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RESEARCH ARTICLE

FIRE REGIME, CLIMATE, AND VEGETATION IN THE SIERRAS DE CÓRDOBA, ARGENTINA

Juan P. Argañaraz^{1*}, Gregorio Gavier Pizarro², Marcelo Zak³, and Laura M. Bellis¹

¹ Instituto de Diversidad y Ecología Animal, CONICET–Facultad de Ciencias Exactas Físicas y Naturales, Universidad Nacional de Córdoba, Avenida Vélez Sarsfield 299, (5000), Córdoba, Argentina

² Instituto Nacional de Tecnología Agropecuaria, Instituto de Recursos Biológicos, Centro de Investigación en Recursos Naturales, De los Reseros y Las Cabañas S/N, (HB1712WAA), Hurlingham, Buenos Aires, Argentina

³ Departamento de Geografía, Universidad Nacional de Córdoba, Casa Verde, Primer Piso, Ciudad Universitaria, (5000), Córdoba, Argentina

* Corresponding author: Tel.: 054-351-4332098 ext. 253; e-mail: argajuan@yahoo.com.ar

ABSTRACT

Wildfires are a primary disturbance in the Sierras de Córdoba, Argentina, with approximately 2 152 000 ha burned between 1993 and 2012. However, little is known about the spatial and temporal patterns of fires and their relationship with climate and vegetation in this area. Such information is of great value for fire risk assessment and the development of strategies for fire management. Our main objective was to analyze fire activity in four sierran ranges, assessing which weather and climate conditions were mostly related to fire activity, and which land cover types were mostly burned. We used a fire database of mid-high spatial resolution and a land cover map derived from Landsat imagery. Fire regimes were different among the different sierran ranges. The Sierras Chicas range was the most affected by fires, with the largest number of fire events, burned area, and fire frequency. Although large fires represented

RESUMEN

Los incendios constituyen uno de los principales disturbios en las Sierras de Córdoba, Argentina, acumulando aproximadamente 2 152 000 ha quemadas entre 1993 y 2012. Sin embargo, poco se conoce acerca de los patrones espaciales y temporales del fuego y su relación con el clima y la vegetación del lugar. Esta información es de gran valor para la evaluación del riesgo de incendios y para la implementación de estrategias de manejo del fuego. Nuestro objetivo fue analizar los incendios en cuatro sistemas serranos, evaluando las condiciones meteorológicas y climáticas que favorecen la ocurrencia de incendios y los tipos de vegetación que más se queman. Utilizamos una base de datos de incendios de resolución espacial media-alta y un mapa de cubiertas de suelo obtenido a partir de imágenes Landsat. Los regímenes de fuego fueron diferentes en los distintos sistemas serranos. Las Sierras Chicas fueron las más afectadas por el fuego, presentando el mayor número de eventos, área quemada y frecuencia de incendios. Los grandes incendios representaron entre 3% y 5% de los incendios, sin embargo,

3% to 5% of fire events, they accounted for 60% to 86% of total burned area in different sierran ranges. Sierras of lower elevation had a winter seasonality of fires, while sierras of higher elevation had a winter-spring or spring fire seasonality. The number of fire events was positively correlated with preceding periods that were wetter than normal, while the burned area was mainly associated with midterm weather conditions. Fires occurred mainly in grasslands and shrublands, but the area of burned forests was important, too. Our results will be useful to determine the times and conditions in which fire risk is highest, and also to identify where preventive efforts should be focused.

quemaron entre 60% y 86% del área quemada total en los diferentes sistemas serranos. Las sierras de menor altitud presentaron una estacionalidad de incendios invernal, mientras que las sierras de mayor altitud presentaron una estacionalidad invierno-primaveral o primaveral. El número de incendios se correlacionó positivamente con periodos precedentes de mayor humedad, mientras que el área quemada se correlacionó con las condiciones meteorológicas ocurrientes en el mediano plazo. Los incendios ocurrieron principalmente en áreas de pastizal y arbustal, aunque la superficie de bosques quemados fue importante también. Nuestros resultados serán de utilidad para determinar los momentos y condiciones de mayor riesgo de incendios y también para identificar las áreas donde se deben concentrar los esfuerzos preventivos.

Keywords: ABAMS, Argentina, Chaco Serrano, Córdoba province, dry forests, fire regime, Landsat

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INTRODUCTION

Wildfires are a primary disturbance in many ecosystems around the world (Bond *et al.* 2005). Fires play a key role in landscapes by causing strong impacts on species composition, vegetation structure, and biogeochemical and hydrological cycles (Whelan 1995, Pyne 1997, Morgan *et al.* 2001). The effects of fires on ecosystems depend on the fire regime, which is defined by the frequency, severity, intensity, area, seasonality, and spatial pattern of fire occurrence (Whelan 1995). However, human-driven changes in historic fire regimes can alter the frequency, intensity, severity, and distribution of fires (Archibald *et al.* 2012, Hantson *et al.* 2015), resulting in large and sometimes negative impacts on ecosystem functioning. Examples include increased fire

in tropical and subtropical forests resulting in conversion to savanna (Cochrane *et al.* 1999, Zak *et al.* 2004), and fire suppression preventing recruitment of fire-dependent species and altering vegetation structure (Agee 1993).

Although at present fire regimes are significantly affected by human activity worldwide, climate also exerts a strong control on fire activity by regulating fuel production and desiccation (Whelan 1995). The relationship between water balance and fire is nonlinear (Bradstock 2010). In wetter ecosystems, fire controls are imposed by the length of the fire season, while in drier ecosystems, fuel availability is generally the limiting factor (van der Werf *et al.* 2008) and fires tend to burn heavily a few years after above-average precipitation (Veblen *et al.* 1999, Grau and Veblen 2000, Bravo *et al.* 2010).

Fire activity is also different among land cover types. Savannas and grasslands can support intensive fires more frequently than forests can, sometimes every 1 to 3 years (Bravo *et al.* 2010, Dubinin *et al.* 2010), due to their capacity of biomass production and the fineness and seasonal curing of fuels. On the contrary, forests are less prone to fires due to the smaller proportion of fine fuel (Kunst and Bravo 2003). Nevertheless, in areas of savannas and fragmented forests, fires usually start in grasslands and then penetrate into forests (Bravo *et al.* 2001).

In Latin America, Argentina has the second largest area affected by fires (Chuvieco *et al.* 2008) and the central mountainous region is of particular concern due to area burned, fire frequency, and the size and distribution of the human population. For instance, nearly 2 152 000 ha were burned in Córdoba province between 1993 and 2012, with almost 95 % of ignitions caused by humans (Provincial Directorate of the Fire Management Plan of Córdoba Province, Córdoba, Argentina; unpublished data). These fires have driven key structural changes in landscapes, degrading and reducing native woodlands (Renison *et al.* 2002, Giorgis *et al.* 2013), increasing soil vulnerability to erosive agents (Cingolani *et al.* 2013), and affecting the quality of water reservoirs (Bonansea and Fernandez 2013). Besides, fires produce important economic losses due to burned structures, livestock killed, consumption of forage resources for cattle, timber burned, and fire-fighting efforts. For instance, a large 18 000 ha fire produced economic losses of around 3 200 000 US dollars in only seven days (Atala *et al.* 2006). Additionally, recent attention has been directed to novel urban developments that occur predominantly in forested valleys (Gavier and Bucher 2004). These developments expand the wildland-urban interface, where risks to human lives and goods are higher due to the proximity of houses and fuels (Radeloff *et al.* 2005).

