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Fire–rainfall relationships in Argentine Chaco savannas

S. Bravo[a,*], C. Kunst[b], R. Grau[c], E. Aráoz[c]

[a] Cátedra de Botánica, Facultad de Ciencias Forestales, Universidad Nacional de Santiago del Estero, Avenida Belgrano 1912 (S), CP 4200 Santiago del Estero, Argentina
[b] Instituto Nacional de Tecnología Agropecuaria, Jujuy 850, CP 4200 Santiago del Estero, Argentina
[c] CONICET, Laboratorio de Investigaciones Ecológicas de la Yungas, Tucumán, Argentina

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ABSTRACT

We used dendroecological techniques to date fire scars in woody species growing in a subtropical savanna of the Argentine Chaco dry forests, and to explore the temporal trends of fire with rainfall variability at different temporal scales during the 20th century. Eight sampling sites were located along an ecotone between savanna and a dry forest, and a composite chronology was developed for a savanna, based on a total of 21 fire dates. The mean fire frequency was 0.18 fires year^{-1} and the mean fire interval was 3.3 years. The period post 1971 (which had 22% more rainfall) experienced a fire frequency more than two times higher than the period 1925–1970 ($p < 0.05$). Decadal fire frequency was correlated to 10-years moving average rainfall ($R^2 = 0.58$). Superposed Epoch Analysis showed that fires occur during years of above-average rainfall, and extensive fires tend to follow two years of above-average rainfall, all these associations being statistically significant. These results indicate a climatic control of fire regime, associated to enhanced fine fuels production during years of high rainfall, and imply that regional increase in rainfall associated to global changes in atmospheric circulation are affecting local ecosystems by significantly changing their disturbance regime.

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1. Introduction

Fire is a disturbance influencing the structure and dynamics of vegetation because of its frequent occurrence in seasonal climatic regimes (Agee, 1993; Engelmark et al., 1993; Gignoux et al., 1997; Grau et al., 2003; Harris et al., 2008). In the dry Chaco region of Argentina, fires usually start in grasslands and savannas, and may spread to surrounding forests and shrublands, depending on the amount of available fine fuel and wind speed (Bravo et al., 2001; Tálamo and Caziani, 2003). Bravo et al. (2001) estimated a high frequency and a medium to high intensity fire regime over the last century for a typical savanna of the Chaco region.

In the Chaco region, fire is considered an anthropogenic disturbance, mainly used as a tool for vegetation clearing and for the improvement of the nutritive quality of savannas and grasslands by promoting regrowth and eliminating unpalatable woody species (Boletta et al., 2006; Kunst et al., 2003; Tálamo and Caziani, 2003). There are no quantitative assessments of ignition sources in the Chaco region and lightning seems to be the main cause of natural fires in early spring.

However, even when ignition sources are purely anthropogenic, climate has a strong impact on fire frequency by regulating growth and desiccation of fuels (Baisan and Swetnam, 1997; Di Bella et al., 2006; Duffin, 2008; Engelmark et al., 1993; Grau and Veblen, 2000; Guyette and Cutter, 1991; Kitzberger et al., 1997; Swetnam and Baisan, 1996). During the last few decades, fires seem to have increased in the Chaco region along with the increasingly intensive use of the land, including deforestation for soybean and plantation of subtropical grass species (Boletta et al., 2006; Grau et al., 2005). These land use changes have happened almost simultaneously with regional climate changes and could also be affecting the fire regime. Total annual rainfall has increased in Northwest Argentina since 1956 (Minetti and Vargas, 1997). In other regions of Argentina, greater water availability modified fire frequency and other parameters of the fire regime, affecting the dynamics and characteristics of native vegetation (Grau and Veblen, 2000; Kitzberger et al., 1997).

We examined the hypothesis that the fire regime of the semiarid Chaco ecosystems are influenced, among others factors, by an increase in water availability, which generates over time a major increase in fine fuel availability for fires. This hypothesis derived from, a) research conducted in other savannas worldwide, which

* Corresponding author. Tel.: +54 0385 4509550.
E-mail addresses: sandrabrav@gmail.com (S. Bravo), ckunst@intasgo.gov.ar (C. Kunst), chilograu@gmail.com (R. Grau), ezequielaraoz@gmail.com (E. Aráoz).

