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Spatial and temporal patterns of wildfires in the Mojave Desert, 1980–2004

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Abstract

Fire has been historically infrequent in the Mojave Desert, and its increased prevalence caused by the invasion of non-native annual grasses is a major concern for land managers there. The most dramatic changes have occurred in middle elevation shrublands dominated by creosotebush (*Larrea tridentata*), Joshua tree (*Yucca brevifolia*), and/or blackbrush (*Coleogyne ramossissima*), where most of the fires occurred between 1980 and 2004. This zone is more susceptible than other areas of the Mojave Desert to increased fire size following years of high rainfall. Increases in fire size are likely related to the flush of non-native annual grasses, *Bromus rubens* in particular, that produces continuous fuelbeds following years of high rainfall. This dynamic also has occurred to some degree at lower elevations, but the background cover of native perennial fuels there is already very low, muting the effects of the ephemeral fuels. At elevations above the middle elevation shrublands, fire size does not vary with rainfall, indicating that native woody fuels dictate fire regimes. These results suggest that an invasive plant/fire regime cycle is currently establishing in the middle and possibly the low elevation shrublands of the Mojave Desert, but not at higher elevations.
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Keywords: *Bromus*; Disturbance; Fire history; Grass/fire cycle; Invasive; *Schismus*

1. Introduction

Deserts worldwide tend to experience less fire than other ecosystems, due to low primary productivity and limited production of fuels. Under a regime of small and infrequent fires

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other major ecosystem disturbances often act as primary selective factors (e.g. droughts, floods) in the evolution of desert species. Unless these other factors lead to the evolution of characteristics that by chance also confer resiliency to fire (exaptations; Gould and Vrba, 1982), then rapid changes in fire regimes, which lead to a greater prevalence of fire may be detrimental to native species. Changes in disturbance regimes that occur over short periods of time may exceed the potential for native species to evolve in response to them, and may lead to their extirpation from the affected region.

Plant invasions are increasingly being recognized for their ability to alter fire regimes (D'Antonio and Vitousek, 1992; D'Antonio, 2000; Brooks et al., 2004). Invasions may change the frequency, intensity, extent, type, or seasonality of fire, and these changes can either result in increased or decreased prevalence of fire on the landscape (Brooks et al., 2004). The ultimate effects of the changes depend on the specific aspects of the fire regime that are affected. If these changes significantly affect key natural selection factors, then they may cause shifts in the species composition which can have ecosystem-wide effects (D'Antonio et al., 1999; Brooks et al., 2004).

Years of high winter rainfall in the Mojave Desert of western North America stimulate the growth of non-native annual grasses that fill interspaces between shrubs with continuous fine fuels and facilitate the spread of fire (Brown and Minnich, 1986; Brooks, 1999). Taxa such as *Bromus* spp. (*B. rubens*, *B. tectorum*) and *Schismus* spp. (*S. arabicus*, *S. barbatus*) provide more persistent and uniformly distributed fine fuelbeds than do native annual plants, breaking down more slowly and persisting longer into the summer and subsequent years (Brooks, 1999). These species often dominate postfire landscapes (Brooks and Minnich, 2006; Brooks and Berry, accepted), and the fuel conditions they produce have the potential to increase the size, decrease the spatial complexity, and shorten the time interval between fires in the Mojave Desert (Brooks and Pyke, 2001; Brooks and Esque, 2002; Brooks et al., 2004).

The effects of wildfires on the Federally threatened desert tortoise (*Gopherus agassizii*) and on general plant diversity and wildlife habitat are major management issues in the Mojave Desert (Brooks and Pyke, 2001; Brooks and Esque, 2002). All of these issues revolve around the central concern that the abundance of invasive annual grasses and the frequency and size of fires are positively correlated, and that an invasive plant/fire regime cycle (Brooks et al., 2004) may be establishing in this region. Similar concerns about the effects of non-native annual grasses on fire regimes exist for the Great Basin (Pickford, 1932; Stewart and Hull, 1949; Piemeisel, 1951; Young and Evans, 1978; Whisenant, 1990; Brooks and Pyke, 2001), Sonoran Deserts (Rogers, 1986; Rogers and Vint, 1987; Schmid and Rogers, 1988; Brooks and Pyke, 2001; Esque and Schwalbe, 2002), and other arid to semi-arid regions of western North America (Keeley, 2001; Klinger et al., 2006) and elsewhere (D'Antonio and Vitousek, 1992; D'Antonio 2000).

Three previous publications describe some aspects of the spatial and temporal distributions of wildfire in the Mojave Desert (US Fish and Wildlife Service, 1994; Brooks and Esque, 2002; Brooks and Minnich, 2006). These publications report that the frequency of fire increased in the California portion of the Mojave Desert between 1980 and 1995 due to increased numbers of fires started by humans, and that most of the area burned occurred in regional clusters often located in remote areas. What these publications do not address include important issues such as the frequency and extent of burning among different ecological zones, distributions of lightning vs. human caused fires, trends in these variables among rainfall years, and general patterns across the entire Mojave

Desert. The purpose of the current paper is to describe these patterns using an updated fire occurrence database that spans the entire Mojave Desert from 1980 to 2004.

2. Methods

Fire data were obtained from the United States (US) Department of the Interior and Forest Service interagency fire record database (http://famweb.nwcg.gov/weatherfirecd; accessed April 2006). This national database is comprised of information contained in individual DI-1202 fire reports completed for every fire that occurs on public lands in the US. Complete data for the entire Mojave Desert were only available for 1980–2004 at the time we accessed the database, which determined the years we analysed. We only included fires with points of origin that were within the boundary of the 130,464 km^2 Mojave Desert as defined by The Nature Conservancy (Groves et al., 2000). We then used the recommendations in Brown et al. (2002) to remove potentially erroneous data and generate the final dataset that we used in our analyses. The primary fire history variables that we reported were number of fires, area burned, and fire size (average size of individual fires).

