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Climate, landscape, and human influences on fire in southern Patagonia: A basin-scale approach

Lucas O. Bianchi [a,*], Ricardo Villalba [b], Facundo J. Oddi [c,d], Ignacio A. Mundo [b,e], Marcos Radins [f], Mariano M. Amoroso [c,d], Ana Marina Srur [b], Anabela Bonada [g]

[a] Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), CENAC-PNNH, Fagnano 244, 8400 San Carlos de Bariloche, Rio Negro, Argentina
[b] Laboratorio de Dendrocronología e Historia Ambiental, IANIGLA-CONICET, Mendoza, Argentina
[c] Universidad Nacional de Rio Negro, Instituto de Investigaciones en Recursos Naturales, Agroecología y Desarrollo Rural (IRNAD), San Carlos de Bariloche – El Bolsón, Río Negro, Argentina
[d] Consejo Nacional de Investigaciones Científicas y Técnicas, Instituto de Investigaciones en Recursos Naturales, Agroecología y Desarrollo Rural (IRNAD), San Carlos de Bariloche – El Bolsón, Río Negro, Argentina
[e] Facultad de Ciencias Exactas y Naturales, Universidad Nacional de Cuyo, Mendoza, Argentina
[f] Facultad de Ciencias Forestales, Universidad Nacional de Misiones (UNaM), Misiones, Argentina
[g] Intact Centre on Climate Adaptation, Univesity of Waterloo, Waterloo, Canada

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ABSTRACT

Human activities and how they interact with climate and landscape to influence fire regimes is complex and still remains a major research challenge in most Patagonian forests. Recent studies on the fire history in Patagonia covered large areas, making it difficult to model fire occurrence and burned patch size. The main objective of this work was to evaluate the influence of climatic variability, landscape variations and human activities on the occurrence and size of fire at the basin scale. We aimed to update previous fire history of the Río de las Vueltas – Río Túnel basin, in southern Patagonian Andes, with the specific aims to (1) reconstruct in detail the spatio-temporal patterns of fire, (2) model fire variability as a function of climate variability, landscape and human activities, and (3) determine the influence of regional climate on fire occurrence at the basin scale. We used dendrochronological techniques to update the fire history of the study basin. At the basin scale, we used (1) maximum entropy models to estimate the influence of climate, landscape, and humans on fire probability, (2) general linear models to assess how these factors modulate fire size, and (3) superposed epoch analysis to assess the influence of regional water deficit on fire occurrence. We found that fire occurrence increased sharply with the arrival of settlers in the early 20th century and decreased in the early 21st century due to the shift in recognition of the ecosystem services provided by forests. Additionally, the mean fire interval, the number of fires during drier years, and fire size, increased along the northwest-southeast gradient of decreasing precipitation. Our results support that fire regimes are largely human driven, and conditioned by climate and landscape characteristics. The analysis at the basin scale facilitated the understanding of how these factors regulate fire regimes, and consequently, our comprehension at larger spatial scales.

1. Introduction

Forest dynamics are modulated by spatial and temporal interactions between disturbances. The patterns of these interactions are used to describe the disturbance regime of a forest. The disturbance regime is determined by the type, frequency, extent, and magnitude (intensity and severity) of the events, as well as their interactions with other disturbances in an area throughout a given time interval (White and Pickett, 1985). In particular, fire regimes may be influenced by the interactions between climate, landscape and human activities, varying at different spatial and temporal scales (Abatzoglou et al., 2018; Marlon et al., 2008; McKenzie et al., 2011). Over long-term scales (decades to centuries), climate drives fire regimes by determining vegetation type and its productivity, and consequently, fuel properties (Meyn et al., 2007; Veblen et al., 1999; Yocom Kent et al., 2017). On shorter time scales, intra-annual climatic variations influence fire regimes by modulating

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* Corresponding author.
E-mail address: lbianchi@conicet.gov.ar (L.O. Bianchi).

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lightning occurrence, moisture content, and flammability of live and dead fuels (Pausas and Paula, 2012). On a daily to weekly scale, meteorological conditions control the drying of medium and fine fuels; influencing the spread and intensity of a given fire (Chandler et al., 1983; Rothermel, 1983). Additionally, landscape characteristics, such as soil type and topography (elevation, aspect, slope), determine the structure and composition of vegetation and affect the intensity and duration of droughts (Collins et al., 2007; Yocom Kent et al., 2017). Finally, human activities interact with both climate and landscape modifying fire regimes at different spatial and temporal scales (Pausas and Fernández-Muñoz, 2012). At times, human influences can mask the effect of climate (Syphard et al., 2017). For example, changes in land use and natural fire suppression influence ignition frequency and fuel structure (Kitzberger, 2012; Mundo et al., 2013a; Mundo et al., 2017; Pausas and Fernández-Muñoz, 2012). However, in ecosystems where fuel is not the limiting factor for fire occurrence, the anthropic influence on the frequency of ignition remains a major research challenge (Holz and Veblen, 2011).

The development of policies for integrated fire management requires knowledge about the socioecological role of fire and its regime (Silva et al., 2010; Veblen et al., 2008). Furthermore, the influence of climate, landscape, and humans over the spread and occurrence of fire has important policy and management implications (Syphard et al., 2017). Research on how these three drivers interact is crucial for understanding how forests ecosystems may respond to climate change (Yocom Kent et al., 2017). Integrating this information into landscape modeling processes provides an opportunity to adapt environmental management to climate and land-use changes (Falk et al., 2011; IPBES, 2019; IPCC, 2022).

Fire is one of the main disturbances shaping landscapes in the Andean Patagonia (38°–50°S). Several fire history reconstructions have been developed for this region, including both dense forests and the forest-steppe ecotones (Holz et al., 2012; Kitzberger et al., 1997; Mundo et al., 2017; among others). However, few studies have spatially modeled the probability of fire occurrences (Mermoz et al., 2005; Mundo et al., 2013a; Paritsis et al., 2013). In addition, most of the previous studies cover large areas, with differences in vegetation types, as well as in the timing of human occupation or land-use history (Paritsis et al., 2013). On the other hand, site-specific studies provide useful information to evaluate aspects of the fire regime that are difficult to detect at large spatial scales (Holz et al., 2016). Moreover, in contrast to northern Patagonia, where fire history and fire regime drivers have been intensively studied (Kitzberger et al., 1997; Mundo et al., 2013b; Veblen et al., 1999), little is known about climate, landscape, and human influences on fire in southern Patagonia at the basin scale. The Río de las Vueltas – Río Túnel basins, in southern Andean Patagonia, is characterized by a vegetation productivity gradient driven by the decreasing precipitation in a northwest-southeast direction, superimposed on a landscape with vast topographic differences and diverse human activities (urban settlements, extensive livestock grazing, rural and specialized tourism). The main forest disturbance in this basin is fire (Mundo et al., 2017). Therefore, this area offers a remarkable opportunity to study how natural and human factors interact in the regulation of the fire regime at the basin level in the Andes.

The main objective of this work was to evaluate the influence of climatic variability, landscape variations and human activities on the occurrence and size of fire events at the basin scale. We expect that fire activity varies along the forest productivity gradient determined by differences in precipitation within the basin, following the global model proposed by (Pausas and Paula, 2012), in addition to landscape attributes and land-use history (Meyn et al., 2007). By focusing on the processes that modulate fires, we intend to understand which factors determine fire ignitions (i.e., the probability of occurrence at a point in space and number of events in the basin) and which factors regulate their magnitude (i.e., the size of the burned area). Taking this into consideration, we specifically aim to (1) complement the existing fire history reconstruction (Mundo et al., 2017) with new records, to provide a more detailed reconstruction of the spatial characteristics of fire (i.e. fire occurrence probability, number of events and size) and temporal variability (i.e. frequency) at the basin scale, (2) model fire variability as a function of differences in climate, landscape and human activities at the basin scale, and (3) study how the variability of the regional temperature and precipitation influences the probability of fire occurrence.

Our results contribute to advancing knowledge on the influence of climate, landscape, and humans on the fire regime at the basin scale. This research intends to provide key information for fire management at the local scale and reveals the importance of basin-scale studies to accurately characterize the fire regime at larger scales. In a global framework, our results provide insights about fire regimes and the main drivers in temperate forests.

