RECONSTRUCTION OF PRECIPITATION AND PDSI FROM TREE-RING CHRONOLOGIES DEVELOPED IN MOUNTAINS OF NEW MEXICO, USA AND SONORA, MEXICO

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Long quantitative records of year-by-year meteorological observations are limited or nonexistent in the southwestern United States and northern Mexico. Such records are invaluable to researchers studying paleoclimate dynamics and forcing functions that influence the climate system.

Trees store information on their annual rings about climates and their effects on the structure and composition of local forest ecosystems. Therefore, tree rings have been used as sources of information to investigate the role of natural and anthropogenic disturbances as well as environmental history as recorded by trees.

The ability to assign actual calendar dates to each ring of certain tree species allows for studies of the yearly climatic conditions necessary for growth. By comparing patterns of growth of climatically sensitive trees with patterns of environmental conditions for the same years, a reconstruction may be derived and applied to past years for which written records of environmental conditions do not exist (Fritts 1976; Conkey 1979).

Given the importance of understanding the influence of climate on forest dynamics, the objectives of this study were to use tree-ring series as proxy data for precipitation and PDSI reconstruction, and to assess the role of climate and land-use practices on forest dynamics.

Background of the Animas Mountains and the Sierra los Ajos

The Animas Mountains are located in southwestern New Mexico (31°35'N latitude, 108°47'W longitude). The highest peak rises to 2600 m, and the mountains cover an area of 100 sq m on the Gray Ranch in southern Hidalgo County (Wagner 1977). The Animas Mountains were formed by regional uplift and widespread volcanic activity during the Tertiary. During the Cretaceous, basalt rock was erupted, followed by granodiorite rock. In the late Tertiary volcanic activity was renewed with eruptions of rhyolite, tuffs, and basalt (Arras 1979; Stone and O'Brian 1990; Wagner 1977).

The Sierra los Ajos are located in Sonora, Mexico (30°55'N latitude, 109°55'W longitude), about 100 km southwest of the Animas Mountains. The main peak rises above 2600 m (COTECOCA 1973) (Figure 1). The Sierra los Ajos comprise a complex geologic formation characterized by a heterogeneous lithic composition. Outcrops from Precambrian and Holocene age are found in these mountains (Aponte 1974).

Both areas are characterized by dissected topography. Rocky to shallow soils are typical (Soil Conservation Service 1973; Garza-Salazar 1993). The Animas Mountains and Sierra los Ajos both have a bimodal precipitation pattern with about 60 percent of the average annual precipitation (450–750 mm depending on elevation) falling in July–September and 40 percent occurring in the winter months. Temperatures above 32°C are common during the summer months and usually range between 12°C and -5°C during the winter months. An average evaporation of 2340 mm can be expected for both mountain ranges (Tonne et al. 1992; Solis-Garza et al. 1993).

Few major drainages in the Animas Mountains extend beyond the edges of the mountains and they rarely carry water. Little permanent water is available with the exception of springs located in canyon bottoms and the lower parts of the mountains (Hubbard 1977; Wagner 1977; Fish and Wildlife Service 1989).

The Sierra los Ajos is part of three important watersheds: the Rio Sonora, the San Pedro, and the Bavispe. Streams rising in the Sierra los Ajos contribute to three major systems: the northward-flowing Rio San Pedro, the southward-flowing Rio Sonora, and the Rio Yaqui (Fishbein et al. 1995). Some of the intermittent or perennial flows rarely reach the major rivers of the valleys. The volume of water produced is important for some rivers of

