twice as much area in the GALWC (Table 1). Human-caused fires were generally smaller than lightning-caused fires in both wilderness areas. Human-caused fires tended to occur near the wilderness boundaries while lightning-caused fires tended to occur in clusters across the study areas. Lightning-caused fires were clustered in the GALWC and more dispersed in the SBWC (Figure 9). Fire size distributions were negatively skewed, with many small and few large fires (Figure 12); this pattern is similar to results from previous research in the study areas and elsewhere (Strauss et al 1989; McKelvey and Busse 1996; Rollins 2000; Rollins et al. 2001).

Spot maps showed that large fires were clustered in the GALWC and dispersed in the SBWC (Figures 13 and 14). This is probably due to the fact that the forests of the GALWC tend to be constrained to moderate-to-high elevations by the steep moisture gradient from low elevation desert to mountaintops. Mountain ranges of the GALWC are not technically ‘skyisland' mountain ranges characteristic of the Madrean Province of southeastern Arizona and northern Mexico (Ffolliet et al. 1996); however, the Mogollon Mountains and the Black Range in the GALWC exhibit the characteristic steep vegetation gradient from low-elevation desert-scrub/grasslands to montane forests found in montanez ecosystems of the Madrean Province. Forests in the GALWC are spatially clustered (i.e. embedded in a matrix of desert-scrub/grassland), so large wildland fires tend to be spatially clustered. This is in contrast to the SBWC, where forests cover nearly the entire area. This fundamental difference in the distribution of vegetation that is likely to effectively carry fire probably contributes to the more striking relationships between vegetation, elevation and fire occurrence in the GALWC when compared to the SBWC.

The period of record for the NIFMID database coincides with an extended period of wildland fire use (WFU) management in each study area. Both the GALWC and the SBWC implemented wildland fire use management in the mid 1970s where certain lightning-caused fires were allowed to burn within specific weather and fuel conditions. A main limitation to using the NIFMID database to describe recent fire history is that fires managed for wildland fire use are not included in the database (USDA Forest Service 1993). This reduces the overall utility of the database for evaluating the risks and benefits associated with wildland fire use for resource benefit. A similar problem exists with digital fire atlases that, in general, lack information about the suppression strategies (including WFU; Rollins 2000). This lack of information in databases for assessing recent fire history could easily be mitigated by creating an attribute in NIFMID for 'management action taken,' and by creating standard national protocols for archiving fire perimeter, spread rate, and severity maps.

There were 335,536 lightning strikes in the GALWC and 68,840 lightning strikes in the SBWC between 1989 and 1999. The number of lightning strikes varied by year with a high of 44,253 in 1996 in the GALWC to 4,239 in 1991 in the SBWC. The number of lightning strikes per year was nearly an order of magnitude greater in the GALWC (Table 1). There was wide variation in the strength and polarity of lightning in both study areas (Table 1). A large proportion of this lightning activity involved medium strength, negatively charged lightning strikes. Positive and negative lightning were randomly distributed with regard to elevation (Figure 15), potential vegetation, and 20th century fire frequency (Figure 16). The distribution of negative lightning strikes was slightly shifted toward higher fire frequency classes in the GALWC, however this shift was not statistically significant. Overall, the spatial distributions of lightning and fire occurrence were random with respect to each other.

While the lack of a direct relationship between lightning and fire occurrence was disappointing, this finding was not unexpected. By not including data for daily weather for each study area, we reduced the probability that we would identify specific relationships between lightning and fire occurrence. Generally, fires are ignited during dry lightning storms; this is particularly true in the GALWC (Schroeder and Buck 1970). Without daily information about precipitation levels it is impossible to determine whether lightning events occurred during dry or wet storms. By temporally stratifying the lightning data it is possible to examine lightning-fire relationships for periods that are characterized historically as having high levels of dry lightning storms. We separated lightning strikes and fire occurrences for June-July in the GALWC and August for the SBWC (historically characterized by dry lightning) and the spatial relationships between lightning density and fire occurrence were still random. This highlights the need to incorporate mapped weather data into future examinations of lightning-fire relationships.

Data quality is surely an important issue when considering the lack of overall relationships between lightning occurrence and fire ignition in the two study areas. Currently the NLDN consists of over 100 remote, ground-based lightning detectors. In 1995 a system-wide upgrade was implemented for the NLDN, which effectively increased the spatial accuracy for the conterminous United States to ±0.5 km. If we separate-out the post 1995 lightning occurrence data and compare 1996 and 1997 lightning occurrence lightning-fire relationships still appear random. This is probably a function of the low spatial resolution of the fire location data (± 1 mile). At any rate, two years is too short a period to make inferences related to fire regimes. This highlights the need for standardized approaches for archiving fire information using GPS locations as opposed to public land survey coordinates for fire locations.

