Reports

Fire–Southern Oscillation Relations in the Southwestern United States

THOMAS W. SWETNAM* AND JULIO L. BETANCOURT

Fire scar and tree growth chronologies (1700 to 1905) and fire statistics (since 1905) from Arizona and New Mexico show that small areas burn after wet springs associated with the low phase of the Southern Oscillation (SO), whereas large areas burn after dry springs associated with the high phase of the SO. Through its synergistic influence on spring weather and fuel conditions, climatic variability in the tropical Pacific significantly influences vegetation dynamics in the southwestern United States. Synchrony of fire-free and severe fire years across diverse southwestern forests implies that climate forces fire regimes on a subcontinental scale; it also underscores the importance of exogenous factors in ecosystem dynamics.

WILDLAND FIRES ARE A SOURCE of economic loss and a fundamental ecological process that are apt to change with future climates. Sophisticated models have been developed to evaluate the influence of daily weather on fire behavior (*1*). However, the role of seasonal or longer term climate is less certain, as became apparent in the debate that followed the 1988 Yellowstone conflagrations (*2*). In ecological terms, a close linkage between fire and climate could diminish the importance of local processes, such as competition, predation, and stochastic variations, in the long-term dynamics of fire-prone ecosystems. The structure and diversity of such communities, which are regulated by fire frequency, extent, and intensity, may have nonequilibrial properties associated with decadal to secular variations in global climate. Successful prediction of vegetation change hinges on a better understanding of climatically driven disturbance regimes (*3*) and the relative contributions of regional versus local processes to community dynamics (*4*).

The southwestern United States is an ideal area for assessment of regional fire-climate patterns. Detailed meteorological records and fire statistics are available for extensive areas, and centuries-long climate and fire history proxies have been obtained from tree rings at many sites (Fig. 1). National Forests in this region lead the nation in average number of lightning fires and area burned by these fires each year (*5*). This vigorous fire regime ensues from an annual cycle of a variably wet cool season, a normally arid foresummer, and isolated lightning storms ushering the onset of the summer monsoonal rains. Lightning fires begin in the spring and peak in late June to early July and decrease significantly as the summer rainy season progresses. Interannual variations in fire activity probably derive from the influence of winter-spring precipitation on the accumulation and moisture content of the fuels. Annual ring growth in southwestern conifers is primarily a function of cool season moisture (*6*). Local surface burns are also recorded as fire scars in tree rings. Thus, tree-ring analysis allows simultaneous evaluation of the linkage between fire and climate.

During the 1982–1983 El Niño episode, arguably the most severe of this century, National Forests in the United States sustained little fire activity while millions of hectares burned in Indonesia (*7*) and Australia (*8*). Subsequently, a nationwide survey suggested that the relation between wildland fires and the El Niño–Southern Oscillation (ENSO) phenomenon is statistically significant only in the southeastern United States (*9*). However, this analysis relied on only 57 years of fire statistics and focused entirely on warm episodes in the tropical Pacific. In this report we evaluate the effects of both warm (El Niño) and cold (La Niña) episodes in a 300-year record of fire activity for the southwestern United States.

Teleconnections with the tropical Pacific are indicated by correlations between the Southern Oscillation index (SOI) (*10*) and rainfall over the Line Islands (LIRI) (*11*) against precipitation (*12–14*), streamflow (*15*), and tree growth (*16, 17*) in the American Southwest. During the high-SO phase (La Niña), when sea surface pressure is higher than normal in the Southeast Pacific, the central Pacific cools anomalously and the Intertropical convergence zone (ITCZ) and South Pacific convergence zone (SPCZ) diverge on either side of the equator, the latter bringing abundant rains to Indonesia and eastern Australia. During the low-SO phase, when sea surface pressure is lower than normal over Tahiti, the central Pacific warms, the ITCZ and SPCZ converge on the equator, and the zone of deep convection shifts eastward to the Line Islands in the central Pacific, where tropospheric dis-