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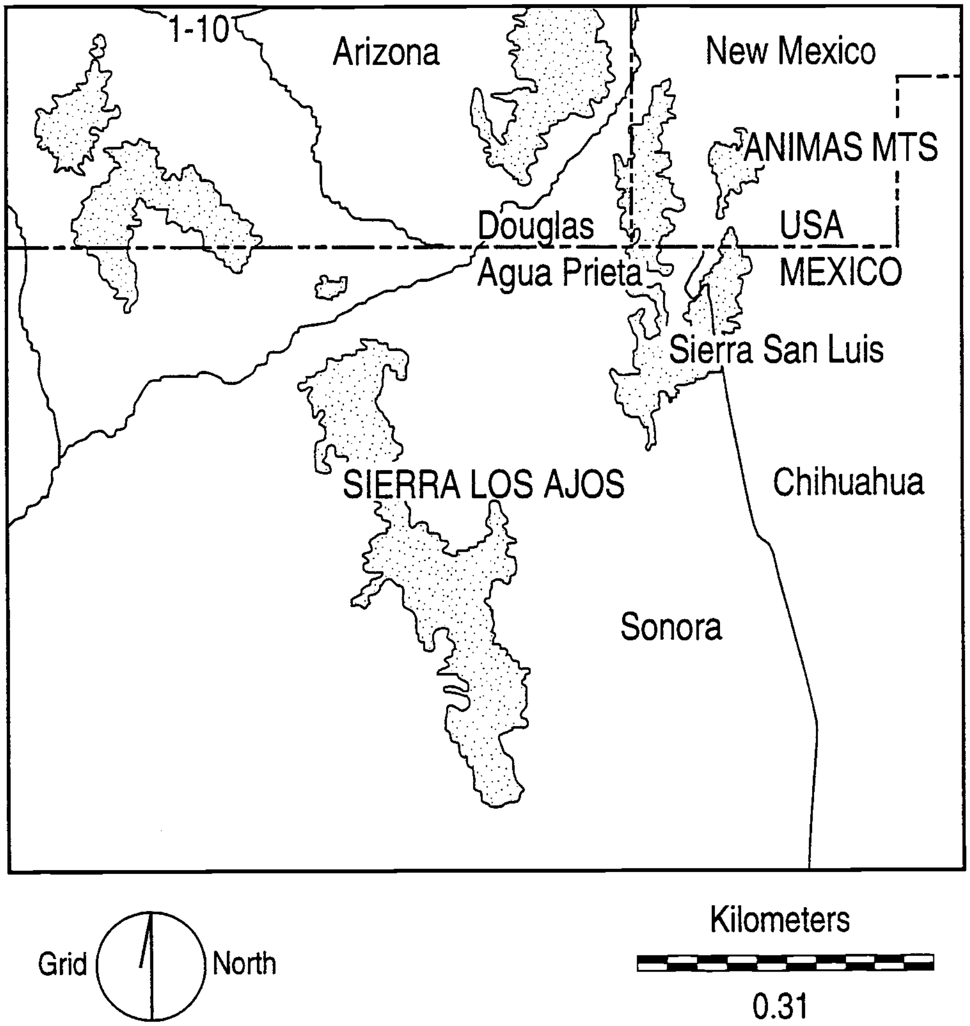

Figure 1. Geographical location of the Animas Mountains, New Mexico and the Sierra los Ajos, Sonora.

the region, such as the Rio Sonora, whose water is used for irrigation purposes in adjacent areas along the river. Some water of this river is confined in larger dams and later released for human use in cities, such as Hermosillo. Important riparian communities have been established along streams coming from the Sierra los Ajos.

The proximity of both the Animas Mountains and Sierra los Ajos to the Sierra Madre and the southern Rocky Mountains has resulted in a floristically diverse vegetation comprised of both northern and southern elements (Wagner 1977; Brown 1982; Fishbein et al. 1995).

Wagner (1977) categorized the vegetation of the Animas Mountains main massif into three basic types: lower encinal, upper encinal, and forests. The forest community is found between 1980 and 2600 m elevation (Hubbard 1977). Some of the major species present in this vegetation type are Douglas-fir (*Pseudotsuga menziesii*), found in canyons and on ridges of the northern portion of the mountain, and mixed with this species are southwestern white pine (*Pinus strobiformis*), ponderosa pine (*Pinus ponderosa* var. *Arizonica*), and Chihuahuan pine (*Pinus leiophylla* var. *chihuahuana*).

The mixed pine forest is found between 2300 and 2600 m elevation and is composed of ponderosa pine, southwestern white pine, Chihuahuan pine, and Apache pine (*Pinus engelmannii*) (Wagner 1977).

The pinyon pine-juniper woodland is found between 2300 and 2450 m and is composed of pinyon pine (*Pinus discolor*), alligator juniper (*Juniperus deppeana*), and oaks (*Quercus* spp.).