Considering fire effects on ecosystems and the associated risks and economic losses,

knowledge of fire regimes is essential for the management and conservation of natural resources, primary production, landscape planning, and risk assessment (Di Bella *et al.* 2006). Moreover, exploring the variability of fire regime characteristics over time and space is crucial to understanding the interaction between landscape patterns, climate, and fire (Morgan *et al.* 2001), especially in a context of climate change and intense human intervention in fire regimes (Rollins *et al.* 2002, Dubinin *et al.* 2010). Notwithstanding this, very few studies have focused on the analysis of different aspects of the fire regime in central Argentina. So far, Fischer *et al.* (2012) studied the regional behavior and patterns of fire, using MODIS hotspots between 2004 and 2007, and related them to vegetation characteristics, land use, and climate. Miglietta (1994), on the other hand, addressed similar questions at a local scale, using non-spatial records of fires from a fire station. Therefore, our main goal was to analyze fire occurrence in central Argentina by addressing the following questions: 1) When and where is fire activity higher? 2) What are the weather and climate conditions that favor fire activity? and, 3) Which are the land cover types mostly affected by fires?

METHODS

Study Area

The study area (24 260 km²) included four sierras belonging to the Sierras Pampeanas of Argentina located in Córdoba province: Sierras del Norte, Sierras Chicas, Sierras Grandes, and Cumbres de Gaspar. These sierras extend from 29° 00' S to 33° 30' S, encompassing a north-south length of ≈430 km, and an elevation range from 500 m to 2790 m (Vázquez *et al.* 1979) (Figure 1).

The vegetation of the area has been classified as Chaco Serrano (Cabrera 1976) and is divided into different altitudinal belts (Luti *et al.* 1979, but see Giorgis *et al.* 2011). Howev-

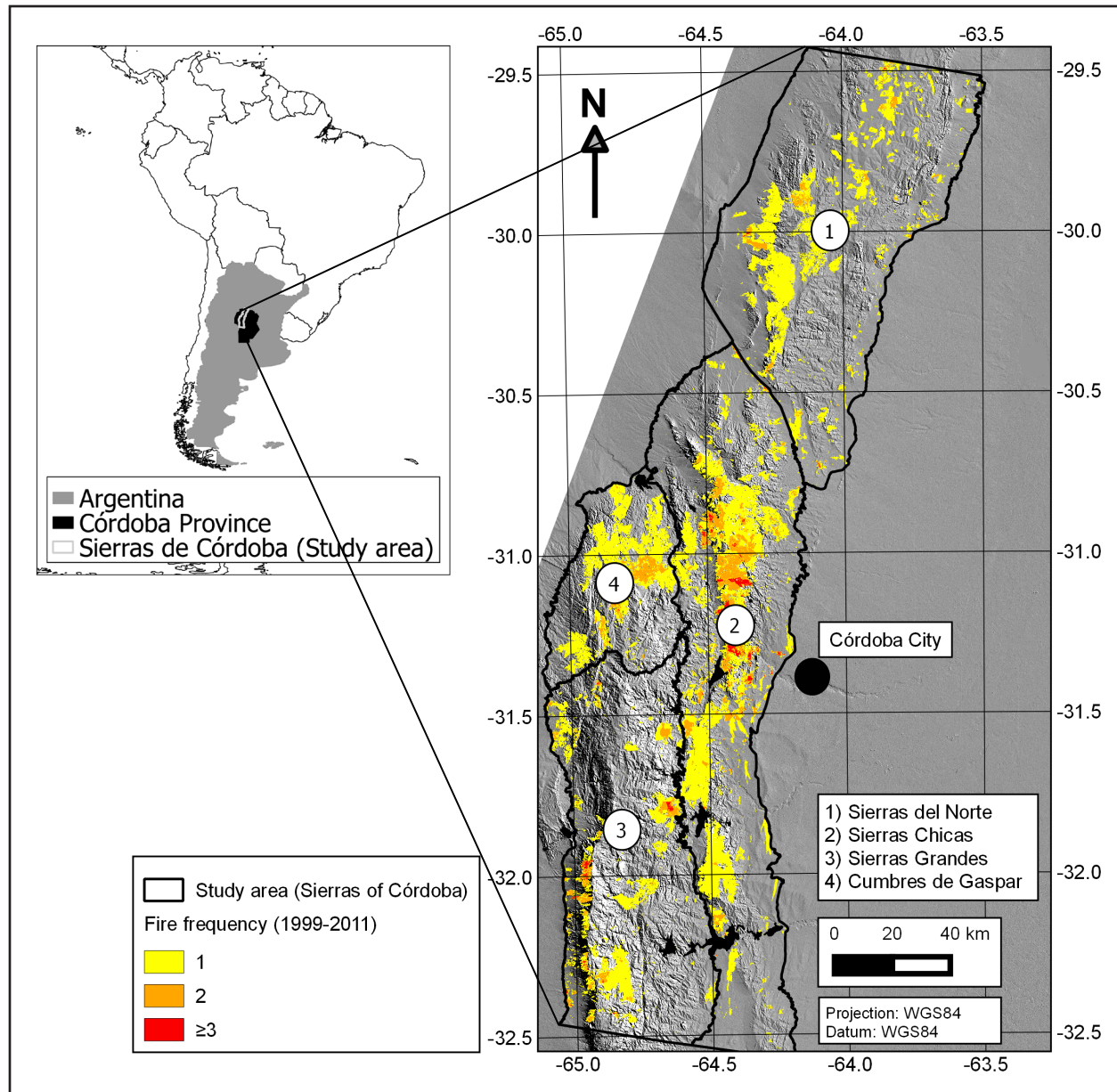


Figure 1. The study area was the Sierras de Córdoba, central Argentina.

er, more recent studies indicated that above 1850 m, vegetation should no longer be considered as Chacoan since most of their floristic elements belong to the Andean ecoregion (Cabrero *et al.* 1998). The lowland forest, dominated by *Aspidosperma quebracho-blanco* Schlectet., *Prosopis* spp. L., and *Acacia* spp. Mill., is found below 750 m. The range between 500 m and 1300 m is mostly covered by Chaco Serrano forests, dominated by *Lithraea molleoides* Vell. and *Zanthoxylum coco* Gillies

ex Hook. f. & Arn. Between 1300 m and 1700 m, there is the romerillal, a type of shrubland defined by the presence of *Heterothalamus alienus* Spreng. (Luti *et al.* 1979). Between 1500 m and 1850 m, the area is mostly occupied by grasslands dominated by *Festuca hieronymi* Hack., *Stipa* spp. L., and *Piptochaetium* spp. J. Presl. Vegetation above 1850 m includes communities of grasslands dominated by *Deyeuxia hieronymi* Hack., *Poa stuckertii* Hack., *Alchemilla pinnata* Ruiz & Pav., and

Festuca circinata Griseb.; shrublands dominated by *Berberis hieronymi* C.K. Schneid.; and woodlands dominated by *Polylepis australis* Bitter (Cabido et al. 1998).

