Climate variability and forest fires in central and south-central Chile

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Abstract. This paper evaluates the relationship between fire occurrence (number and burned area) and climate variability (precipitation and maximum temperatures) across central and south-central Chile (32°–43° S) during recent decades (1976–2013). This region sustains the largest proportion of the Chilean population, contains ecologically important remnants of endemic ecosystems, the largest extension of forest exotic plantations, and concentrates most of the fire activity in the country. Fire activity in central Chile was mainly associated with above-average precipitation during winter of the previous year and with dry conditions during spring to summer. The later association was particularly strong in the southern, wetter part of the study region. Maximum temperature had a positive significant relationship with burned area across the study region, with stronger correlations toward the south. Fires in central Chile were significantly related to El Niño–Southern Oscillation, through rainfall anomalies during the year previous to the fire season. The Antarctic Oscillation during winter through summer was positively related to fires across the study area due to drier/warmer conditions associated with the positive polarity of this oscillation. Climate change projections for the region reveal an all-season decrease in precipitation and increases in temperature, that may likely result in an increment of the occurrence and the area affected by fires, as it has been observed during a multi-year drought afflicting central Chile since 2010.

Key words: Antarctic Oscillation; climate change; El Niño–Southern Oscillation (ENSO); exotic plantations; forest fires; Mediterranean forests; temperate forests.

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INTRODUCTION

Forest fires constitute an important agent that shapes the distribution and ecological properties of major world biomes (Bond et al. 2005). Wildfires are a common feature in Mediterranean areas, being fundamental in the ecology and evolution of flora in these regions (Bond and Van Wilgen 1996, Montenegro et al. 2004, Bowman et al. 2009, Pausas and Keeley 2009, Keeley et al. 2012), and they are an important disturbance agent in diverse ecosystems ranging from boreal forests to tropical savannas (Koutsias et al. 2013).

Wildfire activity in different regions of the world has increased during recent decades, partially related to extended droughts, and it is expected that it will continue to increase owing to climate change (Mouillot and Field 2005, Trenberth et al. 2007, Moritz et al. 2012, Liu et al. 2014, Abatzoglou and Williams 2016). Research

suggests a general increase in fire frequency, burned area, and fire size, as well as a general extension of the fire season and burning intensity in different regions during recent decades (Flannigan et al. 2009, Krawchuk et al. 2009, Pausas and Fernandez-Muñoz 2012, Zumbrunnen et al. 2012, Barbero et al. 2014, Dennison et al. 2014). Since fires can have diverse impacts on ecosystem functioning and biodiversity (Cochrane 2003, Lindenmayer et al. 2014, Thom and Seidl 2016), there is an increasing interest in understanding the drivers of fire activity worldwide (Westerling et al. 2006, Marlon et al. 2008, Krawchuk and Moritz 2011).

Variability of meteorological conditions at both intra-monthly (weather) and interannual (climate) time-scales is a major driver of fire behavior and activity. Weather, for instance, can act directly igniting fires through lightning or modulating their behavior through winds, air temperature, and moisture (Flannigan et al. 2009, Bradstock 2010, Sullivan et al. 2012). The influence of interannual climate variability on fire activity, however, differs among vegetation formations due to differences in the constraints on wildfire activity associated with primary productivity (e.g., biomass to burn), atmospheric conditions suitable for combustion and propagation of fire, and sources of ignition (Westerling et al. 2003, Krawchuk and Moritz 2011, Pausas and Paula 2012). Thus, in xeric ecosystems of low biomass productivity and scarce burnable fuels, previous wet conditions may promote wildfires by enhancing biomass production, fuel loads, and flammability; in contrast, in mesic ecosystems of high productivity and biomass load, dry climate conditions are key for fire occurrence and spread (Renkin and Despain 1992, Kitzberger et al. 1997, Veblen et al. 1999, Pausas 2004, Pausas and Bradstock 2007, De Torres Curth et al. 2008, Littell and Gwozdz 2011). Interannual and longer climate variability mostly arise from changes in the atmospheric circulation in connection with planetary modes. Consequently, phenomena like El Niño–Southern Oscillation (ENSO) and the Antarctic Oscillation (AAO) have been shown to significantly influence fires and vegetation dynamics, mainly through their influence on regional climate and fuel conditions (Swetnam and Betancourt 1990, 1998, Kitzberger and Veblen 1997, Veblen et al. 2000, Holz et al. 2012, Mariani et al. 2016).