The Sierra los Ajos supports biotic communities classified as mixed conifer forest, montane meadows, montane chaparral, oak woodland, and riparian forest (Garza Salazar 1993; Fishbein et al. 1995). The mixed conifer forest is restricted to north-facing slopes between 1900 and 2600 m in elevation. Northern aspects are dominated by Douglas-fir, associated with Gambel oak (*Quercus gambelii*) and madroño (*Arbutus arizonica*).

Methods

Permanent plots were established in each of four representative stands of forest communities in both mountain ranges, during 1992 and 1993. Increment cores were extracted from living trees. Cores were prepared and dated following standard dendrochronological techniques (Stokes and Smiley 1968; Swetnam et al. 1985).

To assign each tree to its exact year of formation, skeleton plots for each core were constructed and crossdated with a composite skeleton plot developed from Douglas-fir and ponderosa pine cores collected in each of the mountain ranges. Crossdating was verified and corrected with COFECHA (Holmes 1994).

The program ARSTAN (Cook 1985; Holmes 1994) was used to remove nonclimatic autocorrelation from each ring series. Standardization of tree-ring measurement series is necessary to remove growth trends produced by normal physiological tree aging, the effects of varying site productivity among different trees, and changes in the tree's environment that are unrelated to climate (Fritts 1976). Linear or negative-exponential single detrending was chosen to find the best fit for each series. Straight-line and negative-exponential methods are conservative in removing only monotonic trends. An index of tree growth for any year was obtained by dividing the actual ring width by that predicted from the curve. Relationships between tree-ring index chronologies and climate were investigated using response-function and correlation analysis (Fritts 1976; Guiot et al. 1982). To define those months or seasons in which precipitation and PDSI were significantly correlated with tree growth, regional climatic data developed for NOAA climatic divisions 09 and 07 for southwestern New Mexico and southeastern Arizona respectively over the period 1896–1993 were considered. Monthly total precipitation was seasonalized for the previous and current year seasons, since the tree integrates the effects of favorable or poor conditions over more than one growing season (Fritts 1976). Monthly PDSI, which integrates precipitation, temperature, soil conditions, sunlight duration, and geographic area into one drought index (Palmer 1965; Karl 1986), was also correlated with ring-width index.

To obtain transfer functions that predicted precipitation and PDSI as functions of tree growth, calibration equations were developed from the tree-ring index chronologies on subperiods (1896–1930 and 1931–1993) using least-square analysis. Calibrated equations were verified by testing performance on the subperiod withheld during calibration. The roles of the two subperiods were then reversed, and the model was calibrated with the subperiod. Predicted climate values were compared to actual climate values using well-established statistics (i.e., correlation analysis, reduction of error tests, nonparametric sign tests, and the product mean test) to determine how near the predicted values were to the actual climate values for the historical period (Fritts 1991).

Since the calibration-verification procedure for both subperiods proved to be a robust estimator of climate, the whole period (1896–1993) was considered to develop a new linear regression equation to reconstruct the selected climatic variables for the entire length of the tree-ring chronology. The use of the complete data period maximizes the number of observations, thus increasing the degrees of freedom for the final regression equation.

Short-term trends in climatic conditions between mountain ranges were analyzed. We fit 10-year smoothing splines through the reconstructed time series. Decadal-length climate episodes may indicate above and below normal climate periods (with respect to the reconstructed mean) that may then be related to stand dynamic processes (e.g., seedling recruitment, rate of tree growth, forest structure and composition, fire frequency).

Periods of above or below normal climate (precipitation and PDSI) were compared to other climate reconstructions generated for the southwestern United States in order to analyze the effect of a regional climate signal on tree growth.

The influences of climate and land-use practices (fire suppression, grazing, logging) were related to the establishment and growth of trees in both mountain ranges.

Results and Discussion

Correlation and response-function analysis for the Animas Mountains chronology indicated a significant response to winter precipitation extending from the previous October to the current January. The variance explained by seasonal precipitation was only 38.5 percent, which was greater than values obtained for other seasonalized periods.

The Sierra los Ajos seasonalized precipitation for previous July to current July explained 36 percent of the variance in cambial growth. A similar seasonal period for reconstruction of precipitation for northern New Mexico was used by Rose et al. (1981) and Grissino-Mayer (1995).