2. Methods

2.1. Study area

The Río de Las Vueltas basin is located in the Patagonian Andes of Santa Cruz province, southwestern Argentina. Its headwaters lie to the east of the South Patagonian Ice Field, near Lago del Desierto, and runs in a north–south direction until draining into Lago Viedma. Of much smaller size, the Río Túnel basin is located south of the Río de las Vueltas. Both rivers form a territorial unit, the Río de Las Vueltas – Río Túnel basins (from now on referred to as RV-RTB) of 970.4 km^2 in the northern sector of the extensive hydrological system of Río Santa Cruz (Fig. 1).

2.1.1. Climate

The main climate features in the region are modulated by the permanent band of mid-latitude westerlies interacting with the Cordillera de los Andes. The distribution of precipitation throughout the year is relatively uniform and the presence of the Andes mountain range causes

Fig. 1. Location of the Río de las Vueltas – Río Túnel basins limits, El Chaltén (black dot) and the 3 weather stations (red dots) with corresponding annual precipitation in parentheses, showing the marked precipitation gradient from north to south.

a marked gradient of precipitation, decreasing in the W-E direction (Viale et al., 2019). In the RV-RTB, there is a marked precipitation reduction from NW to SE following the alignment of the main valley. The annual mean precipitation ranges from 1450 mm year^{-1} at the northwestern extreme of the basin (Glaciar Milanesio station) to 360 mm year^{-1} (Río de las Vueltas station at El Chaltén) at the southeastern end of the basin (Fig. 1 and Table 1). The temperature increases from west to east, modulated by a decrease in elevation and a longer distance from the ice field.

2.1.2. Landscape

On the western side of the RV-RTB, the Cordillera de los Andes reaches an elevation of 2300–2500 m, while in the southeastern sector, the Andean piedmont begins at an elevation of 400–500 m in the forest-steppe ecotone. Variations in precipitation and temperature are reflected in the spatial gradients of the vegetation. In response to low temperatures and prolonged snowpack duration, short grasses dominate at high elevations (high Andean grassland). In their lower part, these high-altitude grasses are bound by the upper limit of the forest (900–1100 m.a.s.l.), which is dominated by 1–2 m tall *Nothofagus pumilio* (Poepp. & Endl.) Krasser trees (Srur et al., 2018). At lower elevations across both basins, pure stands of 10–20 m tall *N. pumilio* trees prevail. At the wetter northwestern sector mixed forest patches occur with *N. betuloides* (Mirb.) Oerst. Poorly drained low elevation sites are dominated by *N. antarctica* (G. Forst.) Oerst. In the dry forest-steppe ecotone, small patches of *N. pumilio-N. antarctica* are surrounded by xeric *Festuca-Stipa* grasslands (Peri and Ormaechea, 2013).

2.1.3. Human activities

In southern Patagonia, wildfires in the forest-steppe ecotone were relatively common before the arrival of the Euro-American settlers. Historical evidence indicates that indigenous peoples used fire for guanaco hunting (*Lama guanicoe;* Musters 1871). However, fire was rare in the humid upper RV-RTB (Belardi and Marina, 2014). With the arrival of the European settlement, an increase of intentional forest burning occurred in much of Andean Patagonia (Mundo et al., 2017; Veblen et al., 2008). Settlers often burned forests to expand the area suitable for livestock grazing (Butland, 1957; Martinić Beros, 2014), and timber extraction (Paritsis et al., 2013). Large-scale sheep husbandry began in the late 19th century near the Atlantic coast and expanded rapidly across southern Patagonia. At the beginning of the 20th century, large herds of sheep grazed in the lower drier portion of the RV-RTB (Halvorsen, 1997; Kölliker et al., 1917). By the middle of the 20th century, most of the Patagonian steppe had been completely converted to sheep farming (Bandieri, 2005). During the 1970′s, the boundaries of Los Glaciares National Park were extended to the north of Lago Viedma, including the Río Túnel Basin and the land presently occupied by the town of El Chaltén (Halvorsen, 1997). This small town, known worldwide as the Argentine Capital of Trekking for its multiple options for mountain sports, was founded on October 12, 1985, as a geopolitical decision at a time when Argentina was facing a sovereignty conflict and dispute with Chile over the Lago del Desierto and the Southern Patagonian Ice Field. The authorities of Los Glaciares National Park ceded an area of 135 ha to the province of Santa Cruz for the new settlement. The population of El Chaltén has increased steadily since its creation. According to national census, there were 41 inhabitants in 1991, 371 in 2001, 950 in 2010, and the population exceeded 1,000 in 2012. Currently the population is around 3,000 inhabitants. Urbanization and tourist ventures continue to develop with many public and private construction projects.

2.2. Data collection

2.2.1. Fire history

We identified old fire patches based on historical photos (de Agostini, 1945) and aerial photos (IGN, 1968). The most recent fires were identified and mapped using Landsat 5–7 and SPOT-6 satellite images with a 30 m and 5 m spatial resolution, respectively. SPOT-6 images allowed identifying patches with a minimum size of 0.5 ha. Due to the frequent presence of clouds in the region, it was not possible to gather enough satellite images for a systematic temporal analysis. To calculate the size of the fire patches we delimited them based on visual recognition of changes in forest structure. Most patches originated by fire showed shapes and locations different from those generated by wind, snow avalanches or rockfalls. We digitized 56 polygons of fire patches on the satellite images and validated 46 in the field based on the presence of snags and fire scars. To complement the existing fire history reconstruction, we collected 165 samples. Samples consisted of small partial cross-sections of living or dead standing trees of *N. pumilio*. We collected 15 samples in each patch in a total of 11 patches distributed along three new sites in the basin: Milodón (MIL), Pliegue (PLG) and Viedma (VDM; Figs. 2 and 3). Once affected by fire, *N. pumilio* wood is very susceptible to decay, reducing the number of well-preserved scars and, consequently, their availability for sampling (González et al., 2005; Mundo et al., 2017). Partial cross-sections were processed following standard dendrochronological procedures (Arno and Sneck, 1977; McBride, 1983; Stokes and Smiley, 1996). Many sections were rotten and, in those cases, it was not possible to date the beginning of the healing callus (Mundo et al., 2017). The dates of the fire-scarred rings were determined by counting backwards from the outermost ring and assigning a calendar year to each ring corresponding to the year in which the ring formation began (Schulman, 1956). The visual dating was verified by cross-dating the tree-ring patterns not affected by fire using the software COFECHA (Grissino-Mayer, 2001; Holmes, 1983). A date was considered as a fire event when it was registered in at least two trees within the same patch.

2.2.2. Climate, landscape, and human activity

Instrumental climate records along RV-RTB (Fig. 1, Table 1) are not long enough for comparative climate-fire analyses. In addition, the rainfall gradient in the basin is not accurately captured by the coarse spatial resolution of gridded data set such as WorldClim version 2 with a 30-second ($\sim$1 km^2) resolution grid (Fick and Hijmans, 2017). For these reasons, we used latitude and longitude as a proxy of precipitation. In the case of the temporal analysis of the regional climate-fire relationship, we used the temperature and precipitation records from the Punta Arenas weather station (Table 1) to compute the Standardized Precipitation-Evapotranspiration Index (SPEI; Vicente-Serrano et al., 2010) using the SPEI package (Beguería and Vicente-Serrano, 2017) in the R software. The SPEI represents an accumulated moisture deficit (precipitation minus potential evapotranspiration) and can be calculated at different time scales. It uses precipitation and temperature data

Table 1
Weather stations used to describe the precipitation gradient along the Río de las Vueltas-Río Túnel basins.

Station	Latitude S	Longitude W	Elevation (m.a.s.l.)	Parameter	Record period	Source
Glaciar Milanesio	49.06	72.96	734	Precipitation	2016–2018	IANIGLA
Los Huemules	49.22	72.96	459	Precipitation	2007–2016	Los Huemules
Río de Las Vueltas	49.33	72.89	400	Precipitation	2007–2016	BDHI/APN
Punta Arenas	53.01	70.84	38	Temperature and Precipitation	1888–2016	KNMI

IANIGLA, Instituto Argentino de Nivología, Glaciología y Ciencias Ambientales; BDHI, Base de Datos Hidrológica Integrada de la Secretaría de Infraestructura y Política Hídrica de la Nación; APN, Administración de Parques Nacionales; KNMI, Koninklijk Nederlands Meteorologisch Instituut of Netherlands.

