El Niño-Southern Oscillation (ENSO) Phenomena and Forest Fires in the Southwestern United States

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ABSTRACT: Fire statistics (area burned) and fire-scar chronologies from tree rings show reduced fire activity during El Niño-Southern Oscillation (ENSO) in forests of Arizona and New Mexico. This relationship probably stems from increased fuel moisture after a wet winter and spring, but also could involve climatic controls on lightning activity at the onset of the monsoon season.

INTRODUCTION

Fire plays an important role in plant communities worldwide, yet one of the more uncertain impacts of climatic change is an altered fire regime. Traditionally, fire research has emphasized meteorology in predicting fire intensity and rate of spread given short-term weather conditions. Early efforts to determine the synergistic influence of climate and fuel accumulation on fire occurrence were mostly unsuccessful (Hardy, 1983).

Renewed interest in fire climatology is partly a response to the emerging science of global change and to recent catastrophic fires, such as those in Indonesia and Australia during the 1982-1983 El Niño (Gill, 1983; Leighton, 1984) and at Yellowstone Park, USA, in 1988. A possible link between fire activity and climatic variability due to ENSO phenomena, implied in the recent literature, could have forecasting value. Not only is the onset of an El Niño sometimes predictable months in advance (Barnett et al., 1988), but also the significant teleconnections for fire climatologies may lag the onset by more than one season.

In the southeastern United States, Simard et al. (1985a) found that fire activity decreased significantly during ENSO events of the last 50 years. There, cool season precipitation is positively correlated with ENSO indicators, such as the Southern Oscillation Index and Line Island rainfall (Douglas and Englehart, 1980; Ropelewski and Halpert, 1986, also this volume). More recently, Simard and Main (1987) developed a regression model for predicting variability of fire activity in the southeast. The regression is derived from the relationships of fire with the quasi-biennial oscillation and the frequency and intensity of ENSO.

ENSO also may influence fire activity in the southwestern United States, where the annual march of precipitation produces a distinctly seasonal fire regime (Figure 1). An extremely arid foresummer follows a highly variable winter and spring. The dryness of May and June ends abruptly in early July with synoptic-scale surges of moist tropical air that continue into September. Commonly referred to as the Arizona monsoon, this is the season of maximum frequency of thunderstorms and cloud-to-ground lightning strikes.

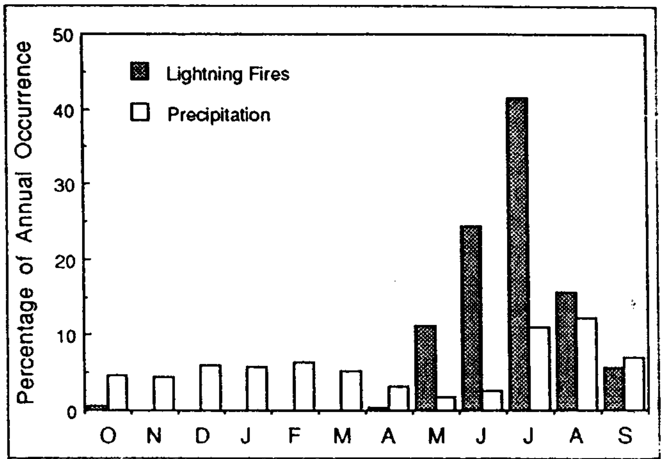

Figure 1. Percentage of mean annual occurrence for lightning fires and precipitation in Arizona and New Mexico (1940-1975). Note peak fire activity just before or at the onset of the rainy season in July.

The fire season closely tracks the rainfall regime. Lightning fires begin in the arid foresummer and peak in July, with a significant decrease as the rainy season progresses (Figure 1). Interannual differences in fire occurrences (area burned or number of fires) may result from the influence of winter-spring precipitation on the accumulation and moisture content of the fuel load. Alternatively, these differences can be attributed to short-term weather conditions, particularly high surface winds and the frequency, intensity, and timing of lightning strikes at the beginning of the summer rainy season.