We evaluated the fire history response variables in relationship to four of the five ecological zones described for the Mojave Desert by Brooks and Minnich (2006). These zones represent the major upland fuel types in this region. The spatial data layers for the ecological zones were created by merging finer-scale vegetation polygons developed for wildland fire and fuel management by the US Forest Service, Prescribed Fire and Fire Effects Research Work Unit, Rocky Mountain Research Station (current cover types v2000; http://www.fs.fed.us/fire/fuelman; accessed April 2006) (Table 1). These finer-scale polygons were derived from the original work of Küchler (1964) who mapped the potential natural vegetation of the conterminous United States. These spatial data did not distinguish the riparian zone, which represents the fifth major ecological zone in the Mojave Desert (Brooks and Minnich, 2006). Riparian fires occurred primarily within the low elevation shrubland zone, and were mostly subsumed by that stratum in our analyses.

For brevity, we shortened the titles of the ecological zones presented in Brooks and Minnich (2006) as indicated in Table 1. The desert montane zone is either dominated by Ponderosa pine (*Pinus ponderosa*) or Bristlecone pine (*P. longaeva*) and occupies relatively small and isolated stands at the tops of the highest mountains in the region (Fig. 1). The high elevation woodland zone lies below the montane zone on higher mountains, and tops the mountain ranges of moderate elevation in the Mojave Desert (Fig. 1). It is typically characterized by pinyon pine (*P. monophylla*) and Utah juniper (*Juniperus osteosperma*), and also includes sagebrush (*Artemisia* spp.) and other shrub species (e.g. *Purshia* spp. and *Ceanothus* spp.) as subdominants in the understory. The middle elevation shrubland zone lies in an elevation band below the high elevation zone on most mountain ranges, and occupies broad valley floors in more mesic regions, at higher elevations, and at the northern and eastern margins of the Mojave Desert (Fig. 1). It is typified by blackbrush (*Coleogyne ramosissima*) shrublands at its upper ectones phasing into mixed woody-scrub vegetation types dominated by creosotebush (*Larrea tridentata*) at its lower ecotones. Perennial grasses (*Achnatherum* spp., *Pleuraphis* spp.) and Joshua trees (*Yucca brevifolia*) are often co-dominants with various shrub species. There are also small inclusions of chaparral, sagebrush, and south-western shrub steppe (Küchler, 1964), which represents minor proportions of the "other shrub" category of the current cover types in the middle

Table 1
Description of how the ecological zone categories used in this paper correspond to those of Brooks and Minnich (2006)

Ecological zones used in this paper	Ecological zones of Brooks and Minnich (2006)	Dominant plant species	Current cover types[a]	% of Mojave Desert
Low elevation shrubland	Low elevation desert shrubland	*Larrea tridentata* *Ambrosia dumosa*	Barren	37
Middle elevation shrubland	Middle elevation desert shrubland and grassland	*Coleogyne ramosissima*	Desert shrub	50
		Larrea tridentate	Other shrub	9
		Yucca brevifolia *Achnatherum* spp. *Pleuraphis spp.*	Grassland	<1
High elevation woodland	High elevation desert shrubland and woodland	*Juniperus osteosperma*	Pinyon Juniper	3
		Pinus monophylla	Western hardwoods	<1
		Artemisia spp. *Ceanothus* spp. *Purshia* spp.		
Desert montane	Desert montane woodland and forest	*Pinus ponderosa* *Pinus longaeva*	Ponderosa pine	<1

[a]Current cover types v2000; accessed online at: www.fs.fed.us/fire/fuelman; analyses did not include urban, agricultural, and water cover types that also fall within the Mojave Desert ecoregion.

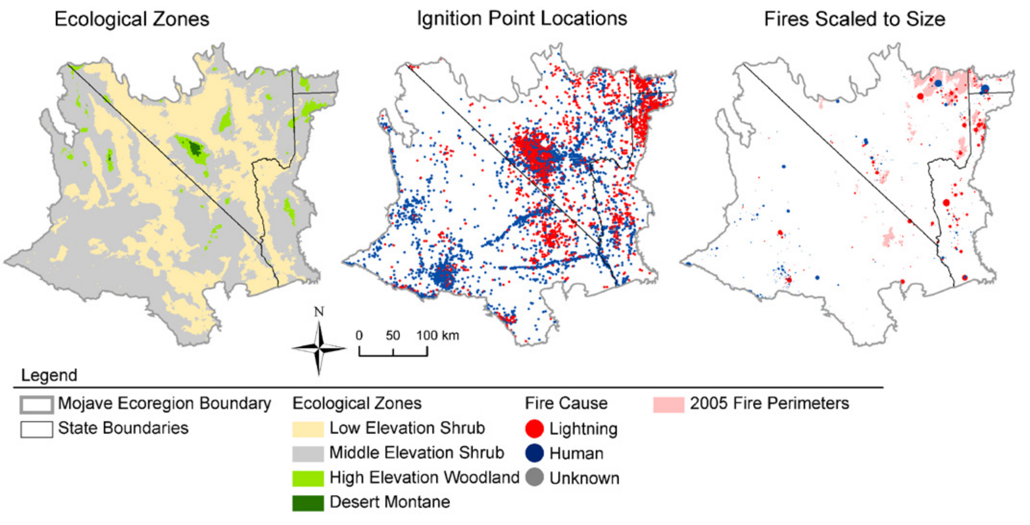

Fig. 1. Maps of the four major ecological zones, ignition points for fires in the Mojave Desert between 1980 and 2004 inclusive, and these ignition points scaled for size and fire perimeters for major fires that occurred during summer 2005.

elevation zone (Table 1). The low elevation shrubland zone occupies the lowest elevations and most arid regions that occur towards the middle of the Mojave Desert (Fig. 1). It is dominated in most places by creosotebush and burrobush (*Ambrosia dumosa*), and in other places by saltbush (*Atriplex* spp.). More details on the general characteristics and responses of vegetation to fire in these ecological zones can be found in Brooks and Minnich (2006).