The amount of variance explained by the chronologies for these mountain ranges was relatively low compared to other chronologies developed in the southwestern region (e.g., El Malpais Long chronology in New Mexico, 57.4%; Jemez Mountains chronology in New Mexico, 63%) (Grissino-Mayer 1995; Touchan and Swetnam 1995). Differences in variance accounted for could be attributed to the lack of suitable meteorological data to relate tree growth and climatic variables, differences in land-use history for compared mountain ranges, or difference in length between chronologies.

Current July PDSI was significantly correlated with tree growth for both mountain ranges. In the Animas Mountains, cambial growth explained 41 percent of the variance in current July PDSI, whereas in the Sierra los Ajos, 45.2 percent of the variance was explained. Other studies in the southwestern United States have demonstrated that PDSI is usually associated with tree growth during the months of June, July, and August (Baisan and Swetnam 1990; Swetnam and Baisan, in press). As indicated by PDSI values, July apparently was the month during which availability of water was more limiting to cambial growth.

Calibration and verification models on subsets of years indicated that precipitation and PDSI reliably predicted tree growth in both mountain ranges. Therefore, new calibration models were developed for the entire period containing climatic data (1896–1993). We used these calibration models to estimate PDSI and precipitation in the Animas Mountains for the period 1760–1992, and PDSI and precipitation for the Sierra los Ajos for the period 1838–1992. Comparisons between actual and reconstructed data confirmed that the calibration models adequately simulated high frequency variability for both precipitation and PDSI in both mountain ranges (Figure 2).

Reconstructions revealed decadal trends in precipitation during the last 250 years at the Animas Mountains (Figure 3). Above-normal precipitation occurred during the periods 1783–1788, 1790–1800, 1849–1852, 1876–1880, 1905–1908, 1918–1933, and 1975–1992. Since 1900, above-normal precipitation has been related to El Niño episodes (i.e., 1915, 1919, 1926, 1958, 1983, and 1993), or decades of frequent El Niño events and expanded circumpolar vortex (1900–1930 and 1960–1993). The latter event is characterized by greater precipitation in fall, winter, and spring, with slightly reduced rainfall during the summer (Andrade and Sellers 1988; Betancourt et al. 1993). Below-normal precipitation occurs during La Niña events (i.e., 1904, 1917, 1925, 1943, 1950, 1955, 1974, and 1989) or decades when the circumpolar vortex contracts (Betancourt at al. 1993). Short-term periods of below-normal precipitation occurred during 1807–1813, 1817–1825, 1899–1904, 1934–1939, and 1947–1957. Some of these episodes have been detected in other southwestern precipitation reconstructions (D'Arrigo and Jacoby 1992; Fritts 1991; Grissino-Mayer 1995; Touchan and Swetnam 1995).

Reconstruction of annual precipitation in the Sierra los Ajos for the last 155 years indicated the presence of dry and wet episodes, coinciding with similar periods in the Animas Mountains and other southwestern United States precipitation reconstructions. Above-normal precipitation (425–457 mm) occurred during 1844–1849, 1856–1864, 1905–1924, and 1975–1991. Below normal precipitation was recorded for the periods 1839–1843, 1863–1864, 1871–1873, 1880–1890, 1899–1904, and 1946–1957.

Reconstructed July PDSI demonstrated a similar trend in both mountain ranges (Figure 4). In general, reconstructed PDSI revealed wet and dry spells that were matched with similar periods recorded by the reconstructed precipitation.

Before the 1900s seedling recruitment of Douglas-fir in the Animas Mountains apparently was enhanced by the presence of fires followed by above-normal precipitation. A similar pattern was observed for establishment of pines in the Sierra los Ajos, where the presence of fires followed by above-normal precipitation periods favored increased establishment of ponderosa pine seedlings. After the 1900s, increased establishment of Douglas-fir seedlings in the Animas Mountains may be attributed to a fire-suppression policy coupled with favorable climatic conditions.