The Timing of Lightning and Fires

There were many years where there was a large discrepancy between lightning activity and fire occurrence. In the GALWC, 1991, 1996, and 1997 were years characterized by many lightning strikes, with fewer fires; while 1989 and 1994 had many fires relative to the number of lightning strikes. In the SBWC, 1995 and 1997 had high lightning activity with fewer fires and 1991, 1992, and 1994 had many fires with few lightning strikes (Figure 17). This is likely due to the timing and magnitude of precipitation events during these years. There was no correspondence between these years and years with anomalous size distributions (Figure 18; Table 3). Size distribution was generally constant between years in the SBWC; one exception is 1988 where there were 7 Class G fires (greater than 5,000 acres). These large fires increased the mean fire size for 1988 to 300 ha. From 1990 to 1995 size distribution in the GALWC was shifted toward class B fires (0.5 to 10 acres; Figure 18), and mean fire sizes were high.

In the GALWC, the majority of fires occurred in June and July, with the bulk of lightning activity occurring in July and August. In the SBWC, lightning occurrence peaks early in the year with the bulk of fires following toward the late summer (Figure 19). This pattern persisted annually through the period of record in both study areas (Figure 20). Diurnally, the distribution of lightning strikes was similar between study areas, with the majority of lightning strikes occurring in the early afternoon (Figure 21).

Topography and Potential Vegetation

Lightning and lightning caused fires occurred at significantly higher elevations in the GALWC when compared with the distribution of elevation over the entire wilderness complex ($P < 0.01$). Lightning and fire occurrence was randomly distributed in the SBWC, with slightly higher lightning occurrence at higher elevations ($P < 0.1$; Figure 22). Lightning and lightning-caused fires were randomly distributed with regard to aspect (Figure 23).

Lightning-caused fires occurred in moderately higher PVTs in each study area. This included the Douglas-fir and mixed conifer PVTs in the GALWC and the Lower subalpine PVT in the SBWC. In the GALWC there was proportionately more lightning occurrence at lower elevations relative to fire occurrence (Figure 24). Monthly proportions of PVTs burned (based on area burned in the spot maps) were variable with mid-elevation PVTs experiencing the most fire during the period of record (Figure 25).

Relatively high fire frequencies at mid-elevations are commonly reported in the literature (Komarek, 1969; Marsden 1982; Minnich et al. 1993; Granström 1993; vanWagtendonk 1993; Barton 1994 McKelvey and Busse 1996; Loope and Anderton 1998; Rollins 2000; Rollins et al.

2001). Martin (1982) defines a graphical model where, along an elevational gradient, the highest fire frequencies are found where neither moisture nor fuel continuity are limiting. Barton (1994) showed that at the lowest and highest elevations, forests in the southern Rocky Mountains are fuel and moisture limited, respectively, leading to lower fire frequencies. Elevations where fire frequencies are highest are characterized by conditions that are dry enough and fuels continuous enough to facilitate fire ignition and spread. Fire occurrence and spread are limited by fuel continuity at the lower boundary and by moisture levels at the upper boundary of this mid-elevation ‘frequent fire zone’. Martin’s (1982) model is largely hypothetical, and gradient analysis or experimentation supporting the model have never been conducted using spatially explicit (i.e. mapped) fire frequency and size data. Overall, the propensity for fires to occur at mid-elevations was more pronounced in the GALWC. This is similar to results from Rollins (2000). It is hypothesized that this is due to steeper gradients between fuel continuity and fuel moisture status in the arid Southwestern United States.

Fire Rotation Periods

Based on digital fire atlas data from after 1975 (when each study area implemented WFU) each study area showed moderately increased rates of burning relative to the preceding decades. During this period (1975-1993) 16% of the GALWC and 10% of the SBWC burned, based on fire atlas data. Overall fire rotations were 121 years and 218 years, respectively, for the GALWC and SBWC (Rollins 2000, Rollins et al. 2001). With the exception of the upper elevation PVTs in the GALWC, the proportional area of PVTs burned increased (Figure 26, Rollins 2000), and fire rotations decreased relative to the subsequent 4 decades (Table 3). Fire rotations ranged from 74 years in the ponderosa pine PVT to 4,324 years in the desert/shrublands PVT in the GALWC.

Fire rotations in the SBWC ranged from 77 years in the persistent shrublands along the main stems of the Lochsa and Selway Rivers to 361 years in upper subalpine PVTs (Table 3).