The elevation range, climate, and vegetation are different in the four sierran ranges. In Sierras Chicas (550 m to 1800 m), the mean annual temperature is 16.8°C¹ and the mean annual precipitation is 960 mm, with most rainfall occurring between October and March (spring and summer). Winter is dry and mild with relatively high temperatures occurring in August and September. This leads to a winter seasonality of fires (Miglietta 1994). Wild vegetation consists mainly of grasslands, Chaco Serrano forests, and shrublands (Zak 2008). In Sierras del Norte (500 m to 1100 m), the mean annual temperature is ≈19°C, the mean annual precipitation is ≈625 mm, and wild vegetation consists mainly of shrublands and Chaco Serrano forests (Zak et al. 2004). In Sierras Grandes, the mean annual temperature is 12.4°C (Colladon 2004) and the mean annual precipitation is 806 mm, mostly concentrated between October and April (Colladon and Pazos 2014). Land cover consists of grasslands, relicts of *Polylepis australis* woodlands and shrublands, and rocky areas (Cingolani et al. 2004). These climatic characteristics are similar to Cumbres de Gaspar (900 m to 1900 m) due to its proximity and altitude (Figure 1). Natural vegetation consists mainly of grasslands and shrublands (Zak 2008). According to the Provincial Fire Management Plan, the season of fires in the whole province begins in June and extends up to December.

Fire Database

Burned scars were mapped over 82 Landsat TM and ETM+ images (30 m of spatial resolution, Path/Rows: 229/81 and 229/82) acquired between 1999 and 2011 (J. Argañaraz, CONICET, Argentina, unpublished data). This

fire database was derived automatically using ABAMS (Automatic Burned Area Mapping Software), a tool based on the algorithm proposed by Bastarrika et al. (2011). We considered any continuous burned patch as a single fire event except when the intensity of the burned signal was markedly different. The minimum mapping unit of the fire database is of 5 ha, because smaller areas had higher confusion rates. Producer's accuracy ranged from 88% to 97% (i.e., 3% to 12% omission error), and user's accuracy from 71% to 96% (i.e., 4% to 29% omission error) (J. Argañaraz, unpublished data). We converted vector layers of burned areas to raster format as binary layers (burned or unburned) and developed the fire frequency map for the period 1999 to 2011 by adding those layers.

Fire Regime Analysis

Fire activity per sierran range. We calculated the number of fire events and total burned area for each sierran range. When fires were shared by more than one sierra, we assigned them to the sierra in which the area burned was larger. We compared the number of fire events and area burned per year, the total burned area, the effective burned area (i.e., some areas burned more than once during the 13-year time frame of our study), the frequency of fire, the distribution of fire sizes, and the number of large fires (>1000 ha) among the four sierran ranges.

Seasonality of fires and weather conditions. We identified the month in which each fire event occurred by overlapping the Landsat-derived burned layers, MODIS hotspots, and Landsat images of each year. We assigned the month of the MODIS hotspots to a vector of burned areas when they overlapped (also checking with Landsat images) or when they were in a radius smaller than 500 m (half of

¹ Mario Navarro, Observatorio Meteorológico Salsipuedes, Salsipuedes, Córdoba. Precipitation data from the period 1988 to 2012 and temperature data from the period 2002 to 2011.

the size of a MODIS pixel used to derive this product). When fires ignited in one month and extinguished in the next one, we assigned them to the month that the ignition took place. If the month of occurrence could not be determined, the visualization of the burned scar over Landsat imagery was used to identify (when possible) the season of occurrence, between winter (June to September) and spring (October to December).

In order to relate climate and weather conditions to fire occurrence, we used the Spearman correlation coefficient to compare the burned area and number of fire events (annually and monthly when possible) with precipitation and water balance variables. Annual comparisons included 1) de Martonne's Aridity Index (MAI) as an indicator of water balance, calculated as

$$\frac{P}{(T + 10)}, \quad (1)$$

where P is total annual precipitation and T is mean annual temperature (de Martonne 1926); 2) accumulated precipitation in the current and previous year (January to December); 3) accumulated precipitation in the previous and second previous hydrological year (July to June); 4) precipitation anomalies (%), calculated as

$$\frac{(P_i - P_{clim})}{P_{clim}} \times 100, \quad (2)$$

where P_i is total precipitation in the year i and P_{clim} is the average precipitation in a year calculated over a certain period of time (climatic variable); and 5) the length of the dry season in months, calculated as 12 minus the number of months in which accumulated precipitation represents 70% of the total annual precipitation (Archibald *et al.* 2009). Monthly analyses included comparison with MAI, calculated as

$$\frac{12P}{(T + 10)}; \quad (3)$$

accumulated precipitation; and precipitation anomalies of the current month as well as the averages up to six months previously.

Meteorological data for the higher sierras (Sierras Grandes and Cumbres de Gaspar) was obtained from INA-CIRSA (National Water Institute of Argentina, Centre for the Semiarid Region), and data for the lower sierras (Sierras Chicas and Sierras del Norte) was obtained from the Observatorio Salsipuedes (Salsipuedes Weather Observatory, 31° 3' S, 64° 18' W). No meteorological records were available for Sierras del Norte; however, we assumed that their meteorological conditions were similar to those tendencies of Sierras Chicas due to their relatively similar geographic position and altitude (Figure 1). We used linear regression to estimate the monthly temperature of 2011 for higher sierras using Salsipuedes Observatory temperature data. Such estimation of missing data was possible because the regression's coefficient of determination was higher than 0.85 (Colladon 2004).

Fire occurrence and vegetation. We analyzed fire occurrence and fire frequency in relation to land cover type. Land cover classes included forests, shrublands, grasslands, cultural lands (mainly cultivated areas), and other land cover classes (including cultivated forests, outcrops, halophytic shrubs). The land cover map was derived from Landsat imagery (30 m spatial resolution) (Zak 2008). We also compared the area, perimeter, and shape (perimeter to area relationship) of the fires occurring in different land cover classes. To this purpose, we calculated the proportion of land cover types burned in each fire event and then we assigned fires to a single land cover class if the proportion was $\geq 80\%$. We did not include the fire events occurring in mixed land cover types for further analysis. We used the Kruskal Wallis test to compare the characteristics of fires occurring in different land cover types. Analyses were performed with Software R

3.0.2 (R Development Core Team 2013). For multiclass comparison, we used the package “pgrimess” (Giraudoux 2013).