We also compared interactions between fire patterns, ecological zones, and cumulative rainfall that occurred during the years prior to the current fire season. The fire season was defined as beginning on 1 May based on the sharp increase in fire occurrences that begins in May each year in the Mojave Desert (Brooks and Esque, 2002). Rainfall that occurred during the previous late spring, summer, fall, winter, and early spring has the most immediate effects on fuel conditions leading up to the current fire season. Thus, fire patterns during each summer fire season were compared to cumulative rainfall that occurred 1 May of the previous year through 30 April of the current year. We obtained monthly rainfall data from stations in and around the Mojave Desert for 1977–2004, allowing us to separately evaluate the effects of rainfall during years 1–3 prior to each summer fire season (National Oceanic and Atmospheric Administration National Climatic Data centre, http://www.ncdc.noaa.gov/oa/ncdc.html; accessed April 2006). Only stations that had $\leqslant 2$ months of missing rainfall data within a given year and >25 total years of total data were used (43 total stations).

At each weather monitoring station we calculated the standardized deviate of rainfall in a given rainfall year using the formula $(x_i - x)/s$, where x_i is total rainfall for year i, x is the average rainfall for the period from 1977–2004, and s is the standard deviation over the same period. For example, a standardized deviate of 1.5 in a given year means that rainfall for that year was 1.5 standard deviations above the overall average. Using the yearly standardized deviates for the 43 stations across the Mojave, we used the kriging tool within ArcGIS version 9.1 (ESRI, 2005) to create a continuous surface of deviates across the Mojave, then attributed each fire with the predicted deviate value at the location of the fire.

Based on our key questions concerning fires in the Mojave, we formulated a number of possible models that might be expected to explain those patterns of interest in the observed data. We specifically modelled the relationships of fire size with four predictor variables: ecological zone and annual rainfall (1 May–30 April) during the previous 1–3 years. We focused on fire size because it represented a single synthetic variable that combined information regarding fire occurrence and area burned. It also allowed us to use each individual fire as a modelling subject, which was not possible for summation data such as total number of fires and total area burned. The candidate models included simple models that contained the main effect of each of the four predictor variables, more complicated models that included the combinations of main vegetation and rainfall effects, and even more complex models consisting of possible interactions between vegetation type and rainfall. We considered a total of 19 different models in our analyses.

We used the GLIMMIX procedure in SAS version 9.1 (SAS Institute Inc., 2002) to analyse the set of candidate models. The GLIMMIX procedure fits statistical models to data with correlations of nonconstant variability and where the response is not necessarily normally distributed. These models are known as generalized linear mixed models which, like linear mixed models, assume normal (Gaussian) random effects. Data can have any distribution in the exponential family, including many of the elementary discrete (e.g. binary, binomial, Poisson, negative binomial) and continuous (e.g. normal, β, γ, χ^2) distributions.

Adequately defining the distribution of individual fire sizes was problematic because small fires (<1 ha) are common, while fires of larger sizes are relatively infrequent. Analyses of a small subset of the fire size data with models assuming normal, lognormal, gamma, or exponential distributions, plus various data transformations, did not adequately fit the data. We decided to classify fires into five discrete categories based on their size: <1, 1–10, 10–100, 100–1000, and >1000 ha. We then modelled the data as an ordinal nominal response by choosing the multi-nomial distribution in GLIMMIX, which produced the cumulative probability distribution that a fire occurs within a certain size class.

We used an information-theoretic approach to choose the model or models that lost the least information about the data relative to the other candidate models (Burnham and Anderson, 2002). Models were ranked according to their sample-size corrected Akaike information criterion (AIC_c) score, which was part of the GLIMMIX procedure output. The model or models with the lowest AIC_c score(s) are more plausible relative to the other candidate models.

3. Results

There were 8699 fires that burned a total of 292,017 ha (721,590 acres) in the Mojave Desert between 1980 and 2004 (Table 2). Most of these fires (63%) and area burned (88%), plus the largest fires, occurred in middle elevation srublands. The fewest number of fires (6%) fires and area burned (2%) occurred in the desert montane zone, where 99% were <1 ha. However, on a per unit area basis, proportionally more fires and area burned in the desert montane zone than anywhere else (Table 2). Thus, between 1980 and 2004, the middle elevation zone accounted for most of the fire activity but the desert montane zone experienced the highest percentage of area burned.

The largest amount of area burned occurred in the northeast and eastern Mojave Desert (Fig. 1), encompassing the Ely, Las Vegas, St. George, Arizona Strip, and Kingman field offices of the Bureau of Land Management (BLM), and the Spring Mountains National Recreation Area of the US Forest Service. Other areas of concentrated fire activity occurred in the eastern Mojave Desert within the Lake Mead National Recreation Area and the Mojave National Preserve of the National Park Service, in the western Mojave Desert within the Barstow Field Office of the BLM, and in the southern Mojave Desert within Joshua Tree National Park.

Human caused fires prevailed in the low and middle elevation and the desert montane zones where human visitation rates are generally highest (Fig. 1). Lightning-caused fires were the norm in the high elevation woodlands which tend to be more remote and experience less human visitation. Lightning-caused fires were also more prevalent in the central and eastern half of the Mojave Desert where most of the high elevations occur and where more summer monsoonal storms that tend to have high amounts of lightning occur. Most of these large fires were ignited by lightning in remote areas along the eastern margin of the study region.