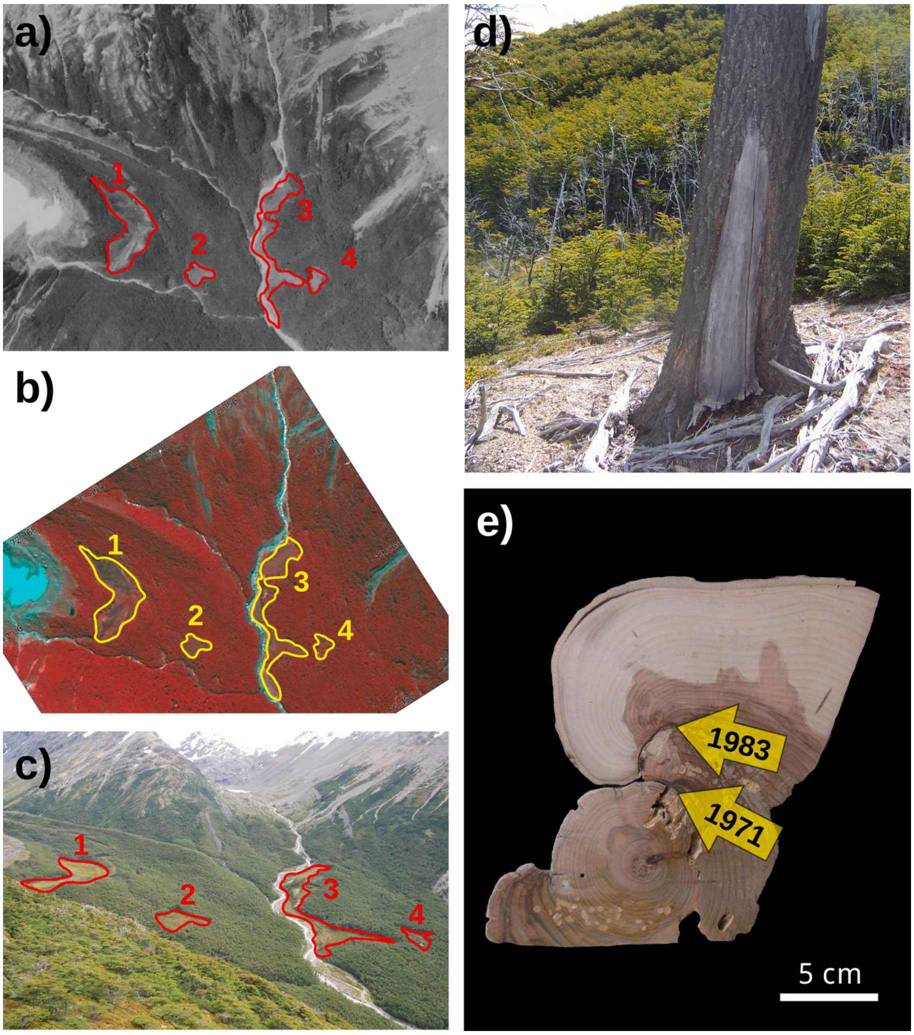

Fig. 2. Mapping and sampling methodology used: (a) identification of forest-free patches on aerial photographs (IGN, 1968), (b) delimitation of burned areas on satellite images (SPOT 6), (c) identification of burned areas and field confirmation that the mapped forest-free patches correspond to a fire, collection of samples and survey of burned boundaries, (d) example of fire scar, and (e) cross-section taken in the field to date the year of fire occurrence.

and is based on the water balance developed by Thornthwaite (1948; Vicente-Serrano et al. 2010). The long and homogeneous climatic records from Punta Arenas are the closest to the RV-RTB.

We considered topography, vegetation and hydrography as the landscape elements affecting fire activity. Topography was characterized using maps of slope, aspect, and potential incoming solar radiation, derived from the digital elevation model (DEM) SRTM4, with a spatial resolution of 90 m (Jarvis et al., 2008). Since aspect is a circular variable, we transformed it using sine and cosine functions. The sine of the aspect produces the easting variable, a measure of east–west aspect where + 1 and −1 represent east and west, respectively. Similarly, the cosine transformation of the aspect generates the variable northing, a measure of north–south aspect where + 1 and −1 represent north and south, respectively. We reclassified the soil cover map over the Andean Patagonia (CIEFAP and MAyDS, 2016) into three categories: forest, steppe (or grassland) and non-flammable cover (ice, snow, water, bare soil). Areas corresponding to this latter category were removed from the fire probability analysis (approximately 55.2 % of the basin). The hydrographic information was obtained from the SIG-250 of the National Geographic Institute (IGN, http://www.ign.gob.ar/).

To account for human activities in the basin, we collected information on current and past rural and urban settlements, campsites, roads and hiking trails (also used for livestock grazing in the past). This information was extracted from historical records (de Agostini, 1945; Halvorsen, 1997; Kölliker et al., 1917) and public sources (SIG-250, internet sites, printed maps, and brochures).

For each fire patch, we calculated the total area (fire size); the area occupied by forests and grassland (landcover variables); latitude and longitude of the centroid of the patch as proxies of precipitation, and mean elevation as a proxy of temperature (climatic variable); slope, easting, northing and potential incoming solar radiation (as a topographic characterization); distance to hiking trails, roads, human settlements (human activity); and water streams (hydrographic component). We constructed a square grid with cells measuring 250 m on each side. For every cell, we computed the mean values for all the variables mentioned. Each cell included the percentage of burnt and unburnt area and a binary variable equal to 1 (burned) when the cell overlapped with a fire polygon and equal to 0 (not burned) otherwise. All GIS processing was conducted with QGIS 3.10 (QGIS Development Team, 2020), GRASS GIS 7.8.4 (GRASS Development Team, 2020) and SAGA GIS 7.6.1 (Conrad et al., 2015).

2.3. Data analysis

The reconstruction of fire dates by dendrochronological methods does not allow the precise delimitation of the area affected by a fire, as only those trees with visible scars are sampled, which are not always possible to date. Consequently, only the location of trees that recorded

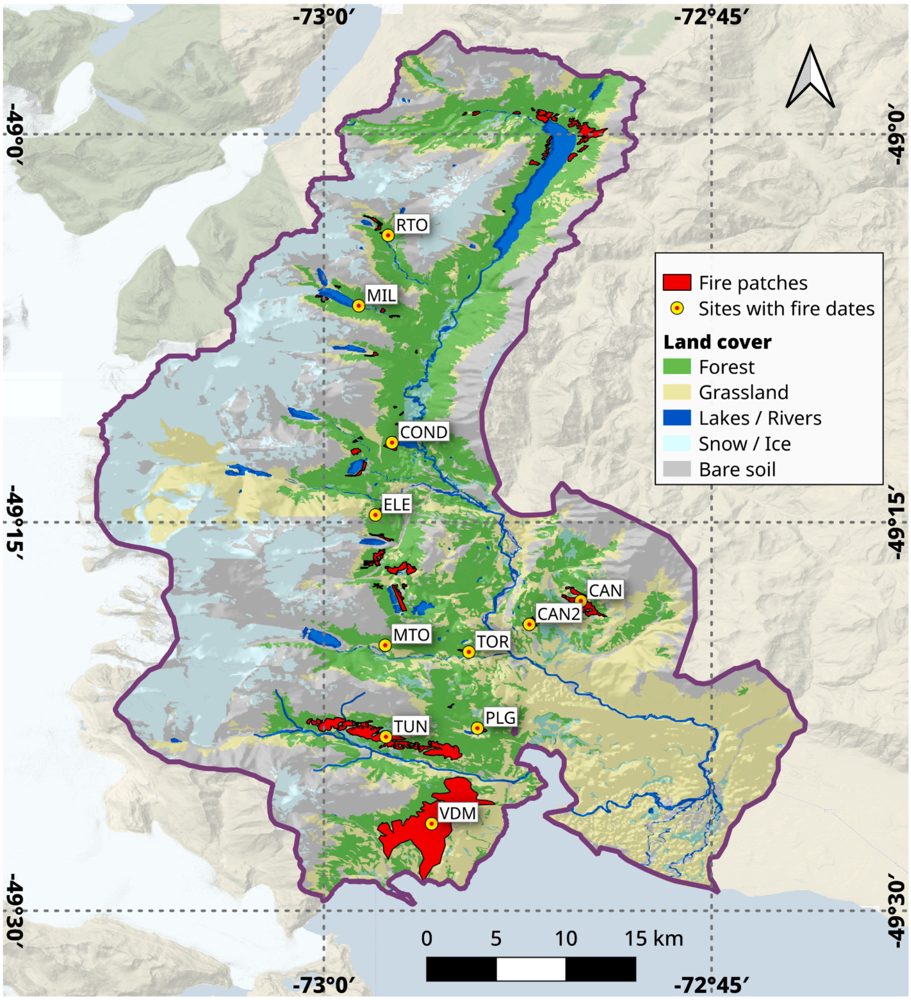

Fig. 3. Location of the fire patches (red polygons) and study sites where it was possible to date fire scars (yellow dots).

fires that could be dated on certain years are available. In addition, most of the fire patches are more than fifty years old, prior to the availability of remote sensing imagery. Moreover, it was not possible to carry out a systematic temporal analysis of the fire patches from recent fires. Therefore, we arrive at two or more fire date per patch. These drawbacks limited our analysis and we were not able to relate each identified fire date to a fire patch size.