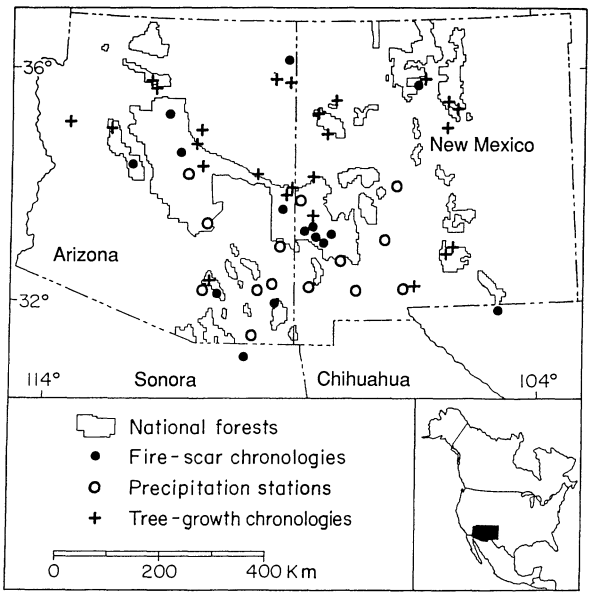

Fig. 1. Map of southwestern United States showing National Forest boundaries and locations of precipitation stations, fire scar, and tree growth chronologies used in the study.

T. W. Swetnam, Laboratory of Tree-Ring Research, University of Arizona, Tucson, AZ 85721.
J. L. Betancourt, U.S. Geological Survey, 1675 West Anklam Road, Tucson, AZ 85705.

*To whom correspondence should be addressed.

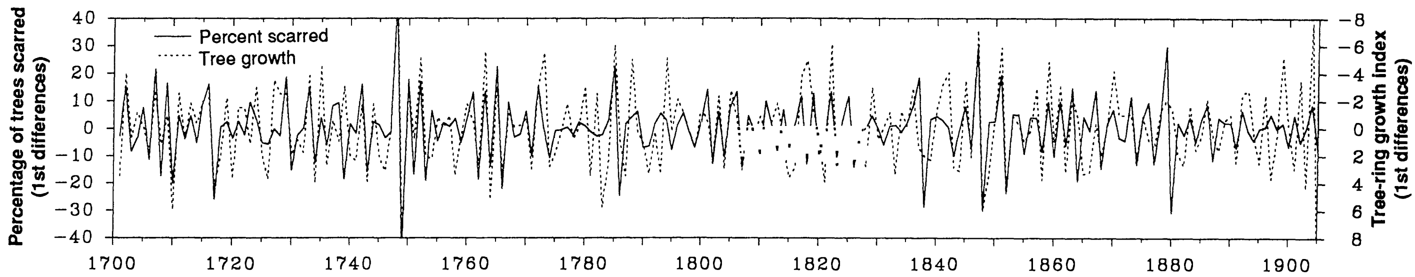

Fig. 2. Time series of percentage of trees scarred and tree ring growth in Arizona and New Mexico. First differences [value (year t) − value (year $t-1$)] were computed to emphasize year-to-year changes and deemphasize trends in the data. Spearman rank correlation for the period 1700 to 1905 is 0.551 ($P < 0.001$).

turbances then propagate to extratropical regions. Northern winter (December to February, DJF) values of SOI are preferred for studying teleconnections because this is the season when the maximum pressure anomalies occur; precipitation surges or deficiencies over the Line Islands are most persistent from August through February. During the low-SO phase (abundant rainfall over the Line Islands), warm waters in the eastern Pacific provide the necessary energy for development of west coast troughs and weaken the tradewind inversion. This situation enhances interaction between tropical and temperate weather systems, and thus more moist air penetrates into the southwestern United States during fall and spring (*11, 18*).

To examine long-term relations between climate and fire in the southwestern United States, we compiled regional values for tree-ring growth (*19*) from Douglas-fir (*Pseudotsuga menziesii*), ponderosa pine (*Pinus ponderosa*), and Colorado pinyon pine (*Pinus edulis*) growing at 28 sites in Arizona and New Mexico (Fig. 1). These data explain at least 50% of the variance in water-year (October to September) precipitation (*6, 19*); the largest response is in autumn and spring, the two seasons with the strongest teleconnections to the tropical Pacific (*11*). We developed an independent fire scar index from 315 ponderosa pine, southwestern white pine (*Pinus strobiformis*), and Douglas-fir growing at 15 sites throughout Arizona, New Mexico, west Texas, and northern Mexico (Fig. 1). Annual rings were cross-dated and position of fire scars in annual rings were noted in full or partial cross sections (*20*). A regional fire scar index was computed by averaging percentages of trees scarred per year at each site. The record was terminated in 1905 because of the lack of fire scars in the 20th century. Episodic surface burns that injure but do not kill mature trees have dwindled with cessation of aboriginal fires, removal of fine fuels by livestock grazing, and a vigorous program of fire suppression.