The amount and rate of burning in the GALWC increased in Douglas-fir and ponderosa pine PVTs during the period from 1975-1993 (Figure 26 and Table 3), even though the two decades from about 1976 to 1993 were the wettest in the 20th century (Swetnam and Betancourt 1998). Fires were large, with 10 fires over 1,000 ha in the ponderosa pine and Douglas-fir PVTs. These fires were primarily managed as low intensity, prescribed natural fires. Fires were largely absent at higher elevations with a fire rotation of 998 yr in the spruce/fir PVT. The fire rotation during this period in the spruce/fir PVT was the longest of any time period. Fire management focused on restoring natural fire processes has reduced the length of fire rotations in mid-elevation forests. Fire rotations have lengthened, however, at high elevations of the GALWC relative to previous decades. These longer fire rotations could be due to the lack of occurrence of fires resulting from continued, effective fire suppression in these high elevation forests.

The period from 1975 to 1993 in the SBWC was characterized by more fire than in the middle of the century, particularly in subalpine forest PVTs (Table 3). Fire rotations based on fire atlas data during this period were an order of magnitude shorter than during the previous four decades. Further, less area has burned during recent years than would be expected under pre-EuroAmerican fire regimes, especially at upper elevations. It is important to note that the recent period includes 1988 and 1994, where several large wildfires burned extensive areas in upper elevation forests despite attempts to suppress them.

Fire rotations based on the NIFMID fire occurrence database were very different from estimates similar to estimates based on fire atlases in the GALWC. This may result from exclusion of fire perimeters from the fire atlas. The majority of area burned in the Desert scrub-Grassland PVT results from a fire in 1993 in the southwestern portion of the wilderness complex. This large fire was not represented in the fire atlas, and may lead to the radically different estimate of fire rotation for this PVT. Records in the digital fire atlas end in 1993 and several fires occurred in higher PVTs in 1995, 1996, and 1997. These fires probably account for discrepancies in fire rotation estimates for the Mixed conifer and Spruce-Fir PVTs. With the exception of the Upper subalpine PVT in the SBWC, fire rotation estimates were very similar between the Wildland Fire Use Period (Table 3, Rollins 2000) and the period of record of the NIFMID data (Table 4). The SBWC fire atlas ended in 1994, and there were several large fires in the Upper subalpine PVT in 1996. These fires may account for the shorter estimate of fire rotation period in this PVT based on the NIFMID database.

Several factors probably caused discrepancies between fire rotation period estimates based on fire atlases and the NIFMID fire occurrence database. They are: 1) slightly different period of record; specifically, the fact that small differences in area burned can cause a major change in rotation estimate when period of record is short, 2) data quality, and 3) using spot maps (e.g. Figure 13 and 14) to determine the areas burned by fires in the NIFMID data. In future research it will be necessary to assure that the same years are used when comparing fire rotation periods from two separate fire history databases. We compared estimates based on fire perimeter data from the wildland fire use period in each study area (1975-1994; Rollins 2000) with estimates from the NIFMID data (1986-1997). These slightly different periods of record can lead to large difference in fire rotation estimates, especially when large areas burned in one database are not represented in the other database as in the Upper subalpine PVT in the SBWC and the Mixed conifer and Spruce-Fir PVTs in the GALWC. Fires may also be present in one database, but absent from the other in the same year, as with the Desert scrub-Grassland PVT in the GALWC. In order to maximize the utility of these databases, standardized techniques need to be adapted to assure that fire occurrence and perimeter data are carefully quality controlled and archived.

Fire Probability Surfaces

Predicting change in landscape composition, structure, and function under altered or changing fire regimes is a major goal for fire ecologists and managers. Spatially explicit, empirically derived models of ignition probabilities are critical for modeling the behavior and effects of future fires and for evaluating the effects of long term changes in fire regimes. Parameterizing the ignition component for spatial models of fire/landscape models is difficult; therefore abstractions or extrapolations are often used as substitutes for empirically derived ignition probabilities. Using broad-scale empirical data will improve the ignition component of landscape-fire models. In addition, the analyses detailed in this report will also allow fire managers and ecologists to delineate 1) areas where fires have been historically frequent and 2) areas where ignitions limit the extent that natural fire occurrence may be used for forest restoration and fuels mitigation. This is particularly important on wilderness landscapes where wildland fire use may be the only tool for returning landscapes to within historical ranges of variability.

Our probability surfaces represent a simple, straightforward application of the NIFMID fire occurrence data for representing areas with high or low densities of fire occurrence (Figures 7 and 8). Attempts to refine these probability surfaces using elevation and vegetation data met with mixed results. However, fires were generally more frequent at mid elevations. One possibility for refining these probability surfaces involves creating a daily index of storm activity during the fire season using daily mapped weather data. This approach will allow for separation of wet vs. dry lightning events and may provide better locational information about areas with high and low ignition rates. Future research will also focus on the spatial patterning of lightning and fire occurrence by using point-pattern spatial analyses. Our hope is to study the actual direction (vector) of the spatial autocorrelation between weather data, lightning occurrence, and fire occurrence using correlogram analysis. This analysis will need to take place at a daily time step so that fuel conditions at the time of lightning occurrence can be evaluated. This approach was not used for the research reported-on here due to data cost and software and programming limitations.