No apparent directional linear trends existed over time in number of fires or area burned during the 25 years encompassed by the dataset. There were a few polynomial relationships

Table 2
Fires within 4 ecological zones of the Mojave Desert from 1980 to 2004

Ecological zone where ignition occurred	Number of fires	Area burned (ha)	Area per fire (ha)	Number of fires per km^2	Area burned per km^2	Proportion of human to lightning caused fires	Percentage of fires within size class				
							<1 ha	1–10 ha	10–100 ha	100–1000 ha	>1000 ha
Low elevation shrubland	1407	15,694	11	0.03	0.3	4.1	86.3	8.5	3.9	1.1	0.1
Middle elevation shrubland	5501	240,173	44	0.07	3.1	1.9	75.9	10.5	8.1	4.5	0.9
High elevation woodland	1267	30,528	24	0.33	7.9	0.3	86.2	6.9	3.8	2.5	0.6
Desert montane	524	5622	11	2.02	21.7	2.0	98.5	0.6	0.6	0.0	0.4

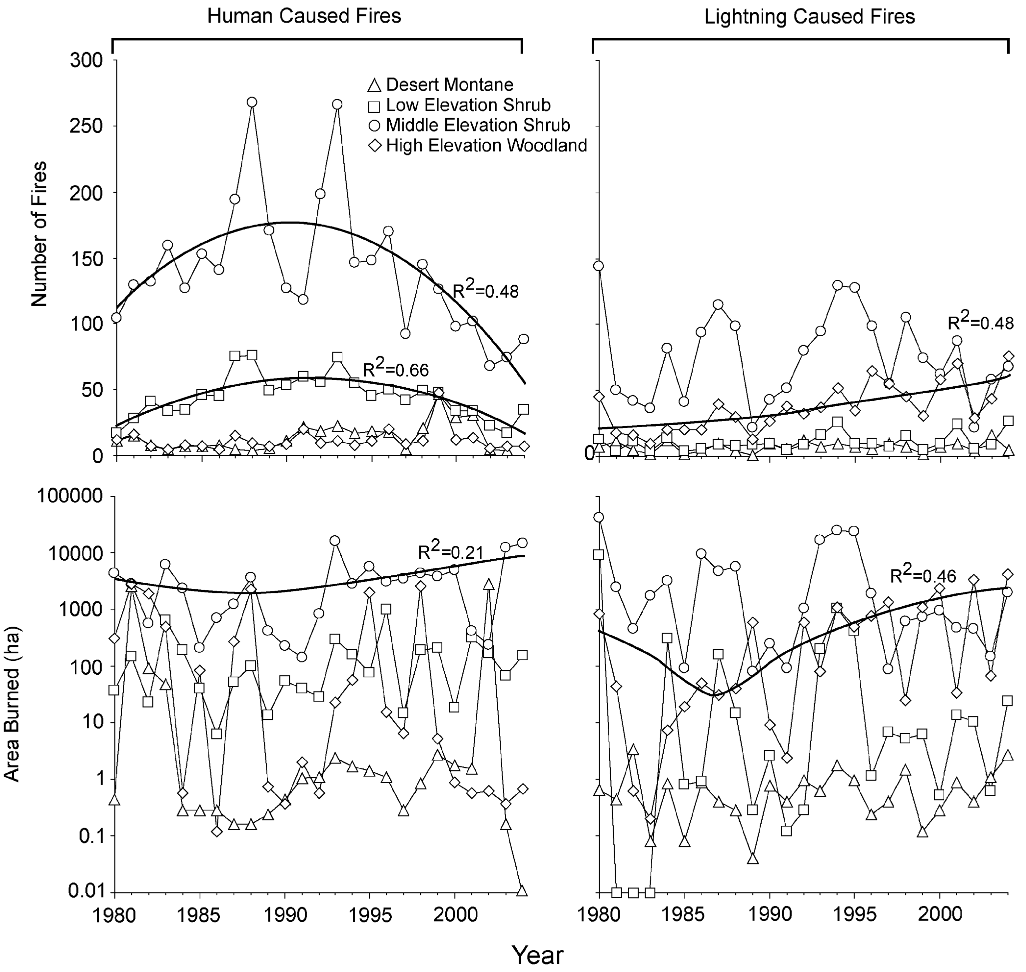

Fig. 2. Trends in human- and lightning-caused fires in the four ecological zones, 1980–2004.

that exhibited reasonable fits to trend curves (i.e. $R^2 > 0.20$). For example, the number of human-caused fires in the middle and lower elevation zones increased until the early 1990s, at which point they began to decrease (Fig. 2). At the same time, the number of human-caused fires was decreasing after the early 1990s, the amount of area burned in the middle elevation shrublands was increasing (Fig. 2). Basically, since the early 1990s the trend has been for fewer human-caused fires but more area burned by these fires in the middle elevation shrubland zone. In contrast, the number of lightning caused fires remained relatively constant between 1980 and 2004, except for a slight upward trend in the high elevation woodland zone matched by an increase in the area burned beginning in the mid-1980s (Fig. 2).