Management and operations with spatial data were performed with Quantum GIS 1.8.0-Lisboa (QGIS Development Team 2012).

RESULTS

Total Burned Area and Fire Frequency

Fire activity differed among the studied sierran ranges, with Sierras Chicas accounting for most burned area and fire events (Figure 2, Table 1). The number of fire events was higher between 1999 and 2003 and then decreased after 2004 in all sierras with certain variability (Figure 2). The distribution of burned area over the 13 years analyzed was different between the sierran ranges. Sierras Chicas was burned heavily every 5 to 6 years during the time span of this study (Figure 2a). The pattern for Sierras Grandes showed peaks of burned areas more regularly distributed in time, with intervals of 1 to 4 years (Figure 2b). Sierras del Norte showed a pattern of fire occurrence every 3 to 4 years up to 2006, although there was no other burned area peak afterwards (Figure 2c). Cumbres de Gaspar did not show a clear pattern of fire occurrence during the time span of this study. It showed maximum peaks in 2002 and 2003 and a moderate peak after 8 years in 2011 (Figure 2d). These observations about annual or multi-annual “cycles” of fire occurrence should be considered as preliminary, since longer time series are needed to analyze such pattern more consistently.

Cumbres de Gaspar and Sierras Chicas were the most affected by fires with 31% and 25% of their area effectively subjected to fire, respectively (i.e., some areas burned more than once during the 13-year time frame of this study) (Table 1). Comparisons between the total burned area and the effective burned area indicates high burning frequencies in Si-

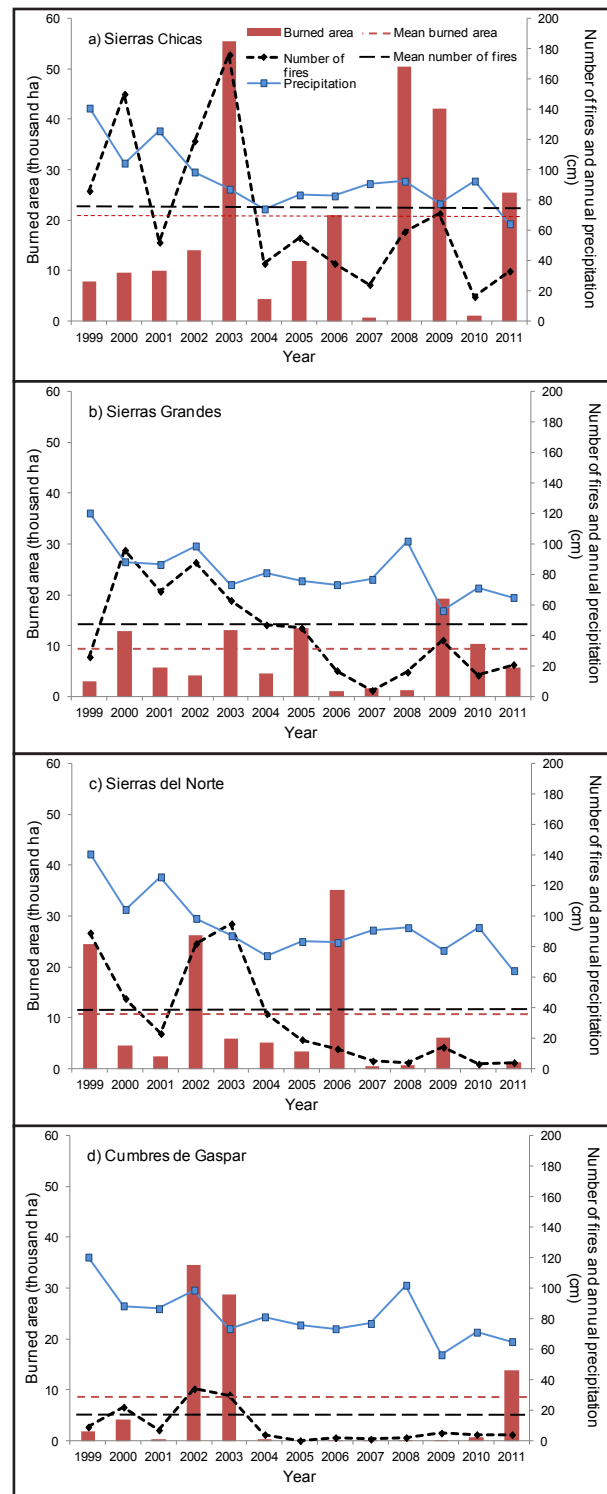


Figure 2. Burned area, number of fires, and precipitation for the period 1999 to 2011 in the Sierras de Córdoba, Argentina.

Table 1. Total and effective burned area in the Sierras de Córdoba, Argentina. Effective burned area is the remainder when reburned area is subtracted from total burned area.

	Total area	Total burned area		Effective burned area	
	(ha)	(ha)	(%)	(ha)	(%)
Sierras Chicas	812 663	253 801	31.2	201 136	24.8
Sierras Grandes	584 668	96 323	16.5	72 685	12.4
Sierras del Norte	785 306	116 245	14.8	108 480	13.8
Cumbres de Gaspar	243 460	85 031	34.9	74 557	30.6
Total area	2 425 944	548 441	22.6	456 834	18.8

Sierras Chicas, Cumbres de Gaspar, and Sierras Grandes, with almost no frequency higher than one in Sierras del Norte (Table 1).

The frequency distribution of fire sizes showed that most fires were smaller than 100 ha in all sierras, but also, all of them underwent large fire events (>1000 ha) several times between 1999 and 2011 (Figure 3). Even though large fires only represented a small proportion of fire events, ≈3.4% in Sierras Chicas, Sierras Grandes, and Sierras del Norte, and 4.8% in Cumbres de Gaspar, they accounted for 77%, 60%, 70%, and 86% of the total burned area, respectively. Very large fires (≥10 000 ha) occurred once in Sierras Grandes (2009: 11 558 ha), three times in both Sierras

del Norte (1999: 12 628 ha, 2002: 13 505 ha, and 2006: 28 025 ha) and Cumbres de Gaspar (2002: 31 215 ha, 2003: 18 952 ha, and 2011: 12 308 ha), and five times in Sierras Chicas (2003: 21 602 ha, 2006: 16 038 ha, 2008: 44 104 ha, 2009: 20 328 ha, and 2011: 17 867 ha) during the time span of this study.