Correlations between ENSO and fall, winter, and spring precipitation in the southwestern states are well known (Douglas and Englehart, 1984; Andrade and Sellers, 1988). All three seasons tend to be wetter during warm ENSO events. Increased winter/spring precipitation stems from a deep and intensified Aleutian low (a southerly displacement of the North Pacific storm track) and a stronger subtropical jet stream that brings moisture directly from the Intertropical Convergence Zone (ITCZ) in the eastern and central Pacific. Relationships with summer rainfall are less clear. Opposition of

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winter/spring and summer precipitation was first noted by Sellers (1960). Reyes and Cadet (1988) suggest that, during ENSO summers, the ITCZ moves south, the South Pacific high weakens, and low-level moisture advection into the southwestern United States is reduced. Rainfall may increase during the following summer due to persistence of warm surface waters off the west coast of Mexico and northward penetration of the subtropical high ridge over the western United States (Carleton et al., in press). Summer teleconnections may have an uneven expression across the southwestern United States, depending on proximity to the different sources of moisture (Gulf of Mexico and Pacific Ocean/Gulf of California).

In this paper, we identify an ENSO teleconnection in archival and tree-ring evidence of fire activity primarily affecting ponderosa pine (*Pinus ponderosa*) forests in the southwestern United States. Because of its thick bark, ponderosa pine is one of the more fire-resistant species of western conifers. Slow-spreading surface fires encourage regeneration of ponderosa pine in forest openings and result in an uneven-aged forest with trees growing in even-aged cohorts (Schubert, 1974; see White, 1985 for opposing view). A better understanding of long-term fire-climate relationships is paramount to wise management of southwestern ponderosa pine forests. These forests provide most of the region's lumber and form the predominant cover in the headwaters of the Rio Grande and Colorado River basins.

METHODS

Reports of the U.S. Forest Service provide records of fire after 1900. The Forest Service keeps annual records of number of fires and area burned on more than 8 million hectares under its jurisdiction (U.S. Department of Agriculture, 1975-1986; see summary in Barrows, 1978). A reliable chronology of fire activity for Arizona and New Mexico is readily available since 1940. Longer records may be gleaned from district offices at individual forests. For Gila National Forest, in southwestern New Mexico (Figure 2), the chronology can be extended from 1909.

Evidence for pre-1900 fires was compiled from fire-scar chronologies developed at the University of Arizona's Laboratory of Tree-Ring Research. Fifteen fire-scar chronologies are available from Arizona (7), New Mexico (5 of 6 in Gila National Forest), west Texas (1), and Sonora, Mexico (1) (Figure 2). Full or partial cross sections were collected from both live and dead fire-scarred trees, the annual rings were cross-dated, and the position of fire scars within annual rings were noted (Dieterich and Swetnam, 1984). Fire-scar dates from 315 trees are included in the fifteen chronologies.

Eleven of the fire-scar chronologies span the period from about 1700 to 1900, three of them extend from about 1750 to 1900, and one chronology extends from 1800 to the mid-1980s (Swetnam, in press). The dearth of fire scars after 1900 reflects reduction of fire due to removal of fine fuels by heavy grazing and a vigorous program of fire suppression by government agencies.

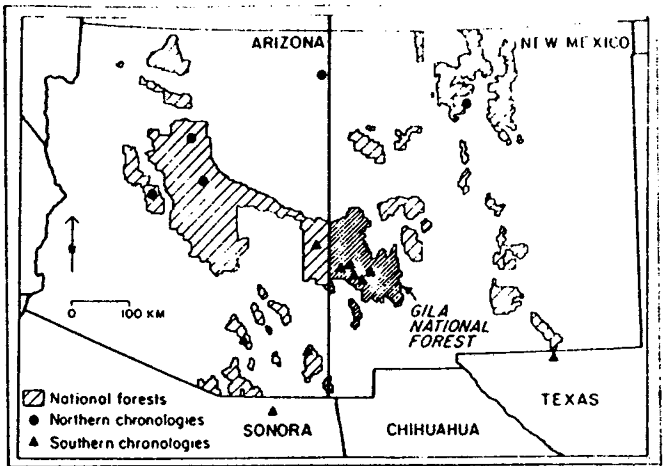

Figure 2. Map of Arizona and New Mexico showing boundaries of National Forests and locations for fire-scar chronologies. Northern Arizona chronologies discussed in the text include all four sites north of 34° latitude. The southern Arizona and New Mexico group includes ten sites south of 34°. The single site in northern New Mexico was used only in compiling overall statistics.