The Sierra los Ajos has not experienced fire suppression, and the relationship between fire, precipitation, and seedling establishment has not changed, as evidenced by the age class distribution (Figure 5). The virtual absence of old ponderosa pine trees in the Sierra los Ajos could be attributed to logging activities but probably not to the effects of fires: ponderosa pine trees are very fire tolerant (Wright and Bailey 1982), and many individuals have survived several fires in this study.

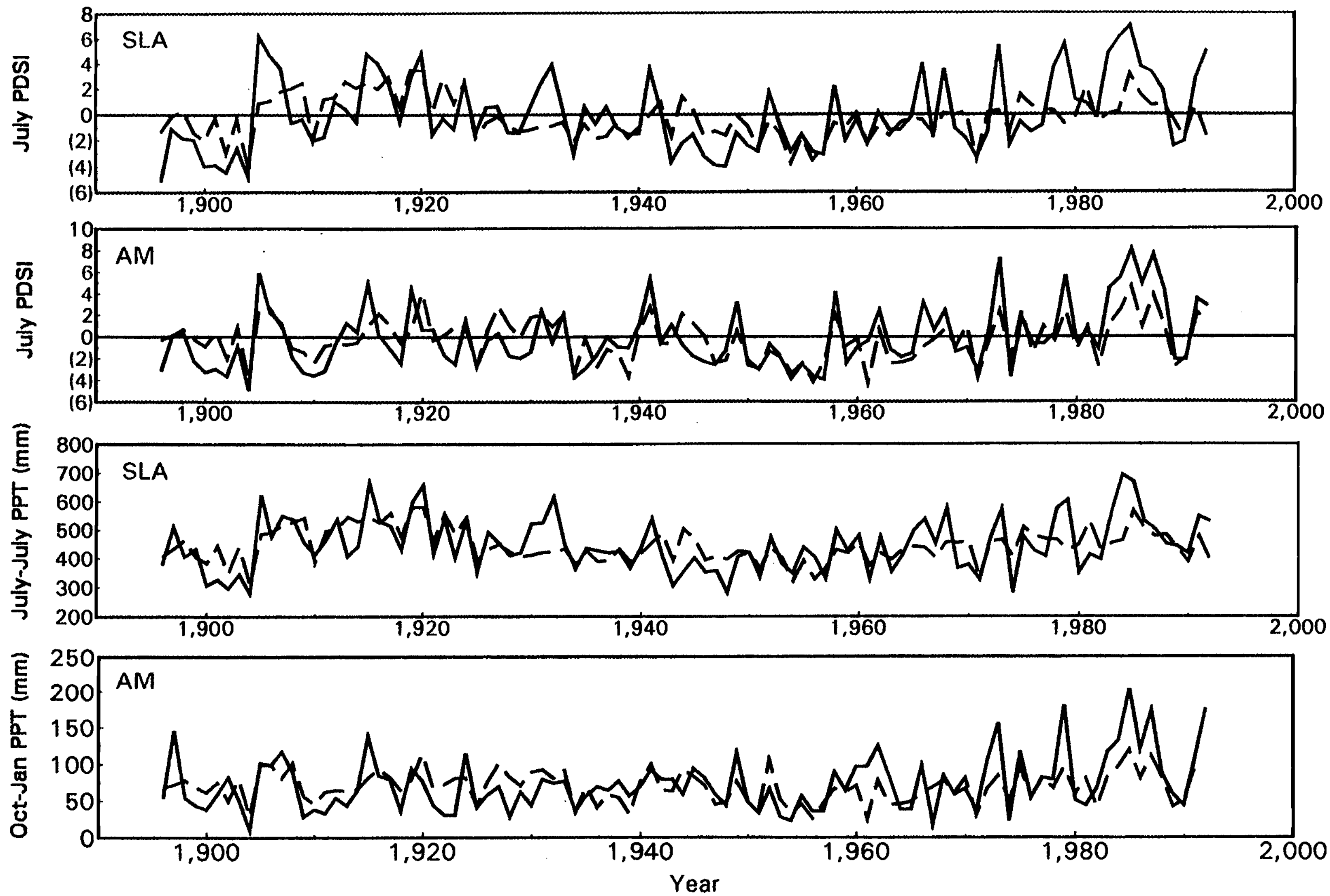

Figure 2. Comparisons between actual (solid line) and reconstructed (dashed line) precipitation and PDSI for the Animas Mountains, New Mexico and the Sierra los Ajos, Sonora, Mexico.