The results presented above indicate that there has been significant variation in numbers of fires and area burned among the four ecological zones (Table 2, Fig. 2). However, the

Table 3
Summary of model selection results (model effects are ez = ecological zone, $r1$ = rainfall the year prior to the fire season, $r2$ = cumulative rainfall for the 2 years prior to the fire season, and $r3$ = cumulative rainfall for the 3 years prior to the fire season)

Model effects	AIC_c	Δ_i	w_i
ez	12,215	249	0.000
$P1$	12,406	440	0.000
$P2$	12,442	476	0.000
$P3$	12,451	486	0.000
$ez+r1$	12,118	152	0.000
$ez+r2$	12,147	181	0.000
$ez+r3$	12,155	190	0.000
$ez+r1+ez \times r1$	12,107	142	0.000
$ez+r2+ez \times r2$	12,139	173	0.000
$ez+r3+ez \times r3$	12,154	188	0.000
$ez+r1+r2$	12,043	78	0.000
$ez+r1+r2+ez \times r1+ez \times r2$	12,023	57	0.000
$ez+r2+r3$	12,092	126	0.000
$ez+r2+r3+ez \times r2+ez \times r3$	12,082	116	0.000
$ez+r1+r2+r3$	11,984	19	0.000
$ez+r1+r2+r3+ez \times r1+ez \times r2+ez \times r3$	11,965	0	1.000
$R1+r2$	12,324	359	0.000
$R2+r3$	12,381	416	0.000
$R1+r2+r3$	12,258	292	0.000

significant variation among years suggests that another factor, namely rainfall, affects the ignition and spread potential of fires as well. We therefore modelled the relationships of fire size with four predictor variables: ecological zone and rainfall during the previous 1–3 years. Based on an information-theoretic approach (Burnham and Anderson, 2002), the best fit model for fire size of the 19 models evaluated was

$$\text{fire size} = ez + r1 + r2 + r3 + ez \times r1 + ez \times r2 + ez \times r3,$$

where ez is the ecological zone, $r1$ the rainfall 1 year prior to the fire season, $r2$ the rainfall 2 years prior to the fire season, and $r3$ the rainfall 3 years prior to the fire season. This best-fit model was 65% concordant and 34% discordant with 1.5% ties among 12,847,685 pairwise comparisons of the 8699 fires in the datasets (Somers' $D = 0.314$). AIC_c scores for all 19 models are listed in Table 2, along with the value Δ_i (difference between a given model's AIC_c score and that of the best-fit model), and the value w_i (probability that a given model is the best-fit of the considered models) (Table 3).

The main effect of ecological zone on fire size is reflected by the differing size class distributions (Table 2). As noted earlier, the middle elevation shrubland zone contained the highest proportion of large fires and the desert montane zone contained the highest proportion of small fires. The main effects of rainfall generally followed a pattern of larger fires following years of high rainfall. This effect is not surprising considering that plant productivity (and thus fuel continuity) is generally thought to be the primary factor limiting fire spread in the Mojave Desert. However, the interaction of ecological zone with

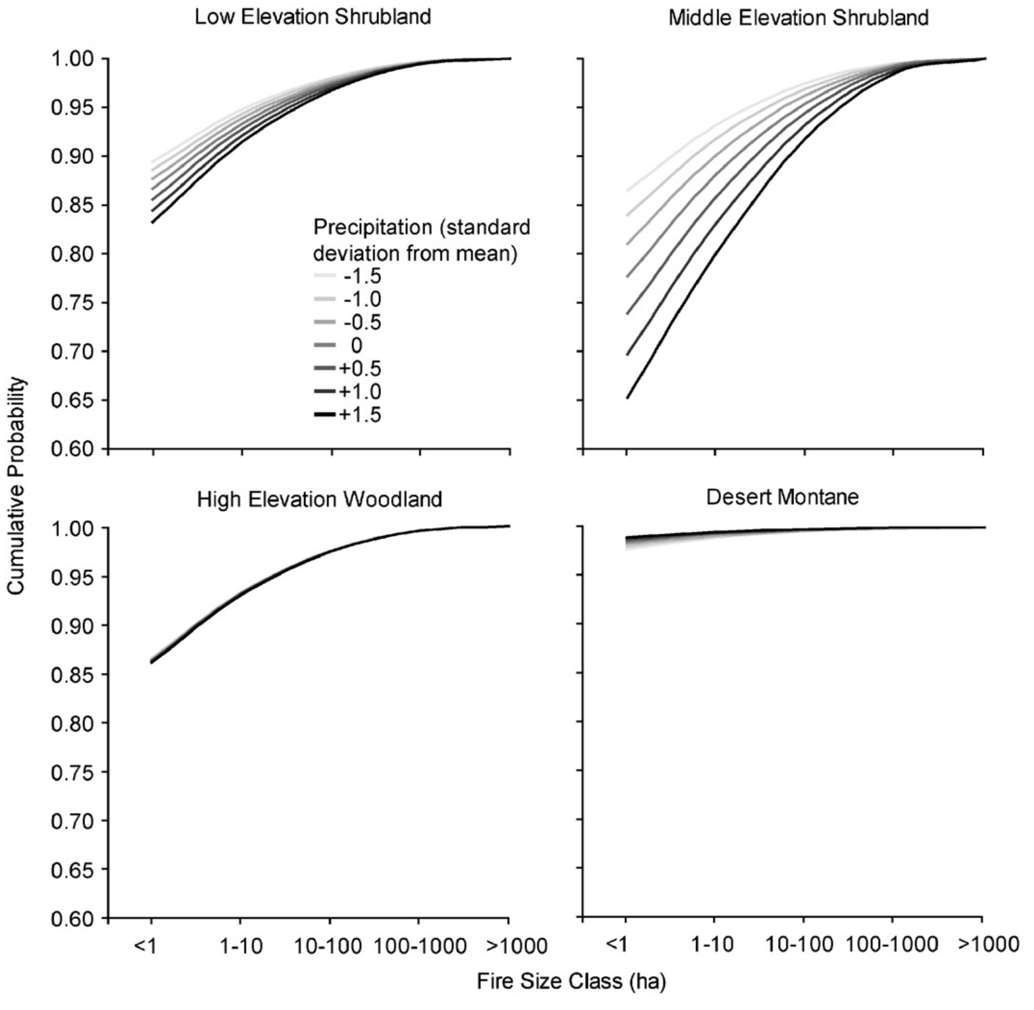

Fig. 3. Relationships between fire size classes and standard deviations of rainfall during the preceding 1 year.