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showed a relationship between rainfall, fuel production and changes in fire regime parameters (Harris et al., 2008; Hély et al., 2003; Swetnam and Baisan, 1996; Grau et al., 2001), and b) the increasing fire frequency in other seasonal environments of Argentina concurrently with a period of greater water availability (Grau and Veblen, 2000; Kitzberger et al., 1997). The objective of this study was to use dendroecological techniques recently developed for native woody species to estimate the relationship between fire frequency and rainfall variability at different time scales and resolutions during the last century in savanna ecosystems of the semiarid Chaco region.

2. Materials and methods

2.1. Study area

The study area was located in the western Chaco region, province of Santiago del Estero, Argentina, in the "La María" Experimental Ranch belonging to the Santiago del Estero Experimental Station, Instituto Nacional de Tecnologia Agropecuaria (28° 3′ S latitude, 64° 15′ W longitudes). The area lies on a transitional plain between the Guasayán Mountains and the alluvial plain of the Dulce River. The plain is 190 m above sea level and was created in a sedimentary basin covered by fluvial and loess materials. The soils of the study area correspond to Eutric Regosol, order Entisols (Lorenz, 1995).

The climate is semiarid and seasonal, with dry, cold winters and hot, rainy summers (Boletta et al., 2006). The mean annual temperature is 19.8 °C, and the means of the warmest (January) and coldest (July) months are 26.1 °C and 10.6 °C, respectively. Freezing temperatures can occur from May to October, reaching extreme temperatures of −10 and −12 °C (Torres Bruchmann, 1981). The average annual rainfall is 579 mm.

During the summer, continental warming creates low-pressure centers in the center and north of Argentina that attract air masses associated with oceanic anticyclones. The contact of air masses with different humidity and temperatures produces intense, frontal rainfalls characterizing the summer season. During the winter, oceanic anticyclones move northward and form on the continent. These weather systems prevent the entry of humid air masses from the north and north-east, resulting in cold, dry winters. During late winter and early spring, the predominant winds are dry and warm, alternating from the south and north (Boletta et al., 2006), causing air humidity to drop below 20% at noon and in the early afternoon (Kunst and Bravo, 2003). These climatic features last for approximately six months, during which time the atmospheric conditions favor fire occurrence. The fire season stretches from May to October coinciding with the dry season.

The vegetation of the Chaco region is a mosaic of thorny semi-deciduous forests, savannas and grasslands (Brassiolo et al., 1993; Bucher, 1982; Morello and Adámoli, 1974). The tree species *Schinopsis lorentzii* (quebracho colorado santiagueño) and *Aspidosperma quebracho-blanco* (quebracho blanco) dominate in upper layers of the forests (c. 15 m tall). *Prosopis nigra* (algarrobo negro), *Ziziphus mistol* Griseb. (mistol), *Cercidium praecox* (brea), and *Geoffroea decorticans* (chañar) are common species in the medium strata. Several species of *Acacia* and *Capparis*, *Jodina rhombifolia* (sombra de toro) *and Porlieria microphylla* (piquillín), characterize the shrubby lower strata (Brassiolo et al., 1993; López de Casenave et al., 1995).

Natural grasslands occupy interfluvial homogeneous soils and are dominated by *Trichloris crinita*, *Trichloris pluriflora*, *Gouinia paraguariensis*, *Gouinia latifolia*, *Setaria argentina*, *Setaria gracilis*, *Digitaria sanguinalis*, *Papophorum pappiferum*, *Papophorum mucronulatum* (Herrera et al., 2003). In savannas, the dominant grass species is *Elionorus muticus* Spreng. ("aibe", "espartillo", "paja amarga") a caespitose plant commonly between 30 and 40 cm tall. Trees such as *A. quebracho-blanco*, *P. nigra*, *Acacia aroma*, *Schinus* sp., *Celtis* sp. are scattered across the savannas in small patches or as isolated trees (Kunst et al., 2003).

2.2. Sample collection

Fire chronologies were based on dendroecological analyses (Kitzberger et al., 2000; Medina, 2003) of samples of *S. lorentzii*, *A. quebracho-blanco*, *A. aroma* and *A. furcatispina*, which are useful for dendroecological studies (Bravo et al., 2008). Eight sampling sites were located along an ecotone between the *E. muticus* savanna and an open-canopy dry forest. The distance between sampling sites varied from 600 to 800 m.