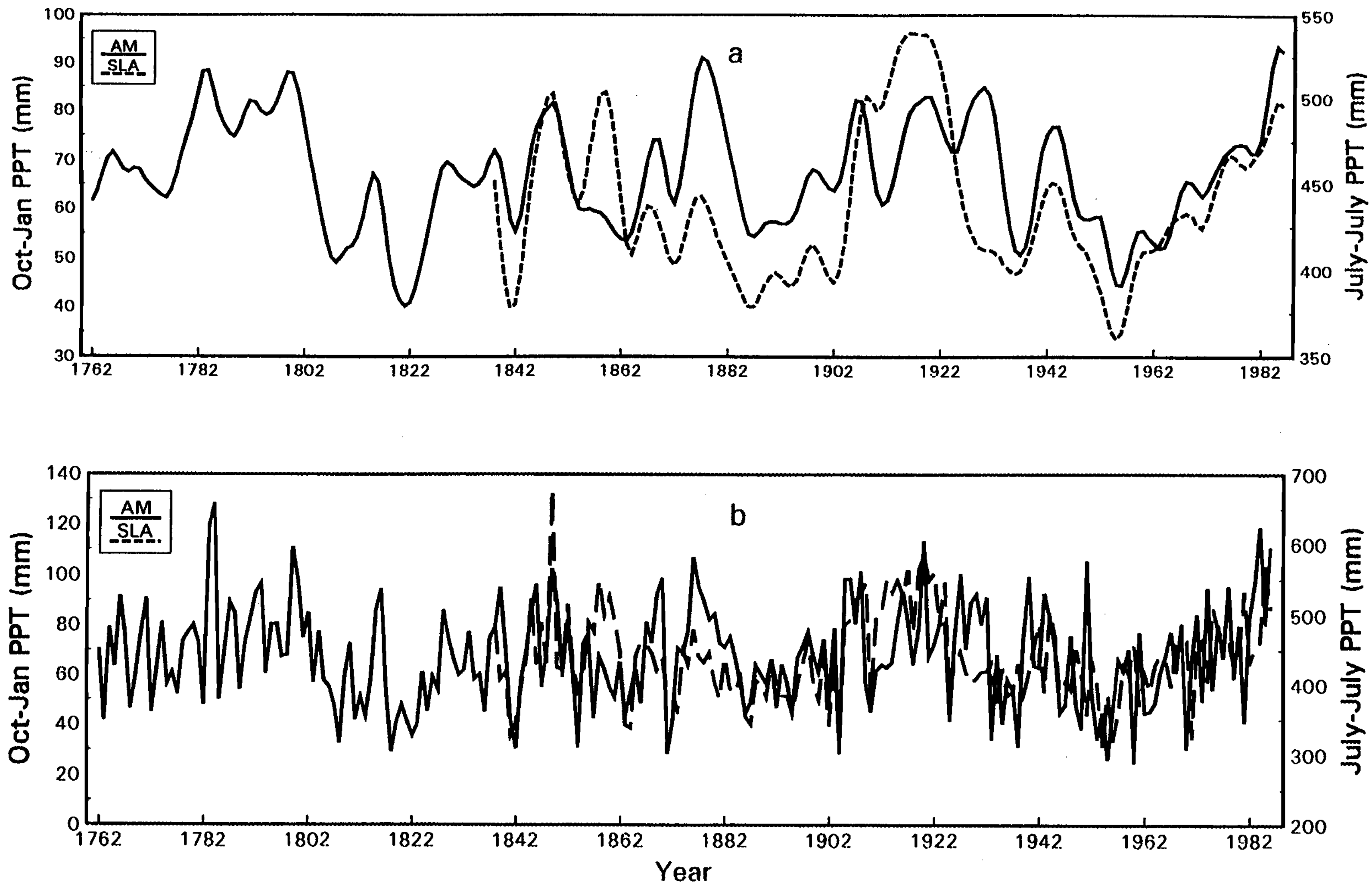

Figure 3. Reconstructed precipitation for mountain ranges using 10-year spline to emphasize decadal-scale precipitation differences (a) and annual precipitation fluctuations (b).