Conclusions

Fire regimes are usually qualitatively defined, using combinations of fire history information, topography, and vegetation, but not climate or ignition data. In the analyses presented here we provided summary evaluation of lightning and fire occurrence for two broad, climatically distinct study areas. This empirical approach forms the foundation for empirically deriving fire regimes over broad areas and for evaluating the biophysical settings that are related to specific fire frequencies. In the future we hope to use this approach to evaluate areas that display ‘fire attractor’ properties. Coupled with mapped weather summaries we hope to develop a standard approach for delineating unique ‘fire environments’ or areas on the landscape that tend to burn with specific characteristics. This empirical approach is in contrast to previous approaches for mapping fire regimes that are based on heuristic rule sets or expert systems (e.g. Barrett and Arno 1991; Brown et al. 1994; Barrett 1995; Morgan et al. 1996; Frost 1998; Morgan et al. 2001).

Strengths of our approach include 1) using several different sources of spatially explicit, time-series of fire data over two broad areas to describe fire patterns, 2) compiling our data into GIS databases to maximize the opportunity for spatial analyses of lightning-fire-landscape associations across spatial and temporal scales, and 3) using regional comparisons to quantitatively describe the generality and specificity of our results. Differences and similarities in results between the two study areas increased our understanding of causal relationships between lightning and fire occurrence that drive fire regimes in remote Rocky Mountain ecosystems.

References

Abolt, R. A. 1996. Surface and crown fire histories of upper elevation forests via fire scar and stand age structure analyses. M.S. Thesis. On file at the School of Renewable Resources, Department of Watershed Management, University of Arizona, Tucson, Arizona.

Agee, J. K. 1993. Fire ecology of Pacific Northwest forests. Island press, Covelo, California.

Arno, S. 1980. Forest fire history in the northern Rockies. Journal of Forestry 78(8):460-465.

Barrett, S. W. 1995. A fire regimes database for coniferous forests in the Inland Northwest. Final Report for RJVA-INT-92676. On file at Fire Sciences Laboratory, Rocky Mountain Research Station. USDA Forest Service, Rocky Mountain Research Station, Missoula, Montana.

Barrett, S. W. and S. F Arno. 1991. Classifying fire regimes and their topographic controls in the Selway-Bitterroot Wilderness. Pp. 299-307. *In*: Proceedings: 11th conference on fire and forest meteorology, April 16-19, 1991. Missoula, Montana. Society of American Foresters, Bethesda, Maryland.

Barrows, J. S. 1978. Lighting fires in southwestern forests. Final Report prepared by Colorado State University for USDA Intermountain Forest and Range Experimental Station Cooperative agreement 16-568-CA. On file at USDA Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado.

Barton, A. M. 1994. Gradient analysis of relationships among fire, environment and vegetation in a southwestern USA mountain range. Bulletin of the Torrey Botanical Club 121(3):121-265.

Beschta, R. L. 1976. Climatology of the ponderosa pine type in central Arizona. Agricultural Experimental Station Technical Bulletin #228. University of Arizona, Tucson, Arizona.

Brown, J. K., S. F. Arno, S. W. Barrett, and J. P. Menakis. 1994. Comparing the prescribed natural fire program with presettlement fires in the Selway-Bitterroot Wilderness. International Journal of Wildland Fire 4(3):157-168.

Clements, F. E. 1936. Nature and structure of the climax. Journal of Ecology 24:252-284

Cooper, S. V., K. E. Neiman, and D. W. Roberts. 1991. Forest habitat types of northern Idaho: A second approximation. USDA Forest Service USDA GTR-INT-236. Intermountain Research Station, Ogden, Utah. 143 p.

Cummins, K. L., E. P. Krider, and M. D. Malone. 1998a. The U.S. National Lightning Detection Network and applications of cloud-to-ground lightning data by electric power utilities. IEEE Transactions on Electromagnetic compatibility 40(4):465-480.

Cummins, K. L., M. J. Murphy, E. A. Bardo, W. L. Hiscox, R. B. Pyle, and A. E. Pifer. 1998b. A combined TOA/MDF technology upgrade of the U. S. National Lightning Detection Network. Journal of Geophysical Research. 103(D8):9035-9044.

Daubenmire, R. 1968. Plant Communities, A textbook of plant synecology. Harper-Row, New York, New York.

Duce, T. E. Voth, and P. Andrews. 1997. Visualization of Historical Wildfire Data Application of a DX-Oracle Interface [Online] http://opendx.npaci.edu/publications /environmental/mtwildfire [September 2001].

ESRI. 1998. Arc/Info 7.2.2 Software. Environmental Systems Research Institute. Redlands, California.