Figure 2 shows a correspondence between first differences of standardized regional tree growth and percentage of trees scarred from 1700 to 1905; climatic conditions that favor tree growth suppress fires, whereas reduced growth coincides with extensive fires. This relation is partially out of phase from approximately 1780 to 1820 and 1880 to 1905, when reconstructed values of SOI attain the lowest amplitudes and El Niño episodes appear to have happened least frequently (*17*). The strength of global teleconnections apparently depends on the amplitude of the SO (*21*).

An SO signal should be expected in the tree-growth chronologies because precipitation in the fall and spring before the growing season exerts the strongest influence on cambial growth in Douglas-fir and ponderosa pine. Negative correlations have been reported between tree growth in the southwestern United States and the SOI, that is, tree growth is enhanced during El Niño conditions (*16, 17*). A SO signal should also be obtainable in the fire scar record if moisture conditions during spring are a primary factor in the synchroneity of regional fires. The comparison in Fig. 3 suggests that, in general, this is the case. Archival evidence from Peru (*22*) indicates that 8 of the 10 years that failed to produce any fire scars were El Niño events of strong or moderate intensity.

Similar results were obtained in a comparison of total area burned in National Forests of Arizona and New Mexico since 1905 (*23*) with regional precipitation, DJF-SOI, and LIRI. A low signal-to-noise ratio was anticipated because the fire statistics include both

Table 1. Associations among December through February Southern Oscillation index (DJF-SOI), percentage of normal August through February precipitation in the Line Islands (LIRI), spring (March through May) precipitation, and fire activity in Arizona (AZ) and New Mexico (NM), as measured by the logarithm of area burned (both person- and lightning-caused fires). The pre-1915 and post-1960 periods were omitted for some comparisons to eliminate the overriding effect of exceptional fires that occurred in 1910 to 1912 after several fire-free decades (*33*) and increasing numbers of person-caused fires after 1960. Values are Spearman rank correlation; probabilities are given in parentheses.

	Log. area burned 1905 to 1985	AZ-NM spring precipitation 1899 to 1985	LIRI 1905 to 1983
DJF-SOI			
1899 to 1985	0.339 (0.002)	−0.416 (<0.001)	−0.773 (<0.001)
1915 to 1960	0.398 (<0.001)	−0.402 (<0.001)	−0.783 (<0.001)
1961 to 1985	0.398 0.464* (<0.001)	−0.402 (<0.001)	−0.783 (<0.001)
LIRI			
1905 to 1983	−0.450 (<0.001)	0.522 (<0.001)	
1915 to 1960	−0.464 (<0.001)	0.554 (<0.001)	
1961 to 1983	−0.446 −0.479* (<0.001)	0.554 (<0.001)	
AZ-NM spring precipitation			
1899 to 1985	−0.304 (0.006)		
1915 to 1960	−0.407 (<0.001)		
1961 to 1985	−0.407 −0.412* (<0.001)		

*Lightning-caused fires only.

lightning and person-caused fires across a wide range of vegetation types from grassland to boreal forests, each subject to different land use and management practices. However, total area burned closely tracks DJF-SOI and LIRI until the 1960s (Fig. 4 and Table 1), when area burned increased and became less variable, possibly because there was an increased number of person-caused fires or because fire suppression resulted in unusual accumulation of fuels. Spring (March through May) precipitation yielded the highest correlations of any season against both area burned and the Southern Oscillation.

Regional climate effects are implicit in the extreme variability of fire occurrence measured by both the fire scar record and fire statistics. In general, area burned was greatest during years with highly positive values of SOI, reduced rainfall in the Line Islands, and severe winter-spring droughts (1934, 1946, 1956, 1971, and 1974). Area burned was reduced after exceptionally wet springs of low-SO phases or El Niño years (1926, 1941, and 1958). Climatic effects are also evident in the general occurrence of narrow rings during years when more than one-fourth of the trees were scarred by fire (1716, 1748, 1785, 1837, 1847, 1851, and 1879). We have no basis for calibrating the fire scar index to area burned because the fire scar record is unreliable for the 20th century. Fire magnitudes in 1748, when more than 40% of the trees registered fire scars, happened under a different set of ecological circumstances than now exist. Such widespread fires, but of greater intensity, may become more probable as fuel accumulates with continued fire suppression, increasing the chances for rapid and pervasive ecological changes.