Seasonality of Fires

From the total number of fires in all sierran ranges, only 34% (683 out of 2017) could be assigned to the month in which they occurred: 34.6% in Sierras Chicas (316 out of 917), 25.0% in Sierras Grandes (136 out of 543), 47.3% in Sierras del Norte (203 out of 433), and 22.6% in Cumbres de Gaspar (28 out of 124). Fire seasonality differed among sierras. For instance, most fire events and area burned in Sierras Chicas occurred in mid- to late winter (August to September) although fire season seems to start in June and last until November (occasionally until December) (Figure 4a). In Sierras del Norte, the peak of fire occurrence and area burned was observed in late winter (Figure 4c), while in Sierras Grandes, fires were more frequent between August and October and most burned area occurred between August and November (Figure 4b). Conversely, in Cumbres de Gaspar, the largest values of burned area were observed in spring (October and November), although the number of fire events was similar between August and November (Figure 4d). Most large fires occurred

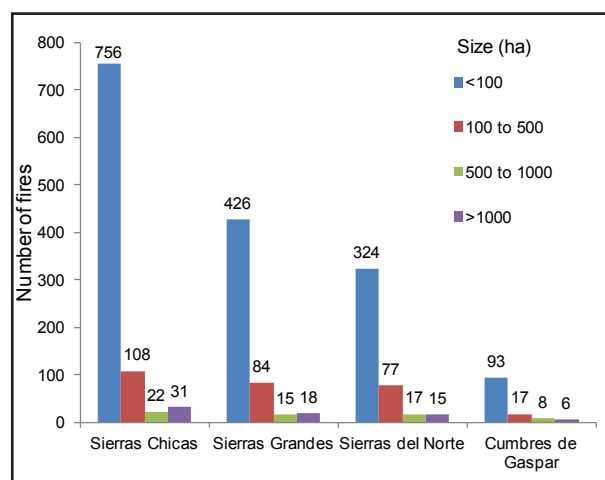


Figure 3. Distribution of burned area sizes for the period 1999 to 2011 in the Sierras de Córdoba, Argentina.

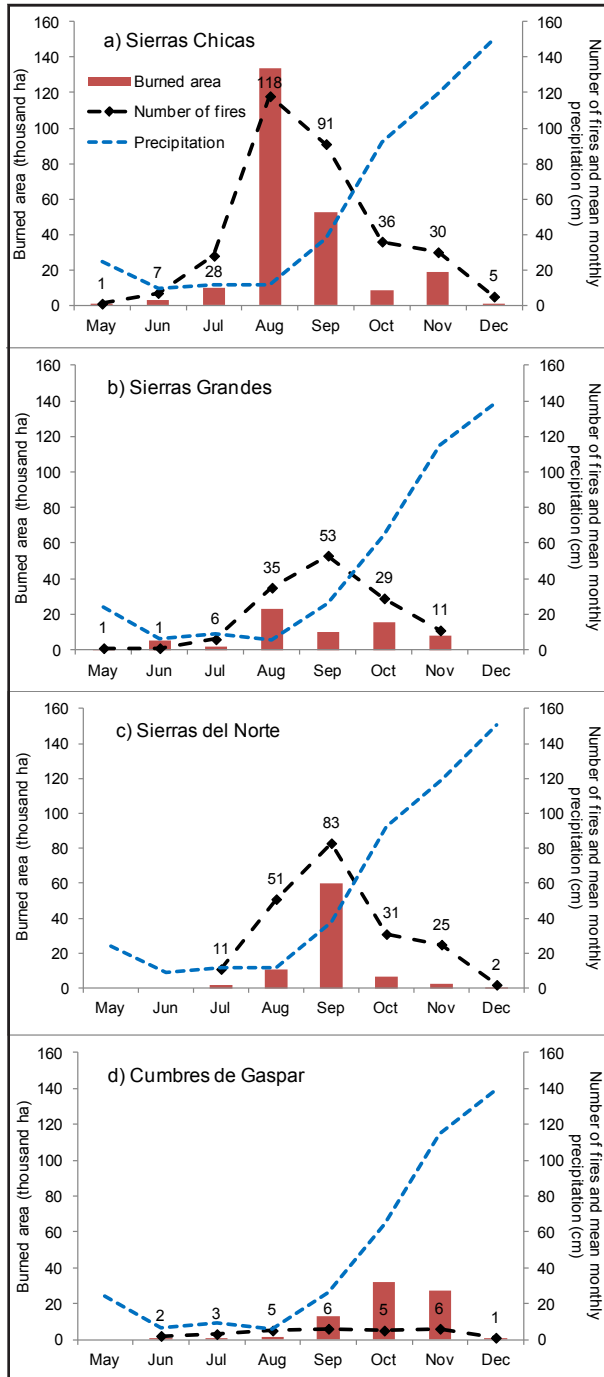


Figure 4. Burned area and number of fires per month for the period 1999 to 2011 (sum of events and area) in the Sierras de Córdoba, Argentina. Monthly precipitation data in Sierras Chicas and Sierras del Norte from Observatorio Salsipuedes (average for the period 1988 to 2012), and in Sierras Grandes and Cumbres de Gaspar from INA-CIRSA (average for the period 1998 to 2011).

in August and September in all sierras except in Cumbres de Gaspar where they were more uniformly distributed over a longer period, between August and November. The same seasonality was observed for each sierran range when considering all fires that could be assigned to winter or spring (1470 fire events accounting for more than 500 000 ha).

Fires and Climate

Total annual precipitation during the studied period was evenly distributed into years of higher, lower, and average precipitation in the higher sierras (Sierras Grandes and Cumbres de Gaspar), while precipitation tended to be lower than average in Sierras Chicas (Figure 2). The number of fire events was positively related to anomalies in precipitation and to MAI average of the previous two years in lower sierras ($r = 0.61$, $P = 0.03$, and $r = 0.58$, $P = 0.04$, respectively; Figure 5a). Similar relationships were found for the two-year average precipitation anomalies in the higher sierras ($r = 0.59$, $P = 0.03$), and the number of fire events was also positively correlated with the precipitation of the previous and second previous hydrological year ($r = 0.63$, $P = 0.02$, and $r = 0.64$, $P = 0.02$, respectively; Figure 5b). The area burned annually was not significantly related to any of the climatic variables included in our analysis. Nevertheless, larger burned areas in Sierras Grandes seemed to occur after years with higher precipitation (Figure 2).

Monthly burned area did not correlate significantly with current precipitation, precipitation anomaly, or MAI, in both higher and lower sierras. Instead, monthly burned area was negatively correlated with precipitation and MAI averages of the previous five months in both cases ($r \approx -0.46$, $P \leq 0.001$, and $r \approx -0.45$, $P < 0.003$, respectively; Figure 5c and d). Averages of larger and shorter periods were also significantly correlated, but the associations were weaker. Additionally, in higher sierras, monthly burned area was negatively correlated