Habeck, J. R. 1972. Fire ecology investigations in the Selway-Bitterroot Wilderness: Historical considerations and current observations. USDA Forest Service Report INT-R1-72-001. On file at USDA Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory, Missoula, Montna. 119 p.

Ffolliet, P. F., L. F. Debano, M. B. Baker Jr., G. Gottfried, G. Solis-Garza, C. B. Edminster, D. G. Neary, L. S.Allen and R. H. Hamre. 1996. Effects of fire on Madrean province ecosystems, symposium proceedings. SDA Forest Service General Technical Report, RM-GTR-289.

Finklin, A. I. 1983. Weather and climate of the Selway-Bitterroot Wilderness. University of Idaho press, Moscow, Idaho.

Flannigan, M. D. and B. M. Wotton. 1990. Lightning-ignited forest fires in northwestern Ontario. Canadian Journal of Forest Research. 21:277-287.

Frost, C.C. 1998. Presettlement fire frequency regimes of the United States: A first approximation. Pp. 70-81. *In*: T.L. Pruden and L.A. Brennan, (*eds.*) Fire in ecosystem management: shifting the paradigm from suppression to prescription. Tall Timbers Fire Ecology Conference Proceedings, No. 20. Tallahassee, FL: Tall Timbers Research Station.

Fuquay, D. M., A. R. Taylor, R. G. Hawe, and C. W. Schmid, Jr. 1972. Lightning discharges that caused forest fires. Journal of Geophysical Research. 77(12):2155-2158.

Granström, A. 1993. Spatial and temporal variation in lightning ignitions in Sweden. Journal of Vegetation Science 4(6):737-744.

Greenwood, W. R. and D. A. Morrison. 1973. Reconnaissance geology of the Selway-Bitterroot Wilderness Area. Idaho Bureau of Mines and Geology. Moscow, Idaho.

Keane, R. E., J. L. Garner, K. M. Schmidt, D.G. Long, J. P. Menakis, and M. A. Finney. 1998. Development of input data layers for the FARSITE fire growth model for the Selway-Bitterroot Wilderness complex, USA. USDA Forest Service General Technical Report RMRS-GTR-3. USDA Forest Service Rocky Mountain Research Station, Fort Collins, Colorado

Keane, R. E., S. A. Minncemoyer, K. M. Schmidt, J. P. Menakis, J. L. Garner. 2000. Mapping vegetation and fuels for fire management on the Gila National Forest. RMRS-GTR-46-CD. USDA Forest Service Rocky Mountain Research Station, Fort Collins, Colorado.

Komarek, E. V. 1969. Lightning and lightning fires as ecological forces. Proceedings of the Annual Tall Timbers Fire Ecology Conference. 9:127-150.

Krider, E. P., R. C. Noggle, and M. A. Uman. 1976. A gated, wideband magnetic direction finder for lightning return strokes. Journal of Applied Meteorology. 15:301-306.

Krider, E.P., R.C. Noggle, A.E. Pifer, and D.L. Vance. 1980. Lightning direction-finding for forest fire detection. Bulletin of the American Meteorological Society 61(9):980-986.

Loope, W. L. and J. B. Anderton. 1998. Human vs. lightning ignition of presettlement surface fires in coastal pine forests of the upper Great Lakes. American Midland Naturalist 140:206-218.

Marsden, M. A. 1982. A statistical analysis of the frequency of lightning-caused forest fires. Journal of Environmental Management 14:149-159.

Martin, R. E. 1982. Fire history and its role in succession. Pp. 92-99. *In* Forest succession and stand development research in the Northwest: Proceedings of a symposium. J. E. Means (*ed.*). Oregon State University, Corvallis, Oregon. On file at USDA Forest Service Research Laboratory, Corvallis, Oregon.

McKelvey, K. S. and K. K. Busse. 1996. Twentieth-century fire patterns on Forest Service lands. Pp 1119-1138. *In* Sierra Nevada Ecosystem Management Project: final report to congress, Vol. II, Assessments and scientific basis for management options. Centers for Water and Wildland Resources, University of California, Davis.

Minnich, R. A., E. F. Vizcaino, J. Sosaramirez, and Y. H. Chou. 1993. Lightning detection rates and wildland fire in the mountains of Baja-California, Mexico. Atmosfera 6(4):235-253.

Morgan, P., S. Bunting, A. E. Black, T. Merrill, and S. Barrett. 1996. Fire regimes in the Interior Columbia River Basin: Past and Present. Final Report for RJVA-INT-94913. On file at Fire Sciences Laboratory, Rocky Mountain Research Station. USDA Forest Service, Rocky Mountain Research Station, Missoula, Montana.