rainfall year was also significant as reflected by the differing effects of rainfall on fire size among the four ecological zones. Specifically, rainfall had its greatest effect on fire size in the middle elevation ecological zone and to a lesser extent in the low elevation zone (Fig. 3). Rainfall had virtually no effect on fire size in the high elevation and desert montane zones. These relative patterns among ecological types and rainfall were similar when fire size distributions were plotted against rainfall during the previous 1–3 years. We only plotted fire size vs. rainfall deviation for 1 year of rainfall prior to the fire season (Fig. 3). As cumulative rainfall for years 2 and 3 were added, the patterns became slightly more pronounced, that is, more separation occurred among the curves within the plots for the middle- and low elevation shrubland zones. The high elevation woodland and desert montane zones did not exhibit any changes in the size distribution of fire in response to any combinations of rainfall years.

4. Discussion

4.1. Spatial patterns of burning

Most fires and area burned between 1980 and 2004 occurred in the middle elevation ecological zone. This zone often has enough cover of native vegetation to carry fire, and likely experienced stand-replacing fires over long return intervals (>100 years) in the past (Brooks and Minnich, 2006). However, the enhancement in fuel continuity that is provided by non-native annual grasses following years of high rainfall is enough to significantly increase the size of fires. In contrast, the low elevation zone has very sparse cover of native vegetation, generally insufficient to carry fire (Brooks and Minnich, 2006). Significant accumulations of fine fuels from non-native annual grasses following years of high rainfall are required to produce moderate (~100 ha) to large (~1000 ha) fires, although the effect of rainfall year is not as dramatic as in the middle elevation zone. Native fuels in the middle elevation zone appear to be just below the threshold of allowing fire to spread, because the flush of fine fuels that occurs after years of high rainfall increases the proportion of large fires more than in any other ecological zone. In contrast, native fuels in the low elevation zone appear to be well below the threshold to carry anything other than relatively small fires. Even years of high rainfall only have only a moderate effect on fire size in this zone.

A similar positive relationship between rainfall and area burned was reported using a 29-year (1955–1983) fire dataset in the Sonoran Desert of North America (Rogers and Vint, 1987). That study from the Arizona Upland subdivision of the Sonoran Desert (Shreve, 1964; Turner and Brown, 1982) is analogous to the middle elevation shrubland zone of the Mojave Desert. Both occur at elevations above the hyperarid shrublands, are often positioned on the lower slopes of mountain ranges, and possess moderate woody plant cover. These ecological zones both appear to possess fuels near the threshold of where fire can spread across large areas.

Native fuels in the high elevation woodland and desert montane zones appear capable of carrying fire regardless of fine fuel increases following years of high rainfall. The evidence is indicated by the lack of change in the size distribution of fires in response to rainfall amounts. Basically, the ability of fire to spread in these zones is predicated more on native woody fuels than on ephemeral fine fuels which are mostly comprised of non-native annual grasses. Although the total area burned was lower in these higher elevation zones compared to the lower elevation zones, the high elevation woodland ($<4\%$) and desert montane ($<1\%$) zones comprised very small proportions of the total extent of the Mojave Desert, and the proportion of the areas that burned were much higher than in the other two ecological zones. Although fires in these higher elevation zones are largely carried by native fuels, the recent increase in the amount of area burned in the high elevation woodland zone, and the prevalence of human-caused fires in the desert montane zone, are causes for concern.

One particular concern in the high elevation woodland and desert montane zones is the occurrence in relatively small disjunct stands, which appear increasingly to be consumed by fire. Stand-replacing fires in these zones lead to very long recovery periods, which may take over a century for pinyon-juniper woodlands (Brooks and Minnich, 2006). After a recent increase in area burned since the 1980s at Joshua Tree National Park, a land manager there estimated that if the rate of burning continued, all of the pinyon-juniper woodland (high elevation shrubland zone) and most of the blackbrush shrublands (part of the middle elevation shrubland zone) would be burned by the second decade of the 21 Century (H. McCutcheon, personal communication). Under this scenario few propagule sources would be available to recolonize the burned areas, requiring centuries for the stands to recover, assuming that the current rate of burning does not continue to rise.

4.2. Temporal patterns of burning

The number of fires or area burned between 1980 and 2004 in the Mojave Desert had no apparent directional linear trends. These results challenge the previous conclusions that the incidence of fire is increasing in the Mojave Desert (US Fish and Wildlife Service, 1994; Brooks and Esque, 2002), especially in the low and middle elevation zones (Brooks and Minnich, 2006). However, upon closer analysis one can see that the number of human-caused fires in the low and middle elevation zones did increase until the mid 1990s, after which time they declined, as represented in the polynomial curve on Fig. 2. Potential explanations for the decline may be related to improved law enforcement or perhaps factors related to reduced incidences of car fires along roadsides, which are frequent causes of fires in the Mojave Desert (agency DI-1202 fire records). It is not related to fuel conditions, because during the same time period, the amount of area that burned actually increased slightly.

This discrepancy with previous publications that used shorter-term datasets emphasizes the extreme caution one must employ when inferring patterns outside of the range of a particular dataset. For example, Schmid and Rogers (1988) is often cited to support the contention that fire frequency and extent are increasing in the Sonoran Desert. The conclusion may still be valid, but the fact that the 29-year (1955–1983) dataset is currently over 20-year old emphasizes the need for an updated analysis.