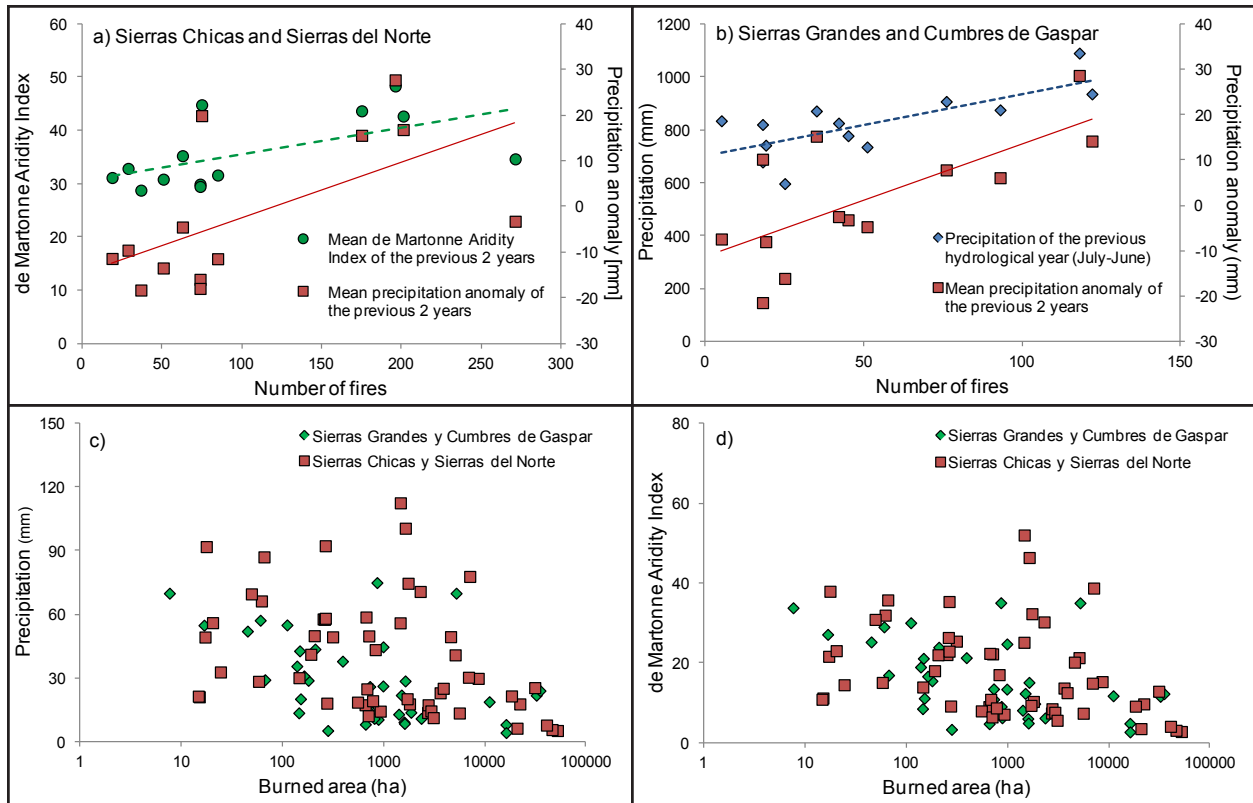


Figure 5. Relationship between the annual number of fires and climatic variables in (a) lower sierras and (b) higher sierras, and relationship between the monthly burned area and the averages of (c) precipitation and (d) water balance of the previous five months.

with precipitation anomalies of the current and two previous months ($r \approx -0.56$, $P \leq 0.001$). Despite these results, we observed that the largest burned areas (in 2002, 2003, 2006, 2008, 2009, and 2011) occurred mostly when monthly MAI was lower than climatic averages (i.e., lower water balance than expected) (Figure 6), during negative rainfall anomalies and prior to the beginning of the precipitation season in all sierras.

Fires and Land Cover

Considering the whole study area, fires burned mainly grasslands (170 000 ha; i.e., 24% of grasslands area), shrublands (135 000 ha; i.e., 25% of shrublands area), woodlands (81 000 ha; i.e., 18% of woodlands area), and cultural lands (51 000 ha; i.e., 10% of cultural lands area). There were differences among the

four sierras regarding fire occurrence according to land cover type. In Sierras Chicas, fires occurred mainly in grasslands, while the burned area of shrublands and woodlands was similar. Comparatively, the burned area of grasslands represented 42% of the total grassland area, while for shrublands and woodlands the burned area represented $\approx 26\%$ of their total area (Table 2). In Sierras Grandes, fires burned almost exclusively in grasslands (the dominant land cover of this range) followed by woodlands. On the other hand, in Sierras del Norte and Cumbres de Gaspar, fires occurred mainly in shrublands, followed by cultural lands and woodlands in the former range, and by grasslands in the latter (Table 2). Comparatively, nearly 20% of the shrublands and grasslands and almost 11% of the woodlands and cultural lands were burned in Sierras del Norte. In Cumbres de Gaspar, on the other

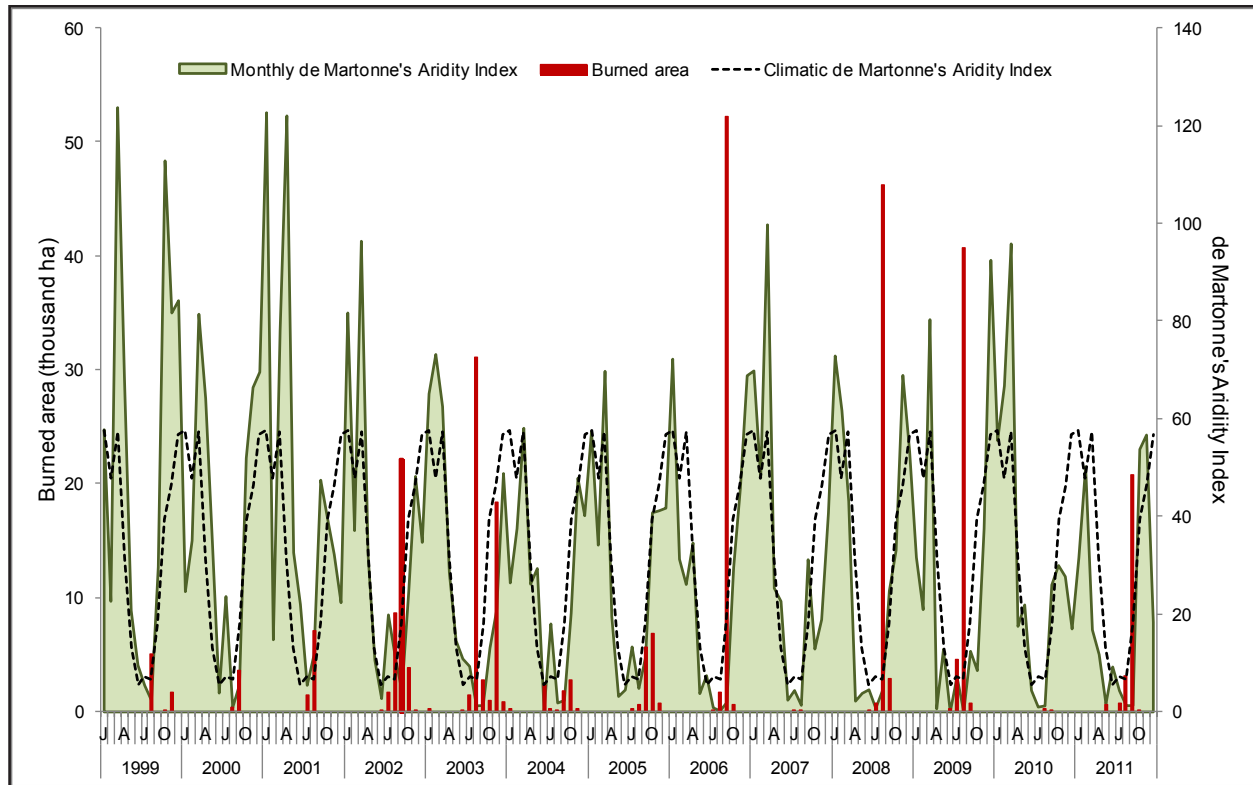


Figure 6. Monthly and climatic de Martonne's Aridity Index (MAI) (Climatic MAI is calculated using monthly precipitation and mean temperature averages for the period 1988 to 2012) and burned area for the period 1999 to 2011 in Sierras Chicas and Sierras del Norte, Córdoba, Argentina. A monthly MAI lower or higher than climatic MAI indicates periods drier or wetter than expected, respectively.