Sampling was guided by external signals of fire (fire scars, charred barks) on bole or/and branches of living individuals. At least three individuals were sampled in each sampling site. Wood samples were extracted from a total of 6 individuals of *S. lorentzii*, 8 of *A. quebracho-blanco*, 8 of *A. aroma* and 8 of *A. furcatispina*, respectively. Bole cross-sections of a width at least 0.02 m were cut using a chainsaw at approximately 0.3 m from the ground. In the tree species (*S. lorentzii* and *A. quebracho-blanco*), additional cross-sections were cut every meter up to 4.3 m height. In the shrub species, cross-sections were cut every 0.3 m due to a smaller development in the length of fire scars. In multi-stemmed forms, the biggest branch was sampled. Cross section samples were sanded and observed under a binocular magnifying glass following standard dendrochronological procedures (Barrett and Arno, 1988; Kitzberger et al., 2000).

Fire dates were determined by counting tree rings backwards from the outermost ring (corresponding to the sampling date) to the ring showing the fire scar or mark.This fire dating was made due to the lack of master dendrochronologic curves of width growth rings in Chaco native woody species. We exclusively sampled live individuals, and considered an error of ±1 year. Fire years were cross-dated, comparing fire data of each individual with the closest individual data in each sampling site (Bravo et al., 2008; Kitzberger et al., 2000).

2.3. Data analysis

A composite chronology was developed for the entire savanna by pooling data from all sampling sites (Agee, 1993). Fires dated in a single individual tree were included as fire years in the composite chronology of the *E. muticus* savanna. Longevity of the selected tree species exceeded one century and the short life span of the shrub species generated an unequal number of fires dated along the fire chronology. To avoid biases generated by an unequal number of fire events, we developed a second composite chronology considering only the fire events recorded in the tree samples (i.e. excluding *Acacia* species).

Fire frequency (FF) was defined as the ratio between the number of fires registered and the period of time comprised between the first recorded fire at each site and the sampling year. Fire frequency was determined for each sampling site and then averaged in order to calculate a mean FF for the entire savanna. The mean fire interval (MFI) was defined as the mean time period between two consecutive fires (Agee, 1993; Payette et al., 1989). In this work, fire interval analysis was based on site information using the program FHX2 (Grissino-Mayer, 1999). This analysis determined the fit of fire intervals to a Weibull distribution using the Kolmogorov–Smirnov Test and changes in MFI and other statistical descriptors of a fire regime.

The influence of climate in the fire regime was analyzed using the climatic record of the city of Santiago del Estero, informed by Bianchi and Yánez (1992) from the period of 1924–1990 and the climatic record of "La María" Experimental Station for the period of 1990–1996. In both cases, the total rainfall recorded was from October to May previous to each fire year. For the recording period common to both locations (1981–1990), the total annual rainfall was highly correlated ($r > 0.73$, Pearson correlation coefficient). This period includes the vegetative growth season and also summer rainfall in the Chaco region (Fig. 2). Using the fire chronology and the rainfall time series, we explored the fire–climate relationships at three temporal scales (century, decadal and annual).

To evaluate the influence of rainfall on fire frequency at a time scale = 1 century we compared FF among periods with the different water availability using the Temporal Changes Analysis using FHX2 (Grissino-Mayer, 1999). This software analyzes weather changes that have occurred in the MFI and other statistical descriptors of a fire regime among two time periods or two or more sites are significant, employing the Weibull distribution to model the fire interval data. We compared the intervals of fires affecting at least 25% of sampling sites at the time of fire events.

To avoid the influence of other ecological changes on our results, we explored the fire–rainfall relationship by mean of the frequency per decade of fires affecting at least 25% of sites. This relationship was studied in ten year moving windows (5 years previous to fire events and 4 years after).

For a more rigorous statistical assessment of the fire–rainfall relationship, we explored this association at interannual scale by conducting a Superposed Epoch Analysis (SEA) performed by the FHX2 program (Grissino-Mayer, 1999). The SEA and the statistical association between discrete fire events and the climatic variables were recorded in time windows centred in the event years. To obtain statistical values, the SEA compares climatic records of the actual distribution of years with fire events with the expected distribution parameters (mean and standard deviations) obtained in Monte Carlo simulations. In these simulations, fire events are randomly distributed over the study time span. For this analysis we used only the composite chronology of the entire savanna and six-year windows (3 years previous to fire events and two years after), taking into account fires affecting at least 25% and 50% of sampling sites and rainfall data. Events affecting at least 50% of sampling sites were considered generalized fires.

Table 1
Mean Fire Interval (MFI), along two periods with different water availability and fire frequency in an *Elionorus muticus* savanna, Argentine Chaco region. Lower case letters indicate statistically significant differences ($p < 0.01$). SD = Standard Deviation. Source of rainfall data: Bianchi & Yánez (1992) and Experimental Ranch, National Institute of Agricultural Technology of Santiago del Estero.