2.3.1. *Fire history*

Fire frequency estimates were derived from eight existing fire chronologies (Mundo et al., 2017) plus three new chronologies: Milodón (MIL), Pliegue Tumbado (PLG) and Viedma (VDM) developed within the RV-RTB (Table 2 and Fig. 3). The MIL chronology is a composite from four patches within the Milodón valley, while PLG and VDM are individual patch chronologies.

Considering the location (see Fig. 3) and similarity in vegetation characteristics between sites, we grouped six chronologies developed by (Mundo et al., 2017) into three composites: ELE + CON, MTO + TOR and CANIGO (CAN + CAN2). The chronologies and composites were developed using the FHAES program (Brewer et al., 2016) and the standard fire statistics calculation performed in R (R Core Team, 2018) with the burnr package, version 0.2.2 (Malevich et al., 2018).

To account for changes in the vegetation gradient, we divided the basin into 100 m horizontal strips and calculated the total area covered by forest and grassland in each band. To explore changes in the number and size of fire patches along the precipitation and vegetation gradients,

Table 2
Summary of fire chronologies and fire interval statistics.

Sites		N	Period	Fire dates†		Fire intervals		
				First–Last	Number of events	MFI	SD	Range
North	RTO + MIL	92 (71 %)	1705–2014	1843–1994	19	8.4	12.0	1–45
	ELE + CON	35 (70 %)	1797–2010	1959–1999	9	5.7	4.0	2–11
Central	MTO + TOR	25 (78 %)	1845–2010	1912–2003	9	11.4	14.8	2–46
	CANIGO	28 (65 %)	1865–2010	1930–1986	6	11.2	11.4	3–31
South	TUN	16 (50 %)	1695–2010	1938–2003	5	16.2	11.1	6–29
	PLG	25 (66 %)	1846–2014	1929–2003	4	24.7	15.7	7–37
	VDM	17 (44 %)	1814–2014	1924	1	–	–	–

N, number of dated samples (% of samples); MFI, mean fire interval; SD, standard deviation; –, too few intervals to perform the analyses. † Recorded in at least two individual trees.

we divided the basin, from north to south, into 5 latitudinal sections each measuring 12.5 km in length. For each section, we counted the total number of fire events and the average fire size.

2.3.2. Fire variability

To evaluate the factors influencing the probability of fire occurrence (i.e., that any given point in space will burn), we generated a fire distribution model (FDM) over grid (see Section 2.2.2). The FDM was fitted with Maxent software (Phillips et al., Internet), which uses a maximum entropy approach. Maxent has previously been successfully applied for the spatial modeling of fire occurrence at regional and global scales (Chen et al., 2021; Fonseca et al., 2017; Kim et al., 2019; Mansuy et al., 2019; Paritsis et al., 2013). To reduce collinearity, we evaluated Pearson's correlations among predictors and removed those showing a coefficient >0.6. Following this criterion, we removed longitude (correlated with land cover and distance to settlements and hiking trails), total radiation (correlated with slope) and distance to roads (correlated with distance to settlements). The algorithm of Maxent uses presence-only data of the variable of interest (i.e., burned points or cells), and compares the environmental predictors associated with these points with the mean environmental variables for the remaining points in the study region (Elith et al., 2011). We fitted the FDM by randomly selecting one cell per fire thus each fire contributed to the model with one presence data, avoiding within-fire spatial autocorrelation. To avoid spatial bias, we used the 'block' method of the ENMeval package for partitioning data into four bins of (insofar as possible) equal numbers of occurrences according to latitude and longitude (Muscarella et al., 2014). To evaluate the model, we used the area under the receiver operating characteristic (ROC) curve (AUC) adjusted for presence only data (Phillips et al., 2006). The AUC measures the ability of a model to discriminate between conditions at occurrence points and those from background localities (Muscarella et al., 2014). An AUC close to 1 denotes a model with perfect discrimination, whereas an AUC of 0.5 is no better than random. We estimated the relative contribution of each variable considering the increase or decrease in model gain in each iteration of the training algorithm, then normalized it to percentages (the contribution increases as the AUC decreases; (Phillips et al., 2006). This contribution depends only on the final Maxent model and not on the path used to obtain it (Muscarella et al., 2014). The effect of each variable on fire probability was analyzed evaluating the fluctuations of its response curves (predicted logistic probability) while holding all the other variables at their sample median value (Hijmans et al., 2017). Once the final FDM was obtained, we used it to generate a fire probability map for the basins. Since the model does not consider temporal variations, the map represents the probability of fire at one point under mean environmental conditions. We ran Maxent and all the associated processes in the R environment, using the packages dismo version 1.1–4 (Hijmans et al., 2017) and ENMeval version 2.0.3 (Muscarella et al., 2014).

For assessing the factors driving fire patch size, we fitted a set of general linear models using individual fires as the statistical unit and their sizes as the response variable. Fire size distribution was characterized by many small fires and a small number of large fires. Therefore, the fire size was log-transformed to correct the skewed distribution. We explored Pearson's correlation coefficient between predictors and conducted a Factor Inflation Variance (FIV) analysis, removing collinear predictors. The global model was fitted using the quantitative predictors for latitude, longitude, and elevation (climate proxies), slope, easting, radiation, distance to water courses (landscape variables), distances to rural roads and buildings (anthropic variables). Model fit failed to improve with spatial correlation structures, probably since latitude and longitude were included as predictors. Therefore, we fitted non-spatial models (ordinary least-squares). Model selection was performed under a multi-model inference framework (Burnham and Anderson, 2010). We used the Akaike Information Criterion (AIC) as a parsimony measure to decide which terms of the global models were the most relevant (Burnham et al., 2011). We calculated the relative importance (ω_i), which sums the 'Akaike weights' over all models including the predictor, and for each predictor we compared the AIC of the global model with that of the corresponding model without the predictor (Δ_i).

2.3.3. Regional climate influence on fire occurrence

To evaluate the influence of the regional water deficit (precipitation minus evapotranspiration) on fire occurrence within the basin, we estimated the proportion of fire events occurring under deficit (−) or surplus (+) conditions according to SPEI. Following Kingston et al. (2015) a six-month accumulation period (SPEI-6) was selected to reflect both summer rainfall and winter snowfall deficits. To determine whether fires occurred disproportionately during a particular condition we divided the basin into three sub-regions, North (RTO + MIL and ELE + CON), Central (MTO + TOR and CAN) and South (TUN, PLG and VDM), and compared the proportion of events under deficit or surplus conditions to the proportion of years that fell within each condition during the 1901–2016 period (*sensu* Schoennagel et al., 2005). For each sub-region, we used Chi-square tests to assess departure from expected frequency and Superposed Epoch Analyses (SEA; Grissino-Mayer, 1995) between fire years of large fires areas (>100 ha) and December SPEI-6 (i.e. from July to December). SEA determines the relationships between fire events and climatic data (or climate proxies) in the years prior to, during, and following a fire event. Average values of December SPEI-6 data were calculated for five and two years prior and after a fire, respectively. December SPEI-6 values during the fire event years were compared to variations in the complete record by performing 1000 Monte Carlo simulations (randomly selecting years) to estimate the expected means and the 95 % bootstrap confidence intervals (Grissino-Mayer, 1995; Mooney and Duval, 1993). In each case, the number of randomly selected years equals the number of actual fire years. We compared standard deviations of the mean values of December SPEI-6 against the averages for years of fires identified in burned areas of>100 ha. SEAs were estimated for both the entire record and two subperiods before and after 1970. In the 1970 decade, a new process of human settlement started in the RV-RTB and the boundaries of Los Glaciares National Park were extended including the forests in the southern part of the basins. SEAs were conducted using the program EVENT version 6.02P (http://www.ltrr.arizona.edu/).