Only the chronology from Mexico extends into the 1980s, probably because fire suppression either was not practiced or was ineffective. In general, the fire-scar chronologies document the timing of episodic, low intensity surface fires that burned unchecked through the understory of ponderosa pine and mixed-conifer forests. Both fire-scar and archival evidence show years in which fires were widespread (Swetnam, in press). In the twentieth century, these events include some of the driest years of record (e.g., 1946, 1956, 1971, 1974, and 1989).

FIRES AND ENSO

Figures 3 and 4 show the average Southern Oscillation Index (SOI) in the Northern Hemisphere winter (December-February) (Ropelewski and Jones, 1987) with annual area burned since 1909 in Gila National Forest (both lightning and person-caused fires) and since 1940 in Arizona and New Mexico (lightning fires only). In both cases, SOI is significantly correlated with mean area burned (Gila: $r = 0.35$, $p < 0.01$; Arizona and Mew Mexico: $r = 0.48$; $p < 0.01$). These correlations are comparable with those obtained between SOI or other ENSO indicators and cool season precipitation in the southwest (Douglas and Englehart, 1984; Andrade and Sellers, 1988).

As with precipitation, the correlations are significant but normally explain less than one-fourth of the variance. The closest association is that of minimal fire activity during strong and very strong ENSO events (1912, 1926, 1932, 1941, 1957-58, 1972-73, 1982-83 [event strength is defined by Quinn et al., 1987]). There is a weaker tendency for severe fire years to occur during La Niña years (cold water events in the equatorial Pacific). A prime example is the current fire season.

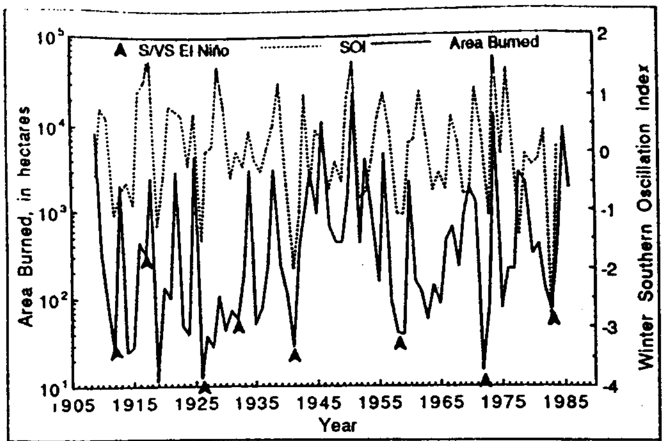

Figure 3. Mean annual area burned in Gila National Forest (lightning- and person-caused fires, 1909-1986) and average December-February Southern Oscillation Index (1909-1984). The Pearson correlation coefficient between log. mean annual area burned and the winter SOI is $r = 0.35$ ($p < 0.01$). Strong and very strong (S/VS) El Niño events, as defined by Quinn et al. (1987), are indicated by arrows.

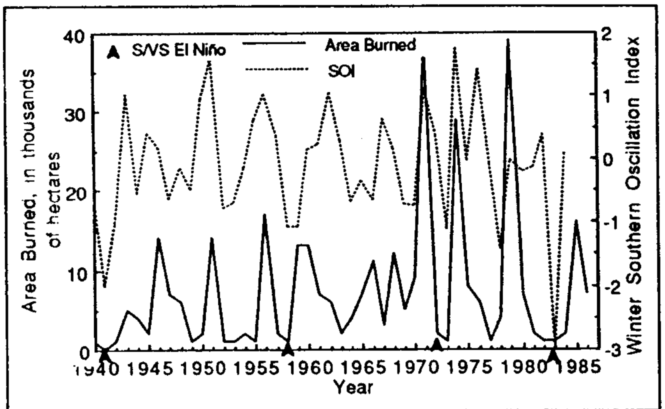

Figure 4. Mean annual area burned in all National Forests in Arizona and New Mexico (lightning fires only, 1940-1986) and average December-February Southern Oscillation Index (1940-1984). The Pearson correlation coefficient between log. mean annual area burned and the winter SOI is $r = 0.48$ ($p < 0.01$). Strong and very strong (S/VS) El Niño events, as defined by Quinn et al. (1987), are indicated by arrows.