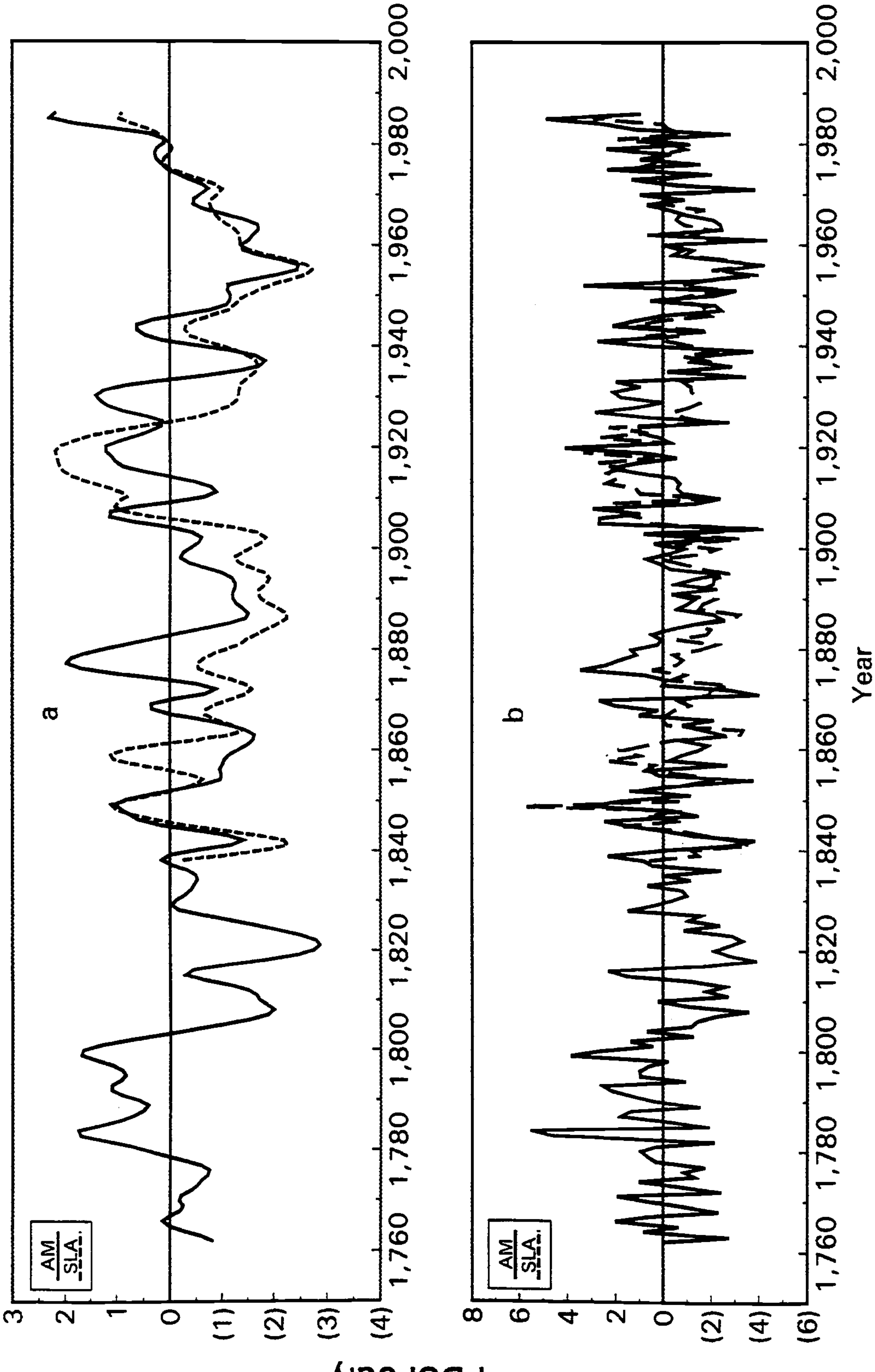

Figure 4. Reconstructed PDSI for mountain ranges using 10-year spline to emphasize decadal-scale PDSI differences (a) and annual PDSI fluctuations (b).