Table 2. Burned area and ratio between the percentage of land cover burnt and the percentage represented by each land cover class in the sierran ranges of Córdoba, Argentina.

Landcover	Sierras Chicas			Sierras Grandes			Sierras del Norte			Cumbres de Gaspar		
	Burned area (ha)	Ratio	Total area (ha)	Burned area (ha)	Ratio	Total area (ha)	Burned area (ha)	Ratio	Total area (ha)	Burned area (ha)	Ratio	Total area (ha)
Cultural	22436	9:32	259966	1382	6:4	23980	27285	12:30	235222	261	5:2	4921
Woodland	47927	26:22	182344	8011	12:11	64171	17509	10:23	179374	7797	26:12	30149
Shrubland	40899	27:19	152865	4936	10:8	48624	47763	20:31	244142	41114	44:38	93348
Grassland	89302	42:26	210709	49841	14:62	361222	6511	21:4	30421	24676	23:44	107720
Other	571	9:1	6611	4521	7:12	67227	21	13:0	161	709	10:3	7248
Unclassified	0		0	3994	21:3	19213	9392	10:9	95839	0		0

hand, 44% of the shrublands and 25% of the woodlands and grasslands were burned (Table 2). Most of the burned area of all these land cover types had burned only once in the period analyzed; however, grasslands areas that re-

burned once or twice had burned areas two to three times higher than other land cover types (Figure 7).

Fire events burning different land cover types showed differences in their size, prime-

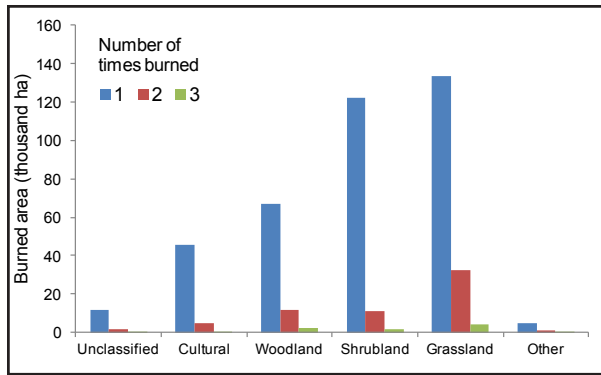


Figure 7. Burned area per fire frequency and land cover type for the period 1999 to 2011 in the Sierras de Córdoba, Argentina.

ter, and perimeter to area relationship. Grassland fires were significantly larger than both forest and cultural fires, but they were no different from shrubland fires (Table 3). Instead, fire perimeter in grasslands was significantly larger than fire perimeter in the other land cover types, which presented no significant differences. Additionally, the perimeter to area relationship was significantly larger in grasslands than in forests and cultural lands, indicating a higher proportion of edge in grassland fires. No significant differences were detected among the other land cover classes (Table 3).

DISCUSSION

Our results showed that fire is a common and important disturbance agent in the Sierras de Córdoba, with large fires affecting the four studied sierran ranges. Higher fire activity was associated with short- and mid-term weather conditions of higher water availability,

suggesting a strong climatic control over fire regime. Nevertheless, fire activity differs among the four sierran ranges, especially in fire seasonality and frequency. This is the first research using spatially explicit fire data at mid-high resolution (30 m) to study the fire regimes in the Sierras de Córdoba (Argentina) including semiarid Chaco forests. Our results provide accurate information about the spatial distribution of fires, fire perimeters, and burned area of the recent fire history of Córdoba sierras.

Sierras Chicas was the range most affected by fires, exhibiting the highest number of fire events, burned area, and fire frequency. This is probably related to the co-occurrence of higher precipitation (i.e., higher fuel loads) and higher human population and tourism in wild areas, which provides more ignition sources. Also, the wildland-urban interface (WUI) communities are growing in Sierras Chicas, where fire activity is expected to be greater because human ignitions would find enough fuels to spread (Radeloff *et al.* 2005). The reduction in the number of fire events after 2003 in all sierras might be related to the fire prevention policies that started in 1999 with the creation of the Fire Management Plan of Córdoba province. Nevertheless, large fires occurred anyway in all sierras, but they are generally related to extreme weather conditions (Whelan 1995) commonly occurring in our study area.

After the first frosts in May (austral cold season), the curing process (leaf dying) of fine fuels begins, reaching nearly 60% of fuels cured by July in grasslands of Sierras Chicas

Table 3. Size, perimeter, and shape of fires burning different land cover types. Different letters indicate significant differences ($P = 0.05$).

	Forest ($n = 184$)			Shrubland ($n = 136$)			Grasslands ($n = 450$)			Cultural ($n = 267$)		
	Mean	SD	Median	Mean	SD	Median	Mean	SD	Median	Mean	SD	Median
Area (ha)	53.2	194.3	16.4a	271.0	2403.3	18.2ab	136.1	654.5	25.2b	74.8	315.4	14.9a
Perimeter (km)	5.1	8.1	2.7a	9.0	40.8	3.0a	7.9	13.4	3.8b	5.2	9.4	2.7a
Perimeter:area	6.8	3.9	5.7a	7.9	6.5	6.1ab	8.8	7.8	6.5b	7.2	5.5	5.4a

(J. Argañaraz, unpublished data). Fire occurrence is highest in mid- to late winter (August and September), the result of the combination of high maximum temperatures (e.g., 41.3 °C in September 2013), low precipitation (sometimes none), and wind speeds that can reach 70 km hr⁻¹ (Fuente: Datos meteorológicos INTA Manfredi, <http://inta.gob.ar/documentos/informacion-meteorologica-mensual-de-la-e.e.a.-manfredi/>). Sierras del Norte also showed a winter seasonality of fires. However, the lower proportion of burned area might be related to a limited fuel accumulation because of lower precipitation and higher temperature than in Sierras Chicas. The lower amount of burned areas after October is associated with the beginning of the rainfall season.