Very little precipitation fell in Arizona and New Mexico between February and July, 1989. By mid-July, tens of thousands of hectares had burned in the region. In addition, many shrubs in the Arizona chaparral died during the 1989 drought and will provide fuel for the 1990 fire season.

Differences in mean area burned per year during ENSO vs. non-ENSO events were evaluated using the Mann-Whitney test. Mean area burned (387 ha) in Gila National Forest during 14 strong and very strong ENSO events is significantly different than for 52 non-ENSO events (1,582 ha) ($p < 0.001$, 2-tailed probability level). Mean area burned (1,412 ha) during 26 ENSO events of all intensities between 1909 and 1986 also was significantly different than for non-ENSO years (1,582 ha). Weak ENSO events apparently are not closely associated with fire activity; Andrade and Sellers (1988) also found that the correlation between ENSO and southwestern precipitation decreases with event intensity.

For Arizona and New Mexico, mean area burned (957 ha) during 8 strong and very strong ENSO events was significantly less than during non-ENSO years (8,676 ha; $p < 0.001$). For 13 ENSO events of all intensities, mean area burned (3,013 ha) was considerably lower than for non-ENSO years ($p < 0.001$).

Comparisons between SOI and southwestern fire activity can be extended to before the turn of the century using fire-scar records. Figure 5 relates percentage of trees scarred in Arizona and New Mexico to the annual SOI for the period 1866-1900. Percentage of trees scarred was computed as the number of sampled trees scarred in a given year relative to the number of sampled trees at the site that had been scarred previously. This percentage was calculated for each of the chronologies and then averaged for the region. The percentage of trees scarred in Arizona and New Mexico was positively correlated with the annual SOI between 1866 and 1900 ($r = 0.50$, p). This is a better correlation than that obtained with twentieth century observational data (area burned). This is because area burned can be affected by a large local fire, whereas percentages of trees scarred reflect fire activity throughout the region.

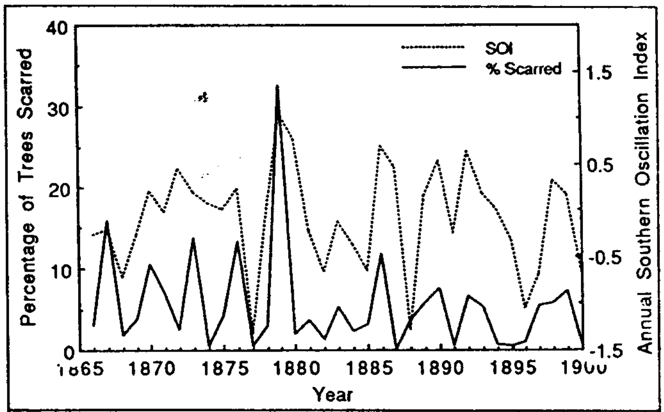

Figure 5. Percentage of trees scarred per year in fire-scar chronologies from Arizona and New Mexico (see text and Figure 1) and the average annual Southern Oscillation Index (1866-1900, both weries). The Pearson correlation coefficient is $r = 0.50$ ($p < 0.01$).

Table 1 lists results of contingency analyses for the time series of mean area burned since 1909 in Gila National Forest and percentage of trees scarred in the southwest between 1700 and 1900 (Quinn, et al., 1987, only note strong and very strong ENSO events prior to 1800). The number of strong to very strong El Niños above and below the median area burned were compared using chi-square statistics.