	Fire intervals (years)			Rainfall (mm)		
	MFI	SD	Range	Average	SD	Range
1925–1970	5.63a	3.58	3–11	496.26a	113.06	297–840
1971–1996	2.22b	0.44	2–3	605.16b	229.28	141–1349

3. Results

A total of 21 fires were recorded from 1925 to 1996, including both the tree and shrub species in fire chronology. The mean fire frequency for the entire savanna was 0.18 fires year^{-1} and the mean fire interval was 3.3 years. Fire frequency has increased since 1970 in the *E. muticus* savanna. The control of fire chronology showed that only two fires (1972 and 1977) were not detected, indicating that they were dated exclusively in shrubby individuals, in two and three sampling sites respectively, but their exclusion did not vary the general tendency of fire recurrence.

The period from 1925 to 1970 differed from the period 1971 to 1996, with 22% more rainfall than the average annual rainfall (Table 1). Temporal change analysis along the fire chronology indicated that mean fire interval differed significantly among the two periods ($p < 0.005$, Table 1). The mean fire frequency per decade was significantly correlated with the mean annual precipitation along the period of 1925–1996 ($R^2 = 0.581$, Fig. 1).

The SEA of fires affecting at least 25% of the sampling sites in *E. muticus* savanna showed that the annual rainfall registered in the fire years was above average ($p < 0.05$; $n = 19$, Fig. 2A). The SEA of generalized fires ($n = 11$ events) showed that they tended to occur two years after one with above-average annual rainfall ($p < 0.05$; Fig. 2B) and the mean fire interval of the generalized fires was 6.7 years.

4. Discussion

The fire frequency and fire interval documented in the studied savanna is representative of a fire regime of high frequency and medium to high intensity during the period of 1925–1996 (Bravo et al., 2001). The MFI of 3 years observed in the study area was

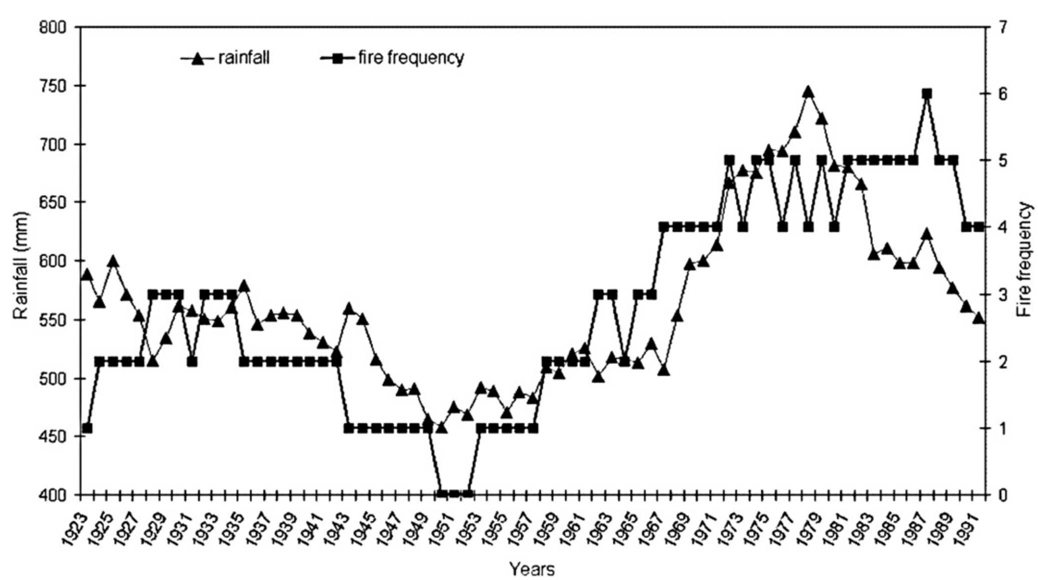

Fig. 1. Relationship between rainfall and fires frequency per decade tacking account fires that affecting at least 25% of sampling sites in *E. muticus* savanna, Argentine Chaco Region.