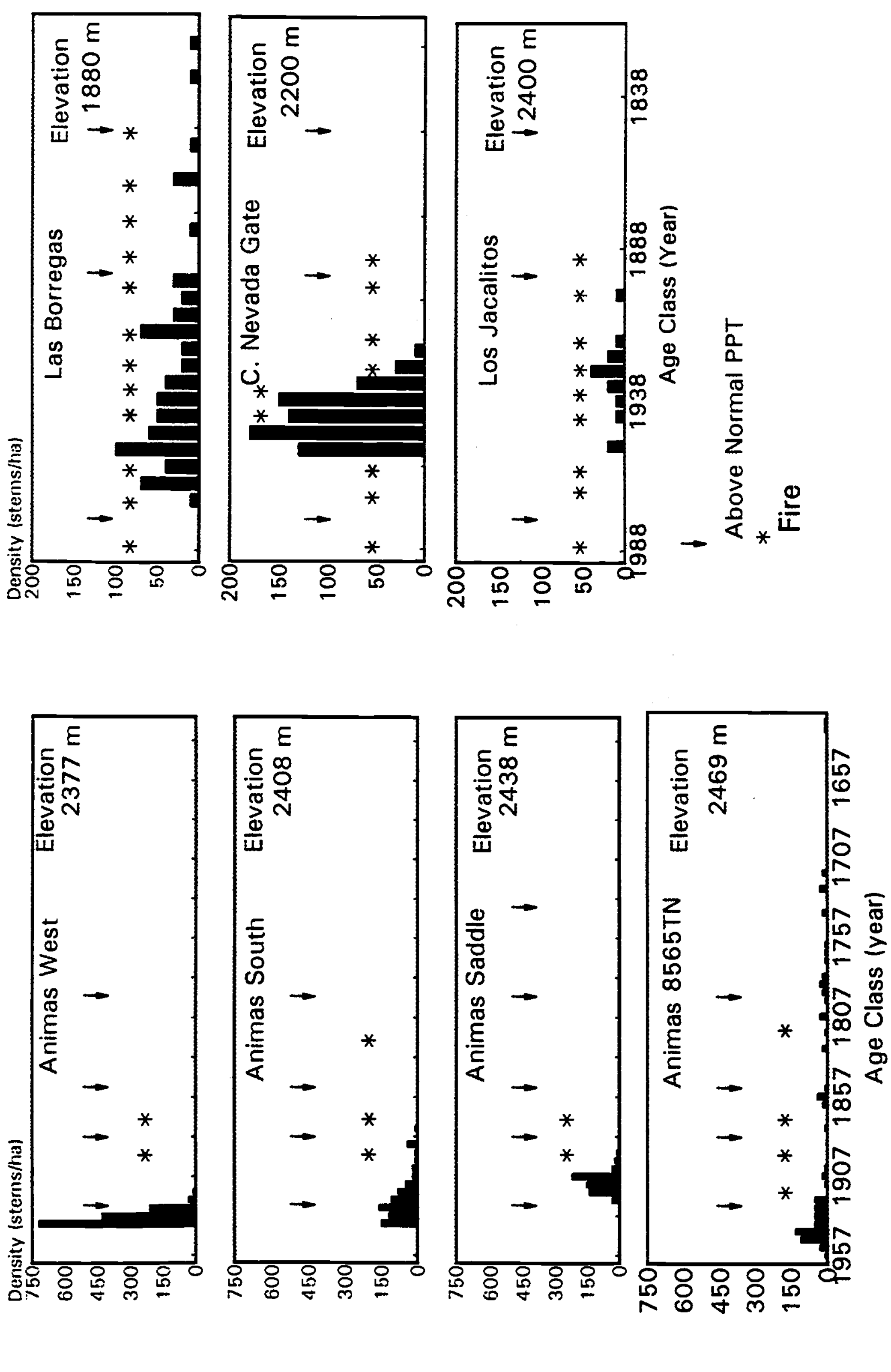

Figure 5. Relationship between fire frequency, precipitation, and establishment dates of Douglas-fir trees in the Animas Mountains, New Mexico and ponderosa pine trees in the Sierra los Ajos, Sonora.

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