Contingency results show that ENSO events are clearly associated with below median area burned in Gila National Forest. Fire-scar data, however, show mixed

Table 1. Results of contingency analysis of numbers of strong and very strong El Niño-Southern Oscillation (ENSO) events above and below *(A/B)* the median values of fire occurrence in four time series. The Gila National Forest series is mean annual area burned, and the fire-scar series is percentage of trees scarred each year. ENSO groupings with (–) exclude first years of 2- or 3-year ENSO events. Yates correction of chi-square and P levels are shown in parentheses for groupings with expected frequencies less than or equal to 10.

	Number of Events			
	Expected A/B	Observed A/B	Chi-Square	P Level
Gila National Forest (1909-1985)				
ENSO	7/7	2/12	8.756 (7.092)	0.004 (0.008)
ENSO (–)	4/4*	1/7	5.029 (3.493)	
Northern Arizona Fire-Scar Chronologies (1700-1900)				
ENSO	13.5/13.5	8/19	5.181	0.022
ENSO (–)	10/10	5/15	5.556 (4.500)	0.018 (0.032)
Southern Arizona & New Mexico Fire-Scar Chronologies (1700-1900)				
ENSO	13.5/13.5	10/17	2.098	0.144
ENSO (–)	10/10	6/14	3.556 (2.722)	0.056 (0.095)
All Fire-Scar Chronologies (1700-1900)				
ENSO	13.5/13.5	10/17	2.098	0.144
ENSO (–)	10/10	6/14	3.556 (2.722)	0.056 (0.095)

* The chi-square critical value for $p \leq 0.05$ is 3.84. The chi-square (non-Yates) exceeds the critical value in this case; however, since expected cell frequency (4) is too low for this test, the significance level is suspect.

results. From 1700 to 1900 fire occurrence during ENSO years was lowest in northern Arizona, suggesting that fire/ENSO relationships may be more coherent to the north. Note that earlier analyses by Simard et al. (1985b) showed that in the western states the highest correlations between fire and ENSO were in Colorado – not in Arizona and New Mexico, as might be expected. This pattern may stem from higher incidence of cloud-to-ground lightning strikes and more common lightning fires in northern parts of the Southwest. (In the western United States, the greatest number of cloud-to-ground lightning strikes for the 1983 and 1984 summers was in the Four Corners area [Reap, 1986]). Alternative explanations may involve some aspect of climate/fuel dynamics, especially the role of winter grasses, or simple geography. The largest contiguous forests, which are vulnerable to large fires during dry years, occur in the northern parts of the southwest.

Though there is an association between annual fire occurrence in the southwest and ENSO occurrence and intensity, the relative dependence on long-term processes (e.g., seasonal drought) versus short-term weather (e.g., lightning) is uncertain. Hypothetically, increased fuel moisture during a wet, cool season discourages the spread of fires. By raising soil moisture, the buildup of moist litter also forestalls normal dieoff of plants during the arid spring and foresummer.

Interannual variability of lightning and its relationship to fire occurrence are virtually unexplored. Reliable lightning data for the western United States are only available since 1976, when the Bureau of Land Management established an extensive lightning detection network (Kridge et al., 1980). An important factor may be the incidence of "dry lightning" storms just before or at the onset of the monsoon season. One possible source is early summer hurricanes in the Gulf of Mexico. As the hurricanes dissipate over land, some of the moisture gets caught in the normal southeasterly flow. When the limited moisture reaches the southwest, strong thermal heating may form isolated thunderstorms that produce enough lightning to ignite fires but not enough rain to put them out. Gray (1984) found a significant decrease in the number of hurricane days during moderate to strong El Niños. Tropical cyclone activity is inhibited by the anomalous increase in upper tropospheric westerly winds characteristic of warm ENSO events.

Obviously, the relationship between the synoptic climatologies of ENSO versus non-ENSO events and early summer lightning activity needs further investigation.

TRENDS IN FIRE ACTIVITY

Unlike annual area burned and percentage of trees scarred, the total number of fires per year has no apparent relationship to ENSO. Simard et al. (1985a) also found no apparent relationship in the southeast.