Morgan,P., C. Hardy, T. W. Swetnam, M.G. Rollins, and D. G. Long. 2001. Mapping fire regimes across time and space: Understanding coarse and fine-scale fire patterns. International Journal of Wildland Fire 10: 329-342.

Nash, C. H. and E. A. Johnson 1996. Synoptic climatology of lightning-caused forest fires in subalpine and boreal forests. Canadian Journal of Forest Research 26:1859-1874.

Noggle, R. C., E. P. Krider, D. L. Vance, and K. B. Barker. 1976. A lightning direction-finding system for forest fire detection. Pp.31-36. *In:* Proceedings of the 4th national conference on fire and forest meteorology, St. Louis, Missouri. USDA Forest Service RM-32. Rocky Mountain Forest and Range Experiment Station, Ft. Collins, Colorado.

Overpeck, J. T., D. Rind, and R. Goldberg. 1990. Climate-induced changes in forest disturbance and vegetation. Nature 343: 51-53.

Pickford, S. G., G. R. Fahnstock and R. Ottmar. 1980. Weather, fuel and lightning fires in Olympic National Park. Northwest Science 54(2):92-105.

Pfister, R. D. and S. F. Arno. 1980. Classifying forest habitat types based on potential climax vegetation. Forest Science 26(1):52-70.

Price, C. and Rind, D. 1994. The impact of a $2XCO_2$ climate on lightning-caused fires. Journal of Climate 7:1484-94.

Rollins, M. G. 2000. Twentieth-Century Fire Patterns in the Gila/Aldo Leopold Wilderness Areas, New Mexico and the Selway-Bitterroot Wilderness Area in Idaho/Montana. Ph.D. Dissertation. On file at the Laboratory of Tree-Ring Research, University of Arizona, Tucson, Arizona.

Rollins, M. G., T. W. Swetnam, and P. Morgan. 2001. Evaluating a Century of Fire Patterns in Two Rocky Mountain Wilderness Areas Using Digital Fire Atlases. Canadian Journal of Forest Research 31:2107-2123.

Ryan, K.C. 1991. Vegetation and wildland fire: implications for global change. Environmental Management 17:169-178.

SAS Institute Inc. 1989. SAS® Language and Procedures: Usage, Version 6, First Edition. SAS Institute, Cary, North Carolina.

Schmoldt, D. L., D. L Peterson, R. L. Keane, J. M. Lenihan, D. McKenzie, D. R Weise, and D. V. Sandberg. 1999. Assessing the effects of fire disturbance on ecosystems: A scientific agenda for research and management. USDA Forest Service PNW-GTR-455. Pacific Northwest Research Station, Portland, Oregon.

Schroeder, M. J. and C. C. Buck. 1970. Fire weather: A guide for application of meteorological information to forest fire control operations. USDA Forest Service Agriculture Handbook #360. United States Government Printing Office, Washington D.C.

Shiplett, B. and L. F. Neuenschwander 1994. Fire ecology in the cedar-hemlock zone of north Idaho. Pp. 41-51. *In* Proceedings, Interior cedar-hemlock-white pine forests: ecology and management. March 2-4, 1993, Spokane, Washington. Washington State University, Pullman Washington.

Strauss, D., L. Bednar, and R. Mees. 1989. Do one percent of forest fires cause ninety-nine percent of the damage? Forest Science 35(2):319-328.

Swetnam, T. W. and J. H. Dieterich. 1985. Fire history of ponderosa pine forests in the Gila Wilderness, New Mexico. Pp. 390-397. *In* Lotan, J. E., Kilgore, B. M., Fischer, W. C., and Mutch, R. W. (*Tech. Coords.*).Proceedings-Symposium and Workshop on Wilderness Fire. USDA Forest Service GTR-INT-182. Intermountain Forest and Range Experiment Station, Ogden, Utah.

Swetnam, T. W. and J. L. Betancourt, 1998. Mesoscale disturbance and ecological response to decadal climatic variability in the American southwest. Journal of Climate 11: 3128-3147.

Thornton, P. E., S. W. Running, M. A. White. 1997. Generating surfaces of daily meteorological variables over large regions of complex terrain. Journal of Hydrology 190: 214-251.

USDA Forest Service. 1992. 1984-1990 Wildfire statistics. State and private forestry, fire and aviation management staff. USDA Forest Service, Washington D.C.

USDA Forest Service. 1993. National Interagency Fire Management Integrated Database (NIFMID) reference manual. U.S. Department of Agriculture, Forest Service, Fire and Aviation Management. Washington, D.C.

USGS. 1965. Mineral and water resources of New Mexico, US Geological Survey Bulletin 87. State Bureau of Mines and Mineral Resources, New Mexico Institute of Mining and Technology, Socorro, New Mexico, USA.