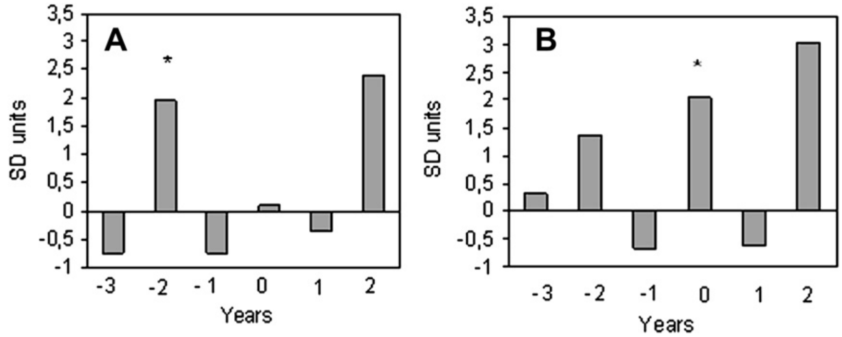

Fig. 2. Relationships between fire events and annual rainfall in moving windows extending from 3 years prior to fire events to 2 years after, for the period from 1925 to 1996, in *E. muticus* savanna. Bars describe deviations from the expected mean value in standard deviation units based on superposed epoch analysis ($p < 0.05$). Superposed Epoch Analysis A) of fires affecting at least 25% of sampling sites ($n = 19$); B) of fires affecting at least 50% of sampling sites ($n = 11$).

similar to values of 3–5 years found in Brazilian Cerrado savannas (Andrade and Kauffman, 1998), 3.6 years in United States savannas and oak forests (Dey et al., 2004), 3.8 years in African savannas (Trollope et al., 1996) and 3–3.5 years in the Chaco savanna region (Kunst et al., 2003). In Chaco regions, local residents perceived that the fire regime is largely controlled by changes in ignition sources associated with the land use changes (Boletta et al., 2006; Tálamo and Caziani, 2003), but our study clearly documents a climatic control. The increase in fire frequency observed since 1970 does not seem to be influenced by the asymmetrical number of surviving individuals present in both periods of fire chronology. Even the exclusion of shrubs as markers of fire events did not significantly change the mean fire interval of the last period in the fire chronology.

The reduction in the mean fire interval from 1970 onwards in the study area coincides with the increase of water availability at a regional level (Table 1), and the statistically significant association found between annual rainfall and fire occurrence at interannual and multidecadal time scales (Figs. 1 and 2) supports our hypothesis regarding the influence of rainfall on fine fuel production for fires. This implies that regional climatic changes are mostly reflected in increasing total rainfall (Minetti and Vargas, 1997), which may be increasing fuel availability and affecting the Chaco region fire regimes.

Fine fuel availability is the main determining factor for fire recurrence in arid and semiarid environments worldwide, where water deficit limits biomass production (Trollope, 1984). Frost (1998) communicated that protected African ecosystems with a greater mean annual precipitation had greater fire frequency during the last decades of the twentieth century, and Hély et al. (2003) found that in wet years, fuel production was significantly higher in western Zambia savannas. Duffin (2008) found a relationship between fire recurrence and rainfall in African savannas where the macroscopic charcoal abundance increased in periods of greater rainfall, even before significant human impact from the early 19th century.

The SEA of fires affecting at least 25% of sampling sites in *E. muticus* savanna coincides with the fire–rainfall relationship discussed previously because it showed that fires occurred in years with above-average annual rainfall (Fig. 2A). The occurrence of generalized fires two years after a rainfall peak, followed by years with below average rainfall, indicates that the fuel accumulation in more wet years and its dissecation in more dry years may be promoting the more extensive fires in Chaco savannas (Fig. 2B). Kitzberger et al. (1997) have found that fire occurrence and spread in the xeric forests of Patagonia were promoted by droughts during fire season and above-average moisture conditions during the preceding growth seasons. Grau and Veblen (2000) explained that fires in mountain forests of Northwest Argentina occur one year after years of above-average moisture availability. Harris et al. (2008) indicated a strong relationship between monsoonal antecedent rainfall and area burnt in Australian ecosystems where large fires occur in the late dry season due to greater fuel volumes and also other factors such as stronger winds that dry the fuels and spread fires.

The multi-scale temporal approach of this study allowed us to relate the increase in fire frequency during the 20th century with the increasing rainfall. The increasing number of fires through the twentieth century in the Argentine Chaco region cannot be attributed exclusively to a long-term trend in land use change, since during the pre-1950 period fire frequency decreased following the rainfall curve (Fig. 1). This implies that regional climatic change produces effects on the ecosystems by influencing fire frequency, one of the main components of its regimes disturbance. The quantitative assessment of climatic and anthropogenic variation sources on fire regime parameters in this region will be the subject of future studies.

In conclusion, this work confirmed our hypothesis and allowed us to quantitatively describe a positive association between increasing rainfall and fire frequency during the 20th century in savanna environments of the Argentine Chaco region. This finding has great value for environmental managers, since it could be used to predict the influence of increasing rainfall on the fire regime and units of vegetation.

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