3. Results

3.1. Fire history

The size of the 56 post-fire patches ranged from 0.5 to 1264.6 ha, with an average of 44.1 ha and a median of 4.5 ha. Of the 155 new fire-scarred partial cross sections collected, 106 (68 %) were successfully cross-dated. However, assessment of fire seasonality was not possible. Regarding the number of scars per sample, 74 samples were classified as single scarred, 23 presented two fire scars and nine had three fire scars. From the 106 samples, we identified 53 fire dates distributed in 18 patches (Fig. 3 and Table 2). The oldest fires occurred in 1843 and 1888 at the RTO site (north of the basin). The first fire of the 20th century was recorded in 1912 at the MTO site (central basin). The following fires dated back to 1924 in VDM and 1929 in PLG, south sector of the study area, in the forest-steppe ecotone. The most recent fires in the basins occurred in 1999 at ELE + CON and MTO + TOR sites and in 2003 at MTO + TOR, TUN and PLG. From 1924 to 1941 we registered the first group of 10 events with a mean fire interval (MFI) of 2.3 years. Following these events, no fire dates were registered between 1942 and 1950, then from 1951 to 2003 the MFI was 2.2 years, similar to the first period (1924 to 1941). From 1951 to 2003, two sub-periods of six years without fires (1951–1956 and 1988–1994; Fig. 4) were registered.

The spatial distribution of fires showed a marked north–south gradient (Table 2 and Figs. 4 and 5). At the temporal scale, changes in location over time were also identified following the north–south

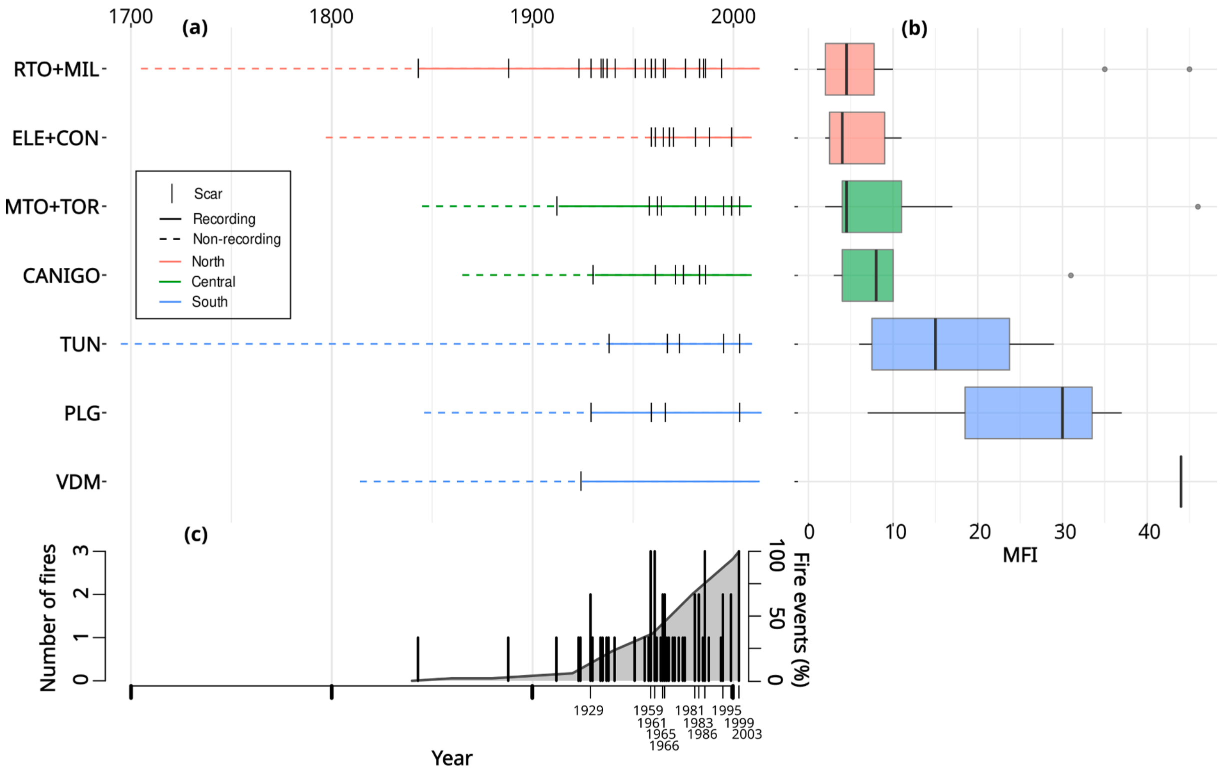

Fig. 4. Study sites where it was possible to date fire scars ordered from north to south, (a) fire chronologies, (b) Mean Fire Interval (MFI) and (c) number of fires (black bars) and accumulated fire events (gray shaded). Dates indicate multiple fires years.

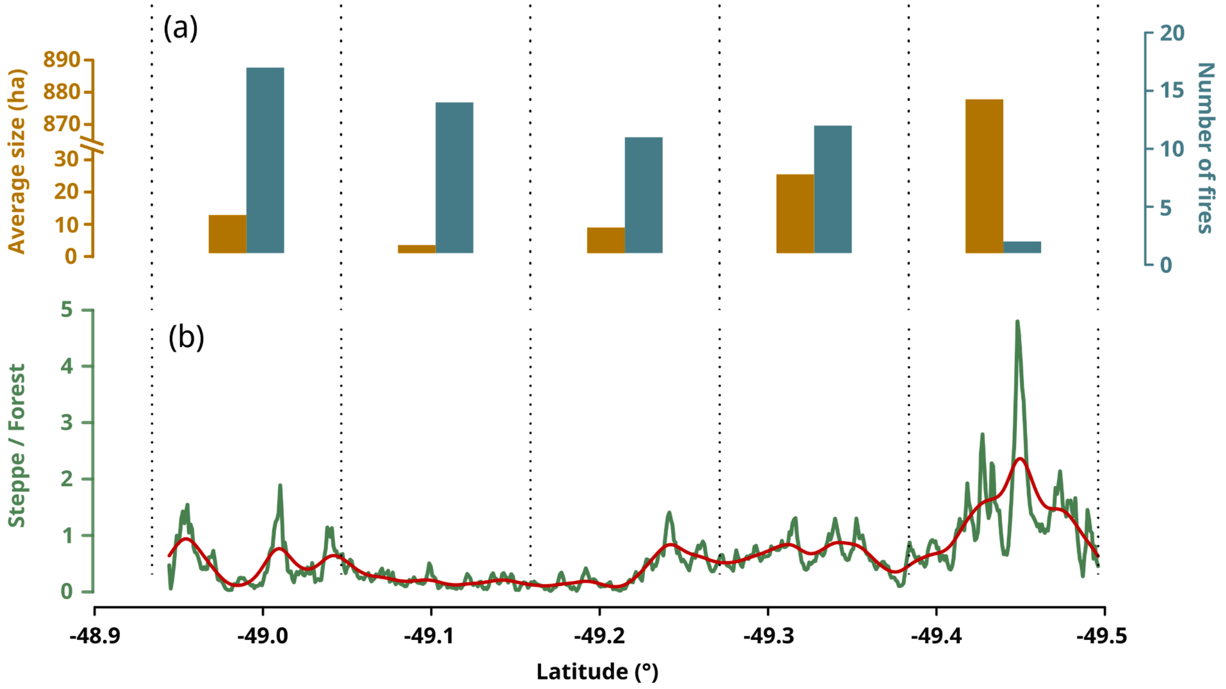

Fig. 5. Spatial distribution of fire patches. The basin was divided into five latitudinal sections (dotted lines), (a) number of fires (light blue) and average of fire size (yellow) in each section, and (b) ratio of steppe/forest area, computed every 100 m (green) and the fitted cubic smoothing spline (red).

gradient. Until 1956, 67 % of the ignitions were located in the northern sector of the basin. During the period 1956–1988, the fire locations were more evenly distributed, 54 % occurred in the north and the remaining 46 % in the center and south sectors of the basin. Finally, between 1994 and 2003, only 25 % of the ignitions occurred in the northern sector. Following the north–south direction along the basin, the number of fires decreased, the size of the burned patches increased and the ratio of steppe to forest cover increased (Fig. 5).

3.2. *Fire variability*

When evaluating the drivers of fire probability, the best FDM model reached an AUC = 0.87 and the most significant variables (ordered according to their contributions) were distance to human settlements (39.3 %), elevation (37.3 %), and latitude (11.0 %). Less significant variables were distance to hiking trails (4.9 %), easting (4.8 %), northing (1.4 %), distance to rivers (0.9 %), and slope (0.5 %). The response curves (Fig. 6) of the three main variables indicated that fire probability decreased with distance to human settlements; increased up to an elevation of ~ 700 m and decreased at higher elevations (the mean elevation of the basin is 641.5 m) and increased towards the north, where the forest is relatively more humid and dense than in the south. These relationships were reflected in the resulting probability map obtained from the FDM (Fig. 7).