Vázquez, A. and J. Moreno. 1998. Patterns of lightning- and people-caused fires in peninsular Spain. International Journal of Wildland Fire 8(2):103-115.

vanWagtendonk, J. W. 1993. Spatial patterns of lightning strikes in Yosemite National Park. Pp. 605-611 *In:* Proceedings of the 12th Conference on Fire and Forest Meteorology. October 26-28, Jekyll Island, Georgia. Society of American Foresters, Bethesda, Maryland.

Table Captions

Table1. Summary descriptions of fire and lighting occurrence in each study area.

Table 2. Annual number of fires, area burned, and mean fire size for each wilderness complex.

Table 3. Annual number of fires, by size class.

Table 4. Fire rotation by potential vegetation type for different periods defined by different fire management strategies. Area burned was determined from digital fire atlases. Data are from Rollins et al. 2001.

Table 5. Fire rotation by PVT calculated from the NIFMID data. Areas burned were estimated from spot maps (figures 13 and 14).

Table 1

Metric	*GALWC*	*SBWC*
Area Burned (ha; 1986-1997)	115,334	64,435
#fires	1,336	1,657
Mean Fire Size (ha)	86.3	38.9
Mean Human Caused	31.8	28.7
Mean Lightning Caused	90.0	40.0
# fires LT 10 ha	1,189	1,224
# fires GT 100 ha	61	122
# Lightning Strikes	335,536	69,840
# Negative	326,083	63,326
# Positive	9,453	6,514
Mean kA	-23.9	-16.5
Min kA	-336.8	-378.6
Max kA	263.7	280.2
Mean multiplicity	2.4	1.9
Min multiplicity	1	1
Max multiplicity	20	15

Table 2

GALWC

Year	Number of fires	Area burned (ha)	Mean fire bize (ha)
1986	55	686	12.5
1987	119	7,429	62.4
1988	110	102	0.9
1989	206	5,072	24.6
1990	84	308	3.7
1991	69	761	11.0
1992	94	18,985	202.0
1993	112	31,816	284.1
1994	169	5,105	30.2
1995	108	22,653	209.7
1996	104	10,062	96.7
1997	106	12,354	116.6

SBWC

Year	Number of fires	Area burned (ha)	Mean fire size (ha)
1986	97	3,890	40.1
1987	118	7,930	67.2

1988	116	34,867	300.6
1989	140	49	0.3
1990	101	106	1.1
1991	176	3,836	21.8
1992	287	422	1.5
1993	25	189	7.5
1994	286	10,420	36.4
1995	45	15	0.3
1996	206	2,655	12.9
1997	60	58	1.0

Table 3

GALWC

Size Class:	A	B	C	D	E	F	G
Year 1986	55	33	9	2	0	2	0
1987	41	41	8	2	3	3	1
1988	51	42	7	0	0	0	0
1989	49	44	5	0	0	0	0
1990	27	63	7	2	0	0	0
1991	33	62	0	1	1	1	0
1992	28	45	11	4	9	2	2
1993	29	52	5	3	4	4	4
1994	28	57	10	2	1	2	1
1995	44	35	11	4	2	2	3
1996	49	38	10	0	2	0	2
1997	51	37	8	0	2	1	1

SBWC

Size Class:		A	B	C	D	E	F	G
Year	1986	62	21	6	3	5	3	0
	1987	53	25	8	2	9	2	1
	1988	50	26	6	5	2	5	6
	1989	72	25	3	0	0	0	0
	1990	62	34	4	0	0	0	0
	1991	61	28	6	1	1	2	0
	1992	67	26	6	1	0	0	0
	1993	80	4	12	0	4	0	0
	1994	53	32	8	3	2	2	0
	1995	76	22	2	0	0	0	0
	1996	63	29	4	2	1	0	0
	1997	67	27	7	0	0	0	0

Table 4

Gila/Aldo Leopold Wilderness Complex

Potential vegetation type	**Entire time period 1909-1993**	Pre-modern suppression 1909–1946	Modern suppression 1947–1975	Wildland fire use 1976-1993
Desert scrub/ Grassland	**15,753**	120,514	40,782	4,324
Piñon/oak/Juniper	**540**	1,156	1,182	188
Ponderosa pine	**200**	382	410	74
Douglas-fir	**180**	353	205	84
Mixed conifer	**245**	612	145	207
Spruce/fir	**537**	508	435	998

Selway-Bitterroot Wilderness Complex

Potential vegetation type	**Entire time period 1880-1996**	Pre-modern suppression 1880–1934	Modern suppression 1935–1975	Wildland fire use 1976-1996
Western redcedar	**368**	41	396,498	359
Persistent herblands	**80**	79	4,167	77

Grand fir	**384**	66	7,380	267
Douglas-fir	**169**	104	4,704	140
Lower subalpine	**519**	117	3,651	230
Upper subalpine	**852**	191	3,361	361

Table 5

GALWC

Potential Vegetation Type	Fire Rotation (years)
Desert Scrub-Grassland	64
Piñon-Oak-Juniper	65
Ponderosa Pine	50
Douglas Fir	39
Mixed Conifer	43
Spruce-Fir	169

SBWC

Potential Vegetation Type	Fire Rotation (years)
Western redcedar	315
Persistent Herblands	67
Grand fir	207
Douglas-fir	116
Lower subalpine	212
Upper subalpine	103

Figure Captions

Figure 1. The 487,000 ha Gila/Aldo Leopold Wilderness Complex (GALWC) in New Mexico and the 547,000 ha Selway-Bitterroot Wilderness Area (SBWA) in Idaho/Montana.