In Sierras Grandes, the burned area is evenly distributed between winter and spring, but the number of fires is higher in winter, suggesting that lower temperatures might not be favoring fire spread. The spring seasonality of fires in Cumbres de Gaspar and the larger proportion of burned area than Sierras Grandes might be favored by warmer temperatures, according to data from WorldClim (Hijmans *et al.* 2005). Previous studies using MODIS data have also indicated higher fire activity between August and October in the Sierras de Córdoba (Fischer *et al.* 2012). This is probably related to the ranching use of fire to burn senescent biomass and promote forage regrowth during the dry season (Renison *et al.* 2006, Fischer *et al.* 2012), a common (but illegal) practice in many ecosystems (Silva *et al.* 2001, Kepe 2005, Pivello 2011).

Higher fire activity was observed in other dry ecosystems after 1 or 2 years with precipitation and water balance above normal (e.g., Chaco savannas [Bravo *et al.* 2010], African savannas [Balfour and Howison 2002, Van Wilgen *et al.* 2004, Archibald *et al.* 2009], northwestern mountains of Argentina (Grau and Veblen 2000), and temperate forests and grasslands of Argentinean Patagonia [Kitz-

berger *et al.* 1997, Veblen *et al.* 1999]). These pulses of water availability stimulate primary production and consequently increase the fuel availability, which is usually the limiting factor for fire activity in drier ecosystems (Bradstock 2010, Krawchuck and Moritz 2011).

The lack of association between the area burned annually and the precipitation and water balance of the same year suggests that fire prone conditions may occur under a normal weather year (Veblen *et al.* 1999, Grau and Veblen 2000). However, it is possible that the intensive grazing of domestic livestock in the Sierras de Córdoba (Cingolani *et al.* 2013) is also weakening this relationship by reducing fuel loads (Grau and Veblen 2000). On the other hand, the positive association between monthly burned area and the occurrence of dry conditions during the previous months has also been reported for the central region of Argentina (Fischer *et al.* 2012).

Previous research in Sierras Chicas also found that the number of fires was independent of annual precipitation, but it was positively correlated with rainfall of the previous November-to-June period (approximately the growing season) (Miglietta 1994). This difference from our results is likely related to the differences in the fire databases used in both studies; Miglietta (1994) used the records of two fire stations that covered a small portion (80 000 ha) of our study area.

In general, grasslands and shrublands are more prone to burn since grasslands are dominated by fine fuels and shrublands usually have high coverage of herbaceous vegetation. Besides, the horizontal and vertical continuity of fuels in shrublands favors fire spread. The high proportion of the burned area accounted for by grasslands and shrublands in the higher sierras (75% in Sierras Grandes and 88% in Cumbres de Gaspar) might explain the higher number of fires after wetter periods in these sierras, due to the capacity of grasses and forbs to increase their biomass rapidly in response to higher water availability. Frequent fires on

grasslands are related to the ranching practice of burning senescent biomass to promote forage regrowth and also to the biomass accumulation capacity of herbaceous stands, which might allow intensive fires every 1 to 3 years (Dubinin *et al.* 2010). A mean fire interval of 3.3 years was reported for Chaco savannas (Bravo *et al.* 2010), which is compatible with our results considering the 13-year time frame. Also, the coverage of herbaceous vegetation can increase after fires, suggesting a mechanism of positive feedback (Russell-Smith *et al.* 2002).

Forests, on the other hand, are less prone to fires due to lower fine fuel load (Kunst and Bravo 2003, Giorgis *et al.* 2013) and microclimate (Chen *et al.* 1999). Nevertheless, even though forests are less involved in fire propagation (Miglietta 1994), fires might start in grasslands and savannas and then spread into shrublands and forests in dry Chaco (Bravo *et al.* 2001). Then, burned forests in Chaco are mainly colonized by herbs, which are more flammable (Tálamo and Caziani 2003, Jaureguiberry *et al.* 2011).

Although forests are less prone to fire, at present only a small proportion of native forests remain in our study area and other Chaco landscapes. In Sierras Grandes, fires are used to promote grass regrowth and to reduce woodland cover, affecting the distribution of *Polylepis australis* woodlands (Renison *et al.* 2006). In Sierras del Norte, fires facilitate the extraction of burned trees for charcoal and wood for fuel, and mountain woodlands are replaced by shrubs (Zak *et al.* 2004). Even though there is no information about land use in Cumbres de Gaspar, it is possible that fires are used for similar purposes given the dominance of grasslands and shrublands. In Sierras Chicas, fire is the main factor structuring vegetation in the transition zone between forests and grasslands (Giorgis *et al.* 2013). Moreover, fire activity in this area is related to higher population densities and the burning of waste disposals to reduce trash volumes and pests (Nirich 2000, Argañaraz *et al.* 2015).

Agricultural lands are also less prone to burn because they are more controlled and their temporal dynamics might interrupt fuel continuity over time and space and thus fire spread. Similarly, at the global scale, there is low presence of forests and high proportion of grasslands in areas with high fire density (Chuvieco *et al.* 2008), and burned area tends to be lower with increasing proportion of cultivated lands in central Argentina (Fischer *et al.* 2012).

Management Implications

The differences in fire regimes among the four sierras indicate the need of differential management approaches for each of them. In Sierras Chicas and Sierras del Norte, preventive efforts should be concentrated in mid- to late winter, while in Sierras Grandes and Cumbres de Gaspar they should continue through spring. Moreover, one or two years after a wetter period, a higher number of fire events should be expected, although the amount of burned area will be associated with the short- and mid-term weather conditions prevailing each year. Additionally, grasslands and shrublands should be monitored more intensively because they burn the most and also because these fires might later spread into forests (Bravo *et al.* 2001). Nevertheless, grasslands are of greater concern because fires tend to be larger and they can burn more frequently than the other land cover types.

Previous research in our study area has found that woody native species have a high survival rate after fire, and post-fire recovery is mainly driven by tree resprouting (Renison *et al.* 2002, Gurvich *et al.* 2005, Torres *et al.* 2014). For that reason, restoration should be based mainly in protecting resprouts from other post-fire disturbances (Torres *et al.* 2014), including subsequent fires (Miglietta 1994, Renison *et al.* 2002), urbanization (Gavier and Bucher 2004, Torres *et al.* 2014), livestock grazing (Renison *et al.* 2006, Cingolani *et al.* 2013), and biological invasions (Gavier and Bucher 2004, Giorgis *et al.* 2011).

Many countries have implemented fire extinction policies for long periods, but in many cases, this led to larger fuel accumulation and catastrophic fires once they did occur (Pausas and Keeley 2009). Novel policies are focused on the management of fuels in strategic locations (Keeley *et al.* 1999). Fuel loads can be reduced by different means (Davison 1996). Experiments with prescribed fires have been carried out in grassland areas of the Chaco for-

ests (Kunst and Bravo 2003), but little is known about fire behavior in semiarid Chaco mountains, where topography might play a key role. Controlled livestock grazing could be a reasonable choice (Davison 1996). However, stocking rates in our study area must be determined with extreme care to prevent erosion processes, with moderate to low densities in some areas and livestock exclusion in others (Cingolani *et al.* 2013).

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