In the southwest, annual number of fires has increased significantly, partly because fire detection has improved with time (Swetnam, in press). For example, in the early part of the century, four or five mounted rangers patrolled Gila National Forest and reported about 40 fires each year. Increase of personnel and the use of aircraft now accounts for detection of about 350 fires per year. Most of the additional fires detected were small (less than 0.25 acre [0.09 ha]). Notwithstanding, there is an increase in the number of large fires reported in southwestern forests. Considering only those fires greater than 10 acres (3.6 ha) in Gila National Forest, an average of five fires per year occurred between 1909 and 1939, compared with eleven fires per year from 1960 to 1980 (Swetnam, in press). Such fires would not have escaped the attention of even a few mounted rangers. The apparent increase in number of lightning-caused fires greater than 100 acres (35.9 ha) throughout Arizona and New Mexico (Figure 6) began in the late 1950s, when most of the technological advances and commitment of resources were already in effect.

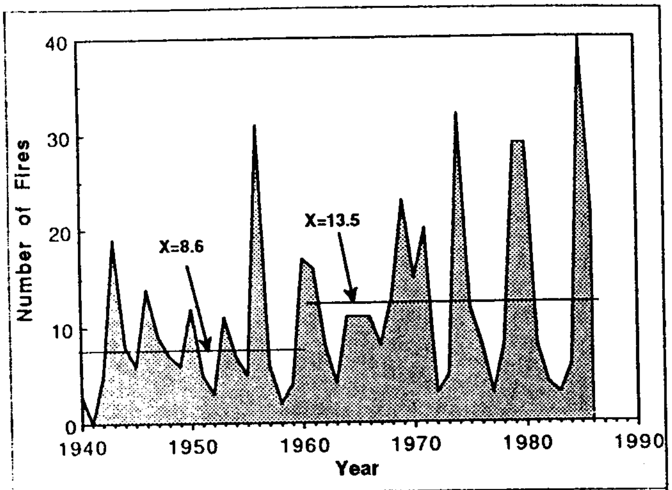

Figure 6. Annual number of lightning-caused fires with an area of more than 100 acres (35.9 ha) in Arizona and New Mexico (1940-1986). Fires allowed to burn under prescribed fire programs were excluded. The mean number of fires from 1940 to 1960 (8.6) was less than the mean from 1961 to 1986 (13.5) (p=0.064).

A climatic explanation for the increasing number of fires is unlikely; cool seasonal precipitation increased after the 1960s, partly in response to more frequent ENSO events. A greater number of large fires per year probably has its origin in fire suppression and increasing fuel loads. When fires are suppressed, dead fuel high in ether extractives continues to accumulate until it is released by fire. Also, without the thinning effect of frequent fires, dense and quite flammable stands of stunted ponderosa pine trees may develop in the understory of mature forests.

Suppression of small fires and greater flammability due to increased accumulation of both dead and live fuel shifts the fire regime from episodic surface burns to infrequent crown fires. Thus, fire regimes in ponderosa pine are becoming more like those in mixed-conifer and spruce/fir forests that consist of fire-susceptible and shade-tolerant trees.

Natural regeneration of ponderosa pine has slowed during the past 70 years (Schubert et al., 1970). This may portend profound changes in the structure and composition of southwestern forests in centuries to come. An interesting analog is the last ice age, when ponderosa pine was much reduced in range and dominance throughout the region. Explanations include a different seasonal distribution of rainfall (and possibly heavy grazing by animals now extinct) that favored a lower fire recurrence than during the Holocene (Betancourt and Van Devender, 1981).

CONCLUSIONS

Correlations comparable to those found for cool season precipitation exist between low values of the Southern Oscillation Index and reduced fire activity in the southwestern United States. The environmental factors responsible for this relationship are undetermined, but they may involve a decrease in the fuel load due to a wet winter and spring and/or the lack of lightning activity before the onset of the monsoon season. Successful forecasting of an El Niño (or La Niña) and its delayed teleconnections could improve fire readiness and scheduling of prescribed burning in the southwest.

Superimposed on the highly variable annual fire occurrence is a trend of increasing number of large fires since 1960. We attribute this trend to systematic fire suppression and the unnatural accumulation of fuel loads. Such manipulation of fire regimes, if they persist, could drive large-scale changes in the composition and structure of southwestern ponderosa pine forests.

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