The best-ranked fire size model included latitude, longitude, and easting as predictors. The estimates of the model indicated that the fire size increased southward and eastward, and fires were larger on hillsides facing east (Table 3). Latitude and longitude (proxies of precipitation and vegetation) were the most important predictors explaining fire size. Both geographical variables had a relative importance close to 1 (Table 4). When latitude or longitude were excluded from the global model, AIC increased (Δ_i) by>7 units indicating a poorer performance of the model without these variables (Table 4). Although easting was selected in the best model and its confidence interval did not included zero (Table 3), suggesting some influence on fire size, the relative importance and the change in AIC when it was excluded from the model were relatively low (ωi ≈ 0.6 and $\Delta_i < 2$, Table 4).

3.3. Regional climate influence on fire occurrence

Between 1901 and 2016, the proportion of fire years across the RV-RTB that occurred under water deficit or surplus was evenly distributed, ~50 % in December SPEI-6 deficit (-) or surplus (+) conditions. However, different proportions were observed when the basin analysis included the North, Central and South sectors (Fig. 8). The proportion of fires that occurred during drier years increased from north (~66 %) to south (~80 %). Fire occurrence during dry conditions was significantly higher than expected in the South sector ($n = 15$, $\chi^2 = 5.096$, $p = 0.024$). In contrast, in the North and Central sectors, even though the recorded fires under dry conditions were higher than expected by chance, they were not significantly different from those observed in wet periods ($n = 18$, $\chi^2 = 1.799$, $p = 0.180$ and $n = 14$, $\chi^2 = 2.369$, $p = 0.124$ respectively). Superposed Epoch Analyses performed over the entire period

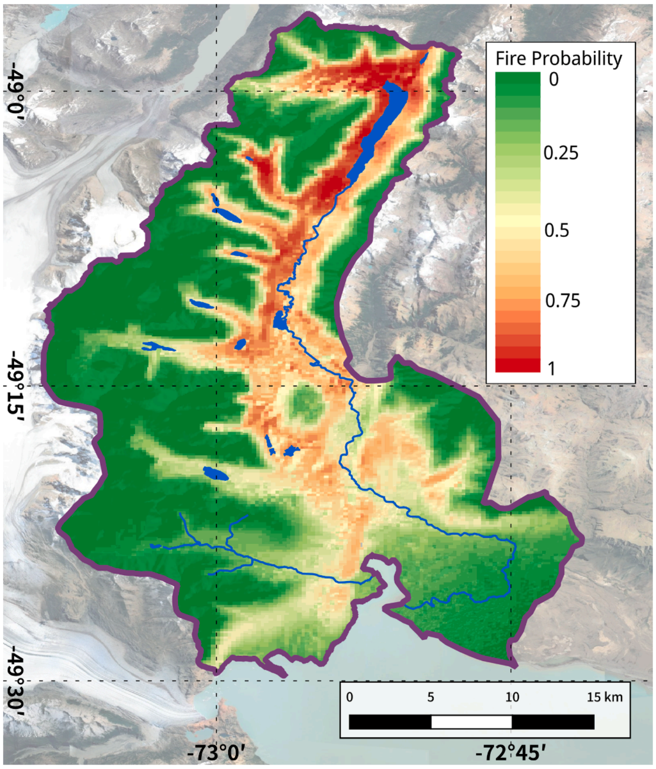

Fig. 7. Fire probability according to the Fire Distribution Model (FDM).

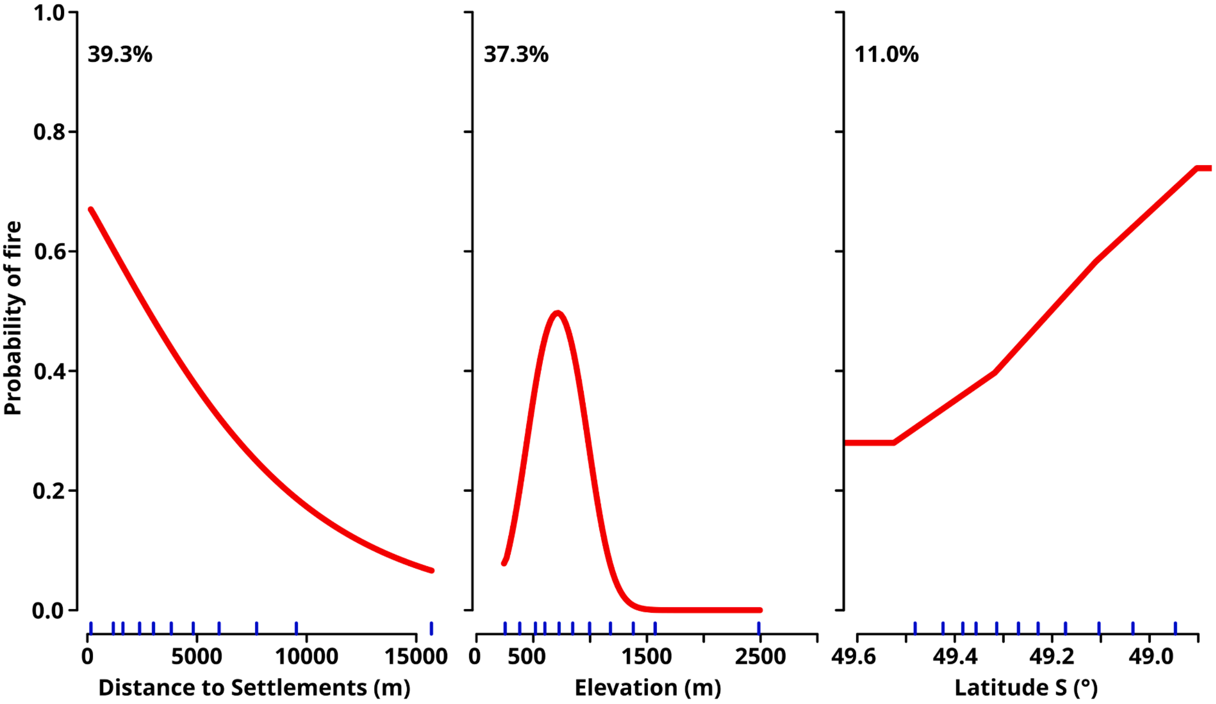

Fig. 6. Response curves of the three main variables of the Fire Distribution Model (FDM) indicating the influence of each one in the final model. The curves show how the logistic prediction changes as each predictor varies while holding all the other variables at their sample median value. Percentage contribution of the predictor variable to the model is shown in the upper-left corner of each plot.

Table 3
Estimated parameters and confidence intervals (CI) for the best-ranked model explaining (ln) fire size after multi-model inference.

Parameter	*Estimate*	CI 95 %
$\beta 0$ *(intercept)*	471.22	−31.24 to 973.68
$\beta 1$ *(latitude)*	−6.72	−9.76 to −3.67
$\beta 2$ *(longitude)*	10.83	3.29–18.38
$\beta 2$ *(easting)*	−0.53	−1.02 to −0.04
σ^2 *(residual standar error)*	1.32	–

Table 4
Metrics used to quantify the relative strength of each fire size predictor. Relative importance (*wi)* sums the ‘Akaike weights’ over all models including the predictor. The difference between AIC of the global model and the AIC of the model without the predictor being evaluated, is represented by Δ*i*.

	Predictor	*wi*	Δ*i*
Climate	*Latitude*	1.00	16.46
	Longitude	0.97	7.67
Landscape	*Slope*	0.26	−1.21
	Elevation	0.23	−1.77
	Easting	0.63	0.80
	Radiation	0.24	−1.88
	Distance to water courses	0.49	0.12
Anthropic	*Distance to buildings*	0.38	−0.98
	Distance to rural roads	0.28	−1.91

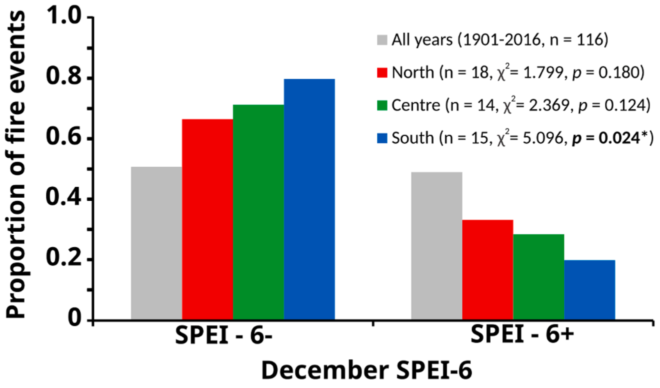

Fig. 8. Proportion of fire events in North (red bars, n = 18), Central (green bars, n = 14) and South (blue bars, n = 15) of the basin relative to the expected total proportion of years during the period 1901–2016 (gray bars, n = 116) under deficit (SPEI – 6−) or surplus (SPEI – 6+) conditions. Chi-square tests show that the proportion of fires in the South of the basin are significantly different from the expected frequency ($p = 0.02$). The frequency of fires in North and Centre did not differ significantly from expected ($p > 0.12$).