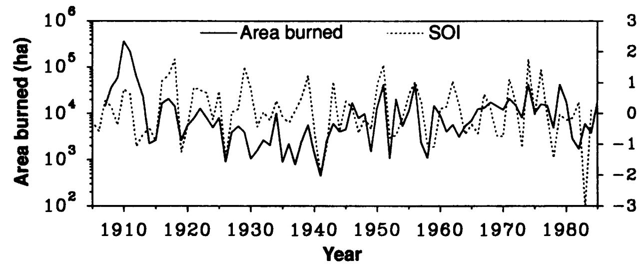

Fig. 4. Time series of annual area burned (logarithm) in Arizona and New Mexico and mean December through February SOI, 1905 to 1985.

Fire suppression has been partly responsible for rapid conversion of grasslands to shrublands in Arizona and New Mexico. Heavy ecological impacts also can be expected in ponderosa pine forests, a widespread vegetation type that is synonymous with watershed and the timber industry in the Rio Grande and Colorado river basins. Low-intensity surface fires eliminate understory reproduction and encourage seedling establishment in forest openings. The result is an uneven-aged forest in which trees grow in even-aged groups (*24*). With fire exclusion, dead fuels accumulate continuously, and dense thickets of suppressed trees invade open stands of ponderosa pine. Near continuous fuels from understory to canopy produce the laddering effect commonly seen in catastrophic crown fires. Thus, fire regimes in ponderosa pine forests have shifted from frequent (2- to 10-year interval) surface fires in early historic times to stand-replacing fires in the modern era. Continued fire suppression could lead to large-scale changes in stand structure and composition, as might already be evident in successional changes to more shade-tolerant trees since the turn of the century (*25*). An interesting analog is the distribution of species during the last ice age, when ponderosa pine was much reduced in range and dominance and less fire-resistant conifers were widespread. The scarcity of ponderosa pine forests in the Southwest during the last glacial period has been attributed to (i) a different rainfall seasonality and (ii) the effects of heavy grazing by animals now extinct, favoring a lower fire recurrence than during the Holocene (*26*).

Even with changing vegetation dynamics due to human intervention, the fire-SO linkage could have forecasting value and thus important implications for fire management. Both statistical (*27*) and dynamical models (*28*) are now being developed to predict the behavior of the SO, which leads Arizona and New Mexico weather by one or more seasons. Extensive fires (~28,000 ha) in early summer of 1989 followed a dry winter and spring associated with an unusually cold episode in the tropical Pacific (La Niña), which might have been predicted from zonal wind and sea surface temperature anomalies in the tropical Pacific in fall 1988 or earlier. The fire-SO relation appears to be strongest during extreme phases of the SOI. Any skill in forecasting fire hazard, however, will be constrained to the 30 to 35% of the annual fire variance explained by indices of the Southern Oscillation.

Synchronous large fires in the Southwest over three centuries, and their association with the high-SO phase, deficient spring precipitation, and reduced tree growth, imply that seasonal climate, and not just fire weather, determines burning of vegetation on a subcontinental scale. If southwestern landscapes are to be regarded as a mosaic of patches recovering from disturbance, as specified in the current paradigm (*29*), then our analyses of these patches must match the spatial and temporal scales of fire as an ecological process.

Similar long-term records for other areas may prove useful in identifying the significant climatologies associated with catastrophic fires, such as those at Yellowstone National Park (~570,000 ha) in September 1988 (*2*) and across Siberia and Mongolia (~7 million ha) in May 1987 (*30*). By injecting greenhouse gases and aerosols into the midlatitude troposphere, such fires can affect both local (*31*) and global (*32*) climates. A global perspective will require better understanding of the linkage between fire and large-scale features of the climate system such as the SO.