Annual and multidecadal variations in the occurrence of fires in south-central Chile, as well as in northern Argentinean Patagonia (38°–43° S), have been related to conditions in the tropical Pacific and to variations in mid- to high-latitude atmospheric circulation patterns (Kitzberger et al. 1997, Veblen et al. 1999, Kitzberger and Veblen 2003, González and Veblen 2006). In these regions, the increase in fire activity in forested areas tends to coincide with droughts, which in turn are associated with a more intense and southerly located Pacific Anticyclone which blocks the influx of Pacific moisture into the continent (Kitzberger et al. 1997, Montecinos et al. 2011). Multicentury fire history studies have linked forest fire activity in southern Chile and Argentina to warm and dry conditions associated with the positive phase of the AAO, as well as to below-average precipitation conditions associated with negative departures of ENSO and the Pacific Decadal Oscillation (Holz and Veblen 2012, Mundo et al. 2013, Holz et al. 2017).

Central and south-central Chile (32°–43° S; Fig. 1) sustain the largest proportion of the Chilean population (~90%), feature a climate transition from Mediterranean to Temperate (Di Castri and Hajek 1976), and contain ecologically important remnants of native ecosystems with an extraordinarily high endemism at the species and higher taxonomic levels (Armesto et al. 1996, Villagran and Hinojosa 1997). This region has suffered profound land-use changes in recent decades, with native forests and degraded lands being replaced by an extensive matrix of forest plantations, which has changed the fuel structure (load, continuity) and flammability of the landscape (Echeverría et al. 2006, Carmona et al. 2012, Nahuelhual et al. 2012, Taylor et al. 2017). Most of fire activity in the country is concentrated within this area, mainly due to the presence of abundant burnable biomass and relatively regular fuel-drying conditions (Holz et al. 2012). Available records of the factors causing fires in Chile during the last decade show that <1% are associated with natural causes (i.e., lightning, CONAF 2015). This indicates that, in contrast to other regions with Mediterranean climate, fires are almost entirely caused by humans in this part of the world (Keeley et al. 2012).

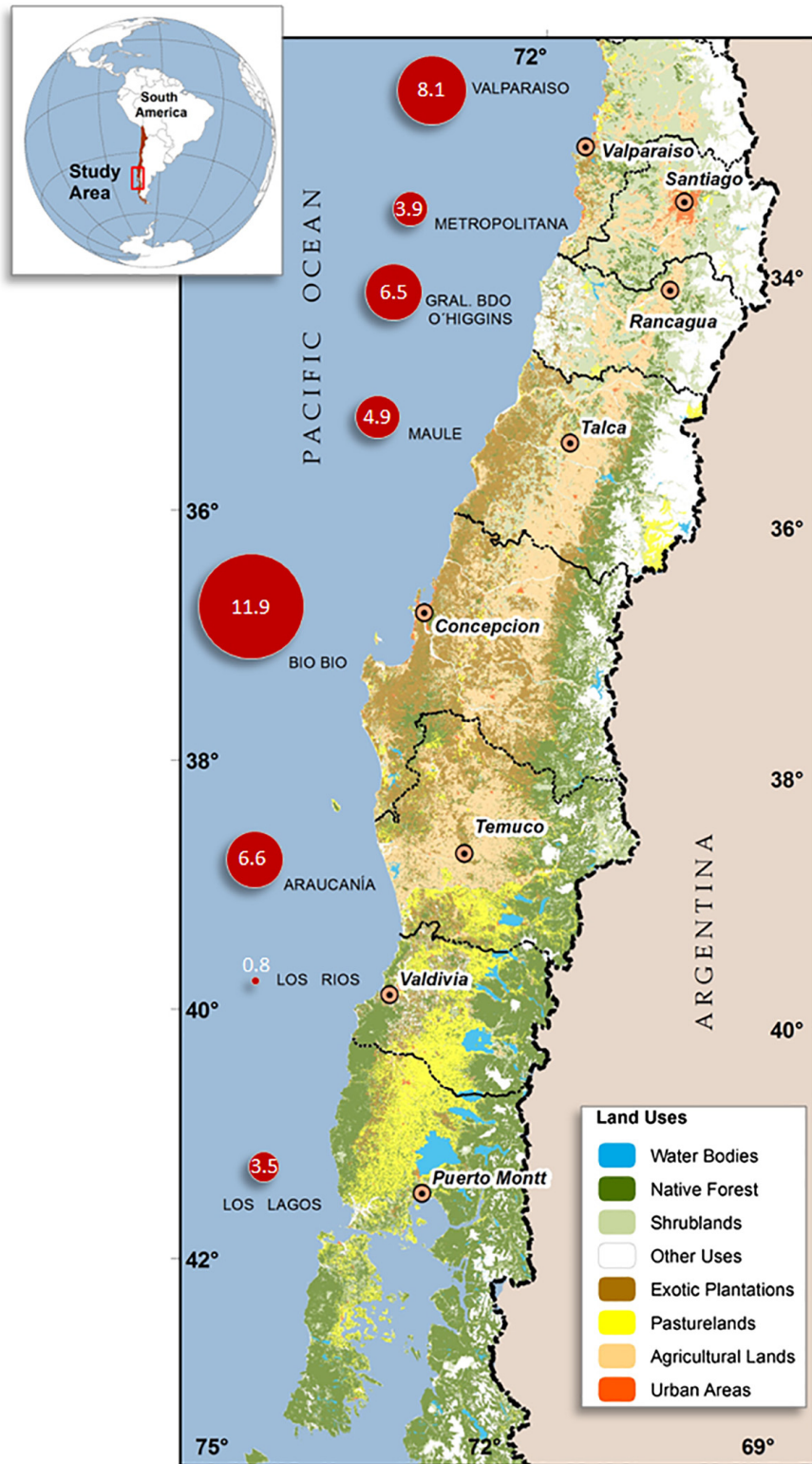In the last January and February 2017, over 500,000 ha were burned in Central Chile, the