Limitations of the dataset we analysed were also highlighted by the 2005 fire season that immediately followed. We did not include 2005 in our analysis because we did not have a complete dataset of all fires for that year at the time the paper was written. Based on our incomplete 2005 dataset that included all major fires, the amount of area burned in the Mojave Desert was 385,357 ha (952,238 acres) (M. Brooks unpublished data), representing 132% of the total area that burned during the previous 25 years. Virtually all of the large 2005 fires were caused by lightning and most occurred in the northeastern Mojave Desert. Approximately, 318,655 ha (787,414 acres) burned in the middle elevation shrublands, 56,083 ha (138,584 acres) in the high elevation woodlands, 10,619 ha (26,240 acres) in the low elevation shrublands, and a negligible area burned in the desert montane zone. By comparing these values to the area burned in lightning caused fires between 1980 and 2004 (Fig. 2), one can see that the results are similar for all zones except for the middle elevation shrubland zone. All other 2005 values fall within the general range of values from the preceding 25 years, except for the 318,655 ha in the middle elevation shrubland, which is more than three times higher than any other value reported in the dataset we analysed. It bears noting that the 2005 fire season was preceded by three years in which rainfall totals were among the top ten highest over an approximately 100-year dataset for the northeastern Mojave Desert (Las Vegas, Nevada, weather data; http://www.ncdc.noaa.gov/oa/ncdc.html; accessed April 2006). Thus, our conclusion that the amount of area burned in the middle elevation shrubland zone is strongly tied to the production of fine fuels following years of high rainfall is only further supported by what occurred during the 2005 fire season.

Analyses to evaluate relationships between fire occurrence and rainfall need to be conducted over many decades to over a century to capture the full range of conditions necessary to infer trends for different vegetation types. For example, the lack of response of fire size to rainfall in the high elevation woodland and desert montane zones may simply be due to the short-term 25-year span of the dataset we used. Fuels in these zones are dominated by woody plants that can take decades to accumulate the biomass necessary to carry large fires (Brooks and Minnich, 2006). This process has been called the cumulative fuel build-up model (Minnich, 2003), whereby woody fuels accumulate over many decades that can span years of high rainfall during which time the ability of the landscape to carry fire may change very gradually. In contrast, shorter-term dynamics may be observed at middle and low elevations where the primary fuels that facilitate fire spread are dominated by ephemeral species that respond rapidly to annual changes in rainfall. The latter process has been called the short-term fuel load model (Minnich, 2003).

Future changes in rainfall regimes have the potential to affect fire regimes in the Mojave Desert. For example, predictions that the region may be entering a multi-decade period of relatively low rainfall in the early 21 Century (Hereford and Webb, 2001; Hereford et al., this volume) have implications for fuelbed conditions. Reduced rainfall leads to lower loads of fine fuels, especially non-native annual grasses, which should reduce the size of fires and amount of area burned at the middle- and low elevation zones (Brooks and Esque, 2002; Brooks and Minnich, 2006). Reduced rainfall also leads to less live fuel moisture, which may increase fire size and area burned in the high elevation and desert mountain zones. However, reduced rainfall may also slow the gradual accumulation of woody fuels, and reduce production of native perennial grasses, which in the long run may limit the amount of area burned at the higher elevations as well.

4.3. Is an invasive plant/fire regime cycle establishing in the Mojave Desert?

The concern that non-native annual grasses are decreasing fire return intervals and increasing the size of fires in the Mojave Desert (Brooks and Esque, 2002; Brooks and Minnich, 2006) is central to many land management decisions. Although this assumption is widely cited, and is often used to justify costly fire management activities, it is a premise that can be surprisingly difficult to confirm. To determine that an invasive plant/fire regime cycle (Brooks et al., 2004) has become established, one must document changes in the spatial and temporal distribution of fire on the landscape and show that the new regime promotes the dominance of the non-native fuels that drive it (Brooks, accepted). Direct evidence is unavailable, because it must include information that spans multiple fire return intervals. However, indirect evidence over shorter time intervals can also provide very useful insights. The results of the current study provide such indirect evidence that can be used to shed light on fire regime dynamics in the Mojave Desert.

The strong positive response of fire size to rainfall year in the middle elevation zone and the moderate response in the low elevation zone indicate that short-term annual fluctuations in fine fuels in response to rainfall can significantly affect fire size. Fine fuels are largely produced by annual plants which can be comprised of 66–91% biomass of non-native species in the Mojave Desert (Brooks, accepted; Brooks and Berry, accepted). These non-native annual plants increase in biomass significantly following years of high rainfall (Brooks and Berry, accepted) and often dominate sites within a few months to a few years following fire (Brooks and Esque, 2002; Brooks and Minnich, 2006). They are comprised primarily of *Bromus* spp., *Schismus* spp., and *Erodium cicutarium* (Brooks and Berry, accepted). The first two genera listed are annual grasses, which are the major fine fuel component that facilitates the spread of fire in the low and middle elevation zones in the Mojave Desert (Brooks, 1999).

The annual trend data provides more support for the link between non-native annual grasses and fire size in the middle elevation shrubland zone. The modest increase in area burned since 1990 in the middle elevation zone, which was punctuated by a dramatic spike in 2005, coupled with a decline in human-caused fires and a relatively constant number of lightning-caused fires, suggests that the increase in area burned was due to increases in fuelbed flammability and not to increased numbers of ignitions. Although there is no trend data suggesting that the dominance of non-native annual grasses increased during our study period, another study from low and middle elevation shrublands in the northern Mojave Desert documented dramatic increases in density of *Bromus* spp. between the 1960s and 1980s (Hunter, 1991). However, more data are needed to determine if the dominance of non-native annual grasses is increasing and specifically where it is increasing across the Mojave Desert.