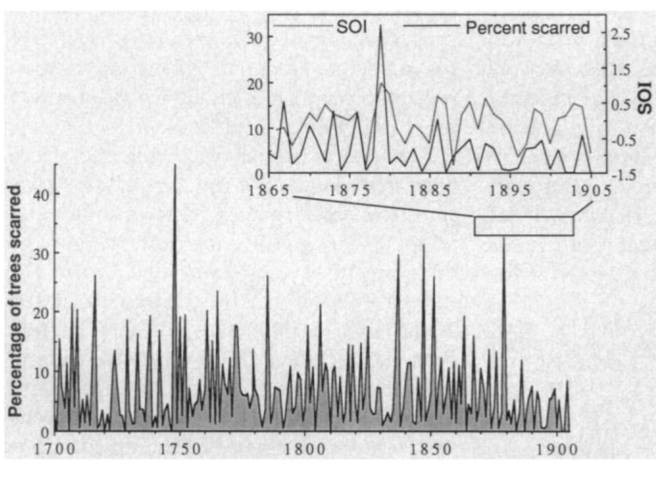

Fig. 3. Time series of the percentage of trees scarred per year in Arizona and New Mexico. The Spearman rank correlation with annual SOI between 1866 and 1905 is 0.468 ($P = 0.002$).

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Triassic Vertebrates of Gondwanan Aspect from the Richmond Basin of Virginia

HANS-DIETER SUES* AND PAUL E. OLSEN

A new locality of early Late Triassic age in the Richmond basin of east-central Virginia has yielded abundant remains of a diversified assemblage of small to medium-sized tetrapods that closely resembles Southern Hemisphere (Gondwanan) assemblages in the predominance of certain synapsids. Associated palynomorphs indicate an early middle Carnian age for the fossiliferous strata. The discovery suggests that previously recognized differences between tetrapod assemblages of early Late Triassic age from Gondwana and Laurasia at least in part reflect differences in stratigraphic age, rather than geographic separation.

DURING THE TRIASSIC, SYNAPSID-dominated assemblages of terrestrial vertebrates, persisting from the late Paleozoic, gave way to the archosaur-dominated assemblages that came to characterize the Age of Reptiles. Despite the importance of this profound change in the structure of continental ecosystems, many details of the faunal succession during the early Mesozoic remain unresolved. The transition from the Middle to the Late Triassic is particularly poorly understood. Recent claims of a mass-extinction event among tetrapods at the Carnian-Norian boundary in the Late Triassic (*1*) probably reflect, at least to some extent, an apparent temporal discontinuity between the geographically disjunct Middle Triassic synapsid-dominated assemblages of Gondwana and the classic archosaur-dominated communities from the Upper Triassic of Laurasia. Discovery of tetrapods of early Late Triassic age in strata of the Newark Supergroup in Virginia sheds new light on this longstanding problem.

The Richmond basin (Fig. 1), located in east-central Virginia, about 19 km west of Richmond, is a half-graben that is surrounded by igneous and metamorphic rocks of the Piedmont Province. It is part of a system of rift-basins along the eastern margin of North America that formed during a 45-million-year episode of crustal thinning and stretching preceding the Jurassic breakup of Pangaea. The strata deposited in these rift-basins are collectively referred to as the Newark Supergroup (*2*). The Richmond basin and the neighboring Taylorsville basin contain the oldest sedimentary rocks of the Newark Supergroup currently known south of Nova Scotia (*2, 3*). The Richmond basin is also one of the geologically most poorly understood basins of the Newark Supergroup because exposures of strata are scarce and the region is characterized by deep and intense weathering. The Richmond and the adjacent Taylorsville basins differ from other basins of the Newark Supergroup in the predominance of gray and black lacustrine to paludal sedimentary rocks, rather than red and brown playa and fluvial sedimentary rocks (*2, 3*).

Tetrapod material was collected from what was originally a small roadside exposure near Midlothian, Chesterfield County, Virginia. In view of its close geographic proximity to Little Tomahawk Creek, the site will henceforth be referred to as the Tomahawk locality. Most of the tetrapod bones and teeth occur in a massive calcareous gray mudstone with root traces, abundant coalified plant debris, and numerous small calcareous nodules. The mudstone is

H.-D. Sues, Department of Paleobiology, National Museum of Natural History, Washington, DC 20560.
P. E. Olsen, Lamont-Doherty Geological Observatory, Columbia University, Palisades, NY 10964.

*To whom correspondence should be addressed.