(1919–2005) for large fires (>100 ha) indicated that departures from the mean December SPEI-6 were non-significant between positive *versus* negative December SPEI-6 intervals (Fig. 9a). However, December SPEI-6 deviations were negatively significant one to two years prior to fire years for the 1919–1969 period (Fig. 9b), but not during the period that followed from 1970 to 2005 (Fig. 9c).

4. Discussion

In this paper, the influence of climate, landscape, and human activities on fires was assessed. In contrast to previous studies in southern Patagonia, which covered areas of several thousand square kilometers (Holz and Veblen, 2011; Mundo et al., 2017; Paritsis et al., 2013), or regions with different climate and settlement history (Holz et al., 2015; Veblen et al., 1999), this manuscript analyzes fire drivers at the basin-scale, specifically for an area of <1000 km^2. This approach allowed us to analyze and interpret the fire records in detail within the context of land use changes in a catchment exposed to pronounced environmental gradients.

4.1. *Human activities influence on spatio-temporal fire occurrences*

Following Mundo et al. (2017), we incorporated additional fire histories in the RV-RTB to improve the spatio-temporal resolutions of fire records. The new data allowed us to detect years with fire events in sites not previously recorded and to identify sectors in the RV-RTB with differences in fire patterns. The environmental gradients imposed by decreasing temperature with elevation and declining precipitation from northwest to southeast, shape the vegetation along the RV-RTB. Since the beginning of the 20th century, the colonization process of this territory interacted with these natural gradients imprinting differences in fire regimes along these contiguous basins. In contrast to many North American regions, where fire activity decreased with the arrival of European settlers by reducing some Native American burning practices by imposing fire suppression policies (Caprio and Swetnam, 1995), the arrival of European, Argentinean and Chilean colonists in the RV-RTB in late 19th-early 20th centuries markedly increased the occurrence of fires. This is a common pattern largely documented along the Patagonian Andes in both Argentina and Chile (Veblen and Lorenz, 1988; Veblen et al., 1999; Holz and Veblen, 2011; Holz et al., 2016). In a basin near the study site, Mancini et al. (2011) also reported extensive areas of burned forest for grazing since Europeans settled in the region at the end of the 19th century. Consistent with these observations, the FDM indicated that human settlement (rural cabins, camping sites and tourist lodges) is the main driver of fire ignition throughout the basin (Fig. 6).

The regional fire history becomes reliable at the end of the 19th century-beginning of the 20th century with the events of 1888 and 1912 (Fig. 4). These two events coincided with the arrival of the very first settlers in the valley (Halvorsen, 1997). The earliest scientific explorations in the region mentioned the presence of extensive cattle ranching activities in the drier southeastern sector of the valley before 1914. However, there are no specific references to the occurrence of forest fires. Maps developed by Kölliker et al. (1917) show the presence of forest cover in nearby Lago Viedma, where very large fire patches, such as VDM and TUN (Fig. 3), are presently located. The priest Alberto de Agostini (1945) was the first to describe and document the presence of large, burned areas in the RV-RTB in the 1930′s. Consistent with de Agostinís descriptions, we recorded an increase in fire frequency between 1924 and 1941 (the first group of fires with a MFI of 2.3 years) linked to the arrival of a new wave of settlers (Halvorsen, 1997).

Human settlements in the RV-RTB can be chronologically divided into two phases with different approaches to fire. Human activities in the basins gradually changed from extensive cattle ranching to tourism. At first, early settlers used fire as a management tool to open forests for livestock. Current residents, mostly concentrated in the touristic town of El Chaltén (Fig. 1), tend to exhibit pro-environmental behavior. While in the early 20th century settlers were the main cause of deliberate burning for cattle grazing, in the last decades of the 20th century unintentional events related to tourism were the main cause of fires. Presently, tourism is the major income for both the residents in the town of El Chaltén and the former cattle ranchers located in the basin, therefore intentional burning to clear forests for grazing is no longer a common practice. Consequently, the cessation of fires since 2003 is unlikely to be related to climate conditions. December SPEI-6 has been predominantly negative since the early 21st century (Fig. 10), and in the context of the past 100 years, the period 2000–2016 has been comparatively warm and dry (Fig. 11). The December SPEI-6 values recorded during this period are equivalent to those observed in the 1960′s, when high fire frequency was observed. Increased awareness of local people on the role that forests play as providers of ecosystem services, more effective performance of fire suppression programs and the increased control on tourism activities, seem to be the factors most strongly associated with the absence of fires in the RV-RTB since 2003. In contrast to Northern Argentinean

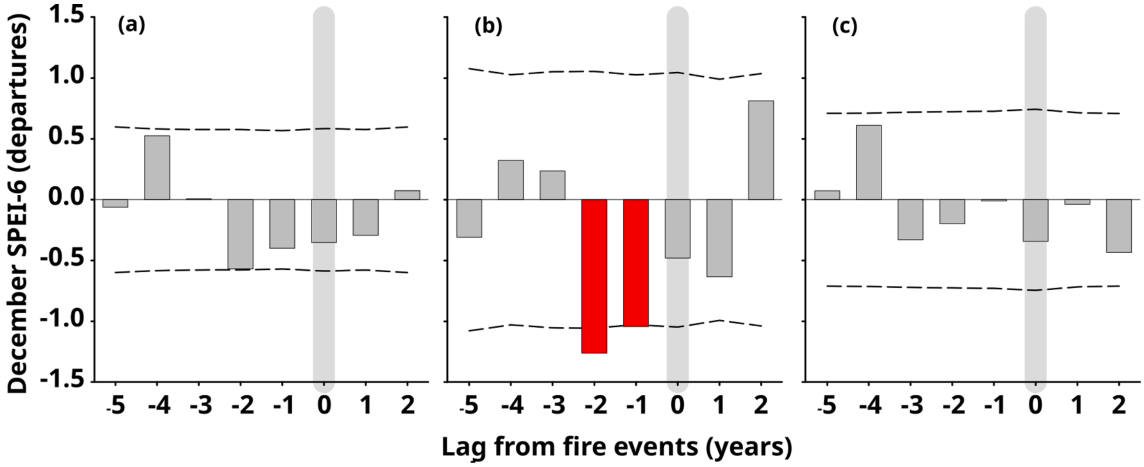

Fig. 9. Results from SEAs performed on years with large fires (>100 ha). Departure (standard deviations) from the mean values of December SPEI-6 over the period: a) 1919–2005 (n = 12), b) 1919–1969 (n = 5) and c) 1970–2005 (n = 7) for years before, during and after fire years (0). Red bars indicate statistically significant differences ($p < 0.05$), dashed lines represent the 95 % confidence limits.