Figure 2. Fire atlas for the Gila/Aldo Leopold Wilderness Complex. Area mapped includes a 5-km buffer around the wilderness boundary. Decades of fire are mapped as separate colors. From 1909 to 1993, 142,700 ha (30% of the study area) burned in 220 mapped fires.

Figure 3. Fire atlas for the 785,090-ha Selway-Bitterroot Wilderness complex. The area mapped includes a 5-km buffer around the wilderness boundary. Decades of fire are mapped as separate colors and the color scheme is identical to Figure 1. From 1880 to 1996, 545,229 ha (70 % of the study area) burned in 524 mapped fires.

Figure 4. National Interagency Fire Management Integrated Database fire occurrence data for both study areas.

Figure 5. Fire and lightning occurrence data for the GALWC. Maps were constructed by gridding the landscape, then tallying the occurrence of fire and lightning in each grid cell.

Figure 6. Fire and lightning occurrence data for the SBWC. Maps were constructed by gridding the landscape, then tallying the occurrence of fire and lightning in each grid cell.

Figure 7. Fire and lightning density surface for the GALWC. Maps were constructed using a neighborhood function that tabulated the occurrence of fire and lighting for a 1,000 ha circular neighborhood around each grid cell.

Figure 8. Fire and lightning density surface for the SBWC. Maps were constructed using a neighborhood function that tabulated the occurrence of fire and lighting for a 1,000 ha circular neighborhood around each grid cell.

Figure 9. Area frequencies of human-caused and lightning-caused fires in each wilderness complex.

Figure 10. Positive and negative lightning strike surfaces for the GALWC. Map was complied by gridding the landscape, then tallying the occurrence of positive or negative lightning occurrence in each grid cell.

Figure 11. Positive and negative lightning strike surfaces for the SBWC. Map was complied by gridding the landscape, then tallying the occurrence of positive or negative lightning occurrence in each grid cell.

Figure 12. Size distribution of fires from NIFMID in each study area. Note the log scale for area. These results are similar to evaluations of fire size distributions for other areas.

Figure 13. Spot map of the NIFMID database for the GALWC. Colors represent the year of individual fires. Sizes of circles are proportional to the size of fires.

Figure 14. Spot map of the NIFMID database for the SBWC. Colors represent the year of individual fires. Sizes of circles are proportional to the size of fires.

Figure 15. The distribution of positive and negative lightning strikes over elevation. Distributions of different types of lightning were random with respect to elevation.

Figure 16. Distributions of positive and negative lightning strike density over areas with different 20th century fire frequencies. Peaks in higher 20th century fire frequencies are due to the small areas in each area that actually experienced high 20th century fire frequencies.

Figure 17. Fire and lighting occurrence by year for the time of overlap between the NLDN and NIFMID databases.

Figure 18. Size classes of fires for different years in each study area. Fires tended to be larger in the early 1990s in the GALWC and in 1988 in the SBWC.

Figure 19. Fire and lighting occurrence by month for each study area. Fires occurred earlier in the GALWC and later in the SBWC. Lighting occurred early in the SBWC and later in the GALWC.

Figure 20. Monthly lighting and fire occurrence by year.

Figure 21. Lightning occurrence by hour.

Figure 22. Fire and lighting occurrence over gradients of elevation. Stars indicate significant maximum likelihood tests. In the GALWC, lighting and fire occurrence was shifted toward moderately higher elevations, probably due to the orographic nature of storms in the region.

Figure 23. Fire and lighting occurrence over gradients of aspect. There was no indication that lighting or fire occurrence were affected by aspect. This is in contrast with findings based on digital fire atlases (Rollins 2000).

Figure 24. Lighting and fire occurrence by potential vegetation types. In the GALWC significantly more fires occurred in the Douglas-fir PVT than expected based on the distribution of this type across the study area.

Figure 25. Percent area burned by PVT, by year. The perimeters of fires in the NIFMID database was simulated by spot maps (figures 13 and 14).

Figure 26. Proportion of PVT burned by fire suppression period. Area burned was determined from digital fire atlases. From Rollins et al. 2001.