Some evidence also exists that fuel loads from non-native annual grasses reach their peak in the middle elevation shrubland zone. Elevations below 800–1000 m in the Mojave Desert were mostly dominated by *Schismus* spp. in a study by Brooks and Berry (accepted), and these elevations are typical of the low elevation zone. In contrast, elevations above 800–1000 m in that same study were dominated by *B. rubens*, and are typical of the middle elevation zone. Fuelbeds comprised of *B. rubens* are much more conducive to fire spread than those comprised of *Schismus* spp. (Brooks, 1999). At the two higher elevation zones, *B. tectorum* is often present, but rarely achieves the landscape-scale continuous cover that *B. rubens* exhibits in the middle elevation zone (M. Brooks, personal observation). Thus, *B. rubens* appears to be the primary fine fuel promoting fire spread in the middle elevation shrubland zone.

In contrast, the lack of response of fire size to rainfall year in the high elevation woodland and desert montane zones indicates that fine fuelbeds did not significantly affect fire size during our study period. This suggests that either non-native annual grasses are not especially abundant in these zones or that some other characteristic of the fuelbed has a stronger affect on the fire regime. It is likely that both factors are at work. As mentioned above, non-native annual grasses are often not abundant except in disturbed areas at these higher elevations (M. Brooks, personal observation), and the primary fuel component affecting fire behaviour and fire regimes are the woody native fuels, which build up slowly over time. Observations during the 2005 Mojave Desert fire season indicate that relatively large areas (>20,000 ha) can burn as stand-replacing fires where non-native fuels are virtually absent (Hackberry Fire Complex; M. Brooks, personal observations), indicating that large fires in native woody fuels are probably part of the natural fire regime. However, the addition of non-native annual grass fuels to the region could change this dynamic by shortening the fire return interval which may preempt the slow accumulation of woody fuels and essentially replace them with fine fuels. Although type conversion does not seem to have yet occurred in the two higher elevation zones of the Mojave Desert, it is a threat that needs to be monitored and dealt with early if it is observed in the future.

The current conclusion from this indirect evidence is that an invasive plant/fire regime cycle is probably establishing in the middle elevation, and to a much lesser degree the low elevation, shrubland zones of the Mojave Desert. The native fuels in these zones are near the tipping point between a fire regime characterized by infrequent small fires and one of frequent large fires. When non-native annual grasses are added to these fuel types, especially when they bridge the interspace fuel gaps between perennial shrubs and grasses, the transition between these alternative fire regime states is much more likely. Altered fire regimes appears to have occurred over broad expanses of middle elevation shrublands in the northeastern Mojave Desert, representing fire clusters 9 and 10 reported by Brooks and Esque (2002). Repeated fires are typically followed by dominance of *Bromus* spp., *B. rubens* in particular, which can create fine fuelbeds capable of carrying fire again soon after burning. Some of these areas have reburned 3 times during the past 60 years (M. Brooks, unpublished data). This dynamic has been documented fairly well during recent decades in the Mojave Desert (Brooks et al., in press), but has also been expressed as a concern since the middle of the 20th Century (Ralph Holmgren, unpublished report, 1960). The other 8 Mojave Desert fire clusters reported by Brooks and Esque (2002) are also mostly in the middle elevation zone and represent areas where numerous fires have occurred since 1980, some of which have burned repeatedly. Although most of these areas are fairly localized, there is a very real potential for invasive plant/fire regime cycles to develop in these areas in the future.

5. Conclusion

Our results provide important insights into patterns of burning in desert regions. For example, they illustrate the need to evaluate fire patterns among major ecological zones within desert regions. Desert regions are typically defined by their external boundaries, and internal variation caused by regional climatic and local elevation gradients is often overlooked. This study demonstrated how the characteristics of fire can vary from east to west across the Mojave Desert, and from lower to higher elevations within the region.

This study also emphasizes the caution one must place in conclusions derived from limited datasets. The results here are based on 25 years of fire data and should be re-evaluated periodically, perhaps at 5-year intervals, to maintain current information to assist in managing fire programs in the region. The unprecedented amount of area burned in the Mojave Desert during 2005 demonstrates how extreme events can be missed by just 1 year. We also recommend that future analyses stratify the region based on the four ecological zones used in this paper, or even more precise vegetation categories if appropriate spatial data are developed for the entire region in the future. Better resolution between areas occupied by the upper ecotones of creosotebush scrub and lower ecotones of blackbrush shrublands and the areas occupied by the upper blackbrush ecotones, sagebrush steppe, and interior chaparral would be especially useful, since the current analysis pools all of these vegetation types into the single high elevation shrubland zone.

It appears that the middle elevation ecological zone is most susceptible to the establishment of a grass/fire cycle, especially where numerous very large fires have occurred in the northeastern Mojave Desert. The low elevation zone is also susceptible, but to a lesser degree. A major concern in these zones is the effect of these fires on the desert tortoise (US Fish and Wildlife Service, 1994; Brooks and Esque, 2002). Other desert vegetation types of the world with similar native woody fuels may be similarly susceptible to altered fire regimes caused by non-native grass invasions. Lower elevation vegetation types that are too sparse to begin with, or higher elevation vegetation types that are already sufficient to carry fire, do not seem to be as sensitive to fire regime changes caused by non-native annual grasses.

This study not only indicates a need for continued research focusing on the impacts of fire and potential for fire on the middle elevation zone, but also the impacts of the change in composition of vegetation on the fauna of this important ecological type. It also has implications that may be useful in the pre-positioning of fire suppression equipment or crews, prioritizing research of rehabilitation or restoration of burned lands in the middle elevations, and developing vegetative material (e.g. seed banks) to be used in such rehabilitation work.

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