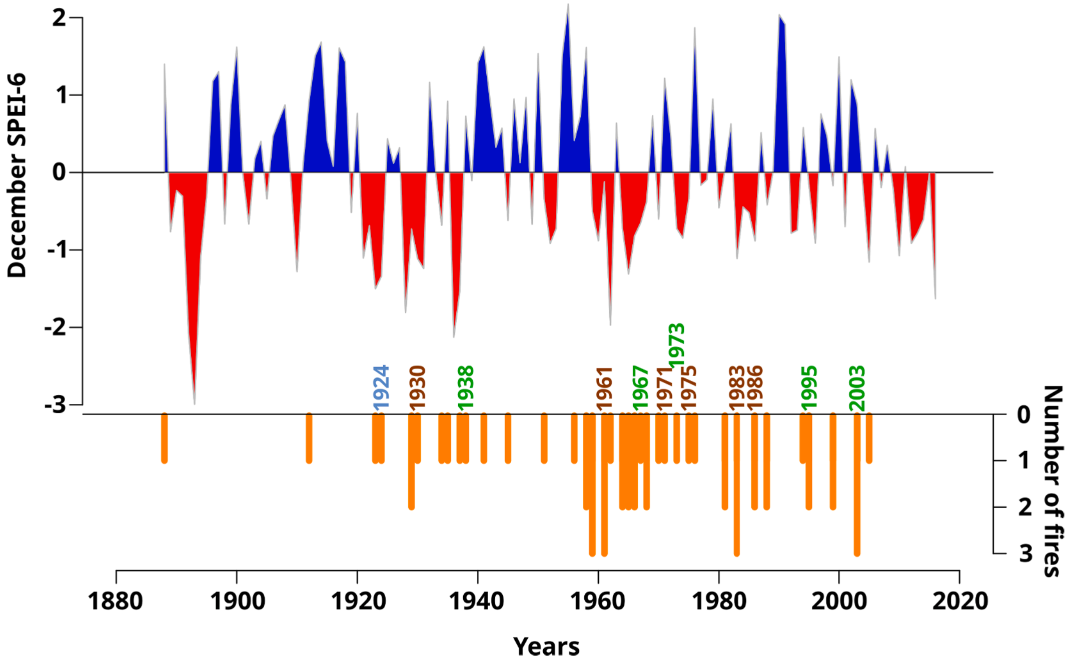

Fig. 10. December SPEI-6 (upper panel) and orange vertical lines indicating year of occurrence and number of fire events (lower panel). Dates indicate years with large fires (>100 ha), light blue = VDM brown = CAN, green = TUN.

Patagonia, where fire control practices started earlier in the 1940′s and 1950′s (Kitzberger and Veblen, 1999), fire control management in the Southern Andes is much more recent.

Changes in fire regimes were also evident in space. At the time of colonization in the first half of the 20th century, small fires were more frequent in the northern sector of the RV-RTB. Sixty-seven percent of the fires ignited in the basin occurred in the humid northern sector to open up areas for livestock. Towards the end of the 20th century, following the increase in tourism activities, fires occurred mainly in the southern sector of the basin nearby El Chaltén town. By the end of the 20th century, only 25 % of the fires occurred in the northern part of the basin.

4.2. *Climate and landscape influence on fires spatial extent*

Although human activities largely modulated fire occurrence in the RV-RTB, we noted a strong relationship between extensive fire occurrence and regional climatic conditions up to the late 1960′s. The size and number of fires are associated with latitude and longitude (Table 4 and Fig. 5), the two spatial proxies that represent variations in annual precipitation, which in turn define the location of the forest-steppe ecotone in the lower sector of the basin (Fig. 5). Consistent with observations by Pausas and Paula (2012), the smallest but most numerous fires were located in the northwestern sites of the RV-RTB, where more abundant precipitation limited fire spread. Conversely, decreasing precipitation towards the southeast reduces forest productivity and increases the abundance of xeric grasslands, providing conditions conducive to fire spread without fuel load limitations. Three of the driest periods on record occurred during the first half of the 20th century. It is noteworthy that the earliest fire dates for the three largest (>100 ha) fire patches in the basins, were concurrent with these extreme dry periods. They occurred after consecutive years with extreme water deficits, suggesting that prolonged dry conditions facilitate fire spread

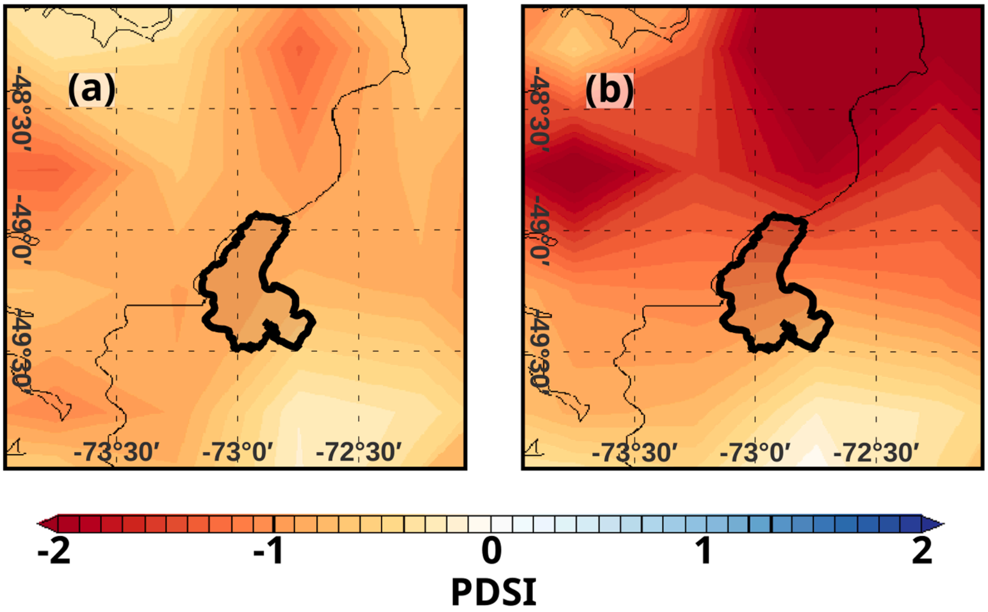

Fig. 11. Basin boundary (gray continuous line) over instrumental PDSI composite of July–December (as in December SPEI-6) for the periods (a) 1901–1999 and (b) 2000–2016 (Morales et al., 2020; http://drought.memphis.edu/SADA/). The PDSI during the period 2000–2006 is noticeably lower than that recorded over the previous 99 years.

(Fig. 9b and 10). The VDM patch, which extends 1264.6 ha, is associated with a single fire date in 1924, which was preceded by 5 years of negative December SPEI-6 values. The other two patches, TUN and CAN, were dated to fires in 1930, 1938 and 1967, all of which took place after several years of negative December SPEI-6 (Fig. 10). Although these fires were anthropogenic in origin, the extensive burned areas reflect the marked long-term water deficits concurrent with their ignition. On the other hand, the influence of climate on fire occurrence in the northern and central parts of the basin is more ambiguous (Fig. 8), suggesting that at a local scale, as recorded in other regions (Kitchen, 2016), human activities prevail as the major forcing of fire occurrence.

5. Concluding remarks

Our work supports previous findings of the large-scale fire history in southern Patagonia, while highlighting the importance of the interactions between environmental gradients and human activities in modulating the fire regime at the basin level. The likelihood of fire occurrence in the RV-RTB largely depends on human activities, however the fire size and number are influenced by climate and landscape conditions. Assessments of fire recurrence, fire spatial patterns and fire probability (FDM) strongly point to the dominant anthropogenic influence on the fire regime at the RV-RTB. Most of the fires occurred during the arrival of European, Chilean, and Argentinean settlers in the early 20th century. Following traditional practices, the new settlers burned the forests to create pastures for cattle. In the southern sector of the composite basin, few extensive, high-intensity fires were sufficient to provide large grazing areas for cattle. In contrast, in the denser rainforests in the north, the small size of burned patches forced settlers to intensify burning practices, increasing the frequency and, consequently, the number of fires. The different fire regimes across the catchments reflect differences in settler fire management, initially conditioned by the fire propensity to spread, but ultimately modulated by site location along the precipitation gradient.

In the present context of climatic changes affecting *N. pumilio* establishment in the lower elevations of the RV-RTB (Aschero et al., 2022), forest conservation will depend on policies based on our understanding of the interactions between climate, landscape, and human-induced disturbances that cause fire. Our contribution to understand fire regimes along biophysical gradients subject to changing anthropogenic activities provides an important link to global approaches searching for future fire trajectories (Paritsis et al., 2013).

Unlike fire studies over large regions, the basin approach can account for the particular history of human occupation. Differences in human traditions and practices of land use, induce marked disparities in relevant settlement processes, which may be blurred or difficult of incorporate in large-scale spatial studies. Interactions between unique occupation history and environmental specificities may introduce differences in fire regimes between neighboring catchments that are not captured at larger spatial scales.

CRediT authorship contribution statement

Lucas O. Bianchi: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. **Ricardo Villalba:** Conceptualization, Funding acquisition, Methodology, Investigation, Supervision, Writing – original draft. **Facundo J. Oddi:** Formal analysis, Writing – original draft. **Ignacio A. Mundo:** Conceptualization, Methodology, Formal analysis, Writing – original draft. **Marcos Radins:** Investigation, Writing – original draft. **Mariano M. Amoroso:** Conceptualization, Writing – original draft. **Ana Marina Srur:** Conceptualization, Writing – original draft. **Anabela Bonada:** Investigation, Writing – original draft.

Declaration of Competing Interest

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Data availability

Data will be made available on request.

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