Fig. 1. Land-use map of central and south-central Chile (Source: data obtained from sit.conaf.cl). The

(Fig. 1. *Continued*)

administrative regions and major cities are also shown. The red filled circles show the mean area burned in each region in the period 1976–2013 (white numbers are thousands of ha), and their size is proportional to this mean.

largest burned area in the last 40 yr (CONAF 2017). Given the social and economic importance of this area and its relatively high fire activity, it is crucial to understand the relationship between the occurrence of forest fires and climatic conditions. Documenting this association is also important to assess the impacts of the projected warming and drying trends during the rest of the 21st century (e.g., Fuenzalida et al. 2007) on the wildfire regime in this region (Veblen et al. 2008, 2011, González et al. 2011). Within this framework, the main objectives of this research are (1) to analyze the relationships between forest fires and maximum temperature and precipitation from weather stations in the region and (2) to examine the relationships between large-scale climate modes and fires across the study area. Holz et al. (2012) documented the climatic controls of fires in southwestern South America. In this research, we expand this previous work by (1) including fire statistics affecting all types of vegetation cover (not only native vegetation), (2) focusing on the most populated and fire vulnerable region of Chile, and (3) using a longer period of fire records and local weather stations in order to have a higher resolution analysis and a more detailed understanding of fire–climate relationships in the area. We end the article discussing the probable implications of current and future climate and land-use changes on fire regimes in the study area.

Study Area

The study area encompasses central and south-central Chile including eight administrative regions from about 32°–43° S (Fig. 1). This is the most populated area in the country (15.5 million inhabitants) and has undergone significant land-use changes throughout its history (Donoso and Lara 1996, Camus 2006). Extensive forest exploitation started with the arrival of European colonizers in the 16th and 17th centuries (Donoso and Lara 1996). Later in the 1800s, extensive native forests areas were cleared to be converted to agricultural crops (Nahuelhual et al. 2012).

More recently in the last decades (starting in the 1970s), extensive forest exotic plantations mainly composed by *Pinus radiata* and *Eucalyptus* spp. have been replacing native forests across the entire study area (Fig. 1; Echeverría et al. 2006, Lara et al. 2009, Nahuelhual et al. 2012).

The northern part of our study area (Valparaíso, Metropolitana, O'Higgins and Maule administrative regions) features a semiarid, Mediterranean-type climate with mean annual rainfall ranging from 100 to 500 mm in the central valley. Precipitation is largely concentrated in the austral winter (June–August; e.g., Viale and Garreaud 2015), thus leading to a long dry season with high solar radiation, low relative humidity, and high temperatures from approximately September to April (Miller 1976). To the south of ~38° S (Bío Bío, Araucanía, Los Ríos and Los Lagos administrative regions), climate is temperate with some Mediterranean influence and mean annual rainfall along the central valley increases to 1000–1500 mm. In contrast to the northern part, summer precipitation events do occur in the south every other week but only account for 15% of the annual accumulation (Lara et al. 2009, Viale and Garreaud 2015).

Interannual rainfall variability across the study area is driven by both low- and high-latitude climatic forcings (Garreaud et al. 2009). El Niño–Southern Oscillation accounts for about half of the winter rainfall variance in central Chile (30°–35° S), with a tendency for above (below) average precipitation during warm, El Niño (cold, La Niña) years (Montecinos and Aceituno 2003, Garreaud et al. 2009). South of 38° S the ENSO impacts during winter decrease but there is a weak relationship with late spring and summer precipitation that tends to be below average during El Niño years (Montecinos and Aceituno 2003). In addition to ENSO, the AAO or Southern Annular Mode (e.g., Thompson and Wallace 2000) also influences the climate of southern South America (Gillet et al. 2006, Garreaud et al. 2009). The positive polarity of the AAO is associated with stronger westerlies in the Antarctic periphery and

reduced westerlies at midlatitudes, thus leading to a significant rainfall decrease and positive temperature anomalies over southern Chile (37°–47° S; Quintana and Aceituno 2012, Villalba et al. 2012).

Natural vegetation in central Chile is characterized by matorral shrublands and woodlands of evergreen sclerophyllous species (~33°–35°30′ S; Fig. 1, Donoso 1982). These communities show a mixed dominance of many shrub species (e.g., *Escallonia pulverulenta* (Escalloniaceae), *Colliguaja odorifera* (Euphorbiaceae), and *Baccharis linearis* (Asteraceae), among others). Typical trees or tree-like shrubs include *Acacia caven* (Mimosaceae), *Quillaja saponaria* (Rosaceae), *Lithraea caustica* (Anacardiaceae), *Cryptocaria alba* (Lauraceae), and *Peumus boldus* (Monimiaceae). Farther south at higher elevations in the Coastal and Andean cordilleras, deciduous *Nothofagus* species (*N. obliqua*, *N. alessandrii*, and *N. glauca*, Nothofagaceae) become dominant. In the transition from the Mediterranean region of central Chile to the Temperate forests (35°30′–38° S), *N. obliqua* and *Nothofagus nervosa* are more abundant, and evergreen species (*Nothofagus dombeyi*, *Laureliopsis philippiana* [Monimiaceae], *Drimys winteri* [Winteraceae]) dominate the landscape in the southernmost Los Ríos and Los Lagos regions (39°–43° S).

DATA AND METHODS

Forest fire database

The forest fire database used in the present study comprises the period 1976–2013 (including the fire season 2013–2014). The data were provided by the National Forest Service (CONAF, www.conaf.cl/conaf/seccion-stadisticas-historicas.html) and include the number of fires and burned area per administrative region (Valparaíso to Los Lagos; Fig. 1) affecting all vegetation types (native and exotic), and only excluding agricultural open burnings of crops and grasses. Over 99% of the total fire events are included in this dataset (J. Bosnich, CONAF, *personal communication*). The fire season spans from 01 July to 30 June of the next year and fire statistics (number, burned area) are assigned to the year when the fire season starts. However, most fires occur between October and April (spring–summer), and their frequency peaks during January and February (more than 50% of the total

number of fires, CONAF 2015). Chilean fire management agents assess fire occurrence and burned area on site during firefighting campaigns, and fires >50 ha are mapped using a satellite-based navigation system reaching a precision of ±0.01 ha (J. Bosnich, CONAF, *personal communication*).

Climate data

Records of monthly accumulated rainfall and monthly mean maximum temperatures were available throughout the study area from the National Water Administration (DGA) and the National Weather Service (DMC). Mean temperature was not included in this study, because preliminary analyses suggested a stronger relationship between fires and maximum temperatures.

We employed 221 rainfall stations and 45 maximum temperature stations across central and south-central Chile (Fig. 2). These stations were selected from a larger pool of stations, because they contained at least 20 yr of records within 1976–2013. Given the large number of stations, and the known transition from Mediterranean to temperate climate in the area, a principal component analysis (PCA) was run for annual accumulated precipitation and annual mean maximum temperature separately, and groups of stations were identified latitudinally according to their major contribution (factor loading) to each of the leading three principal components. Regional series were then constructed averaging monthly records (standardized anomalies or Z values) of the stations assigned to each component. According to the PCA, the three groups of precipitation records across the latitudinal gradient were North (31°–34.5° S), Central (34.5°–36.9° S), and South (36.9°–43.6° S) and the explained variance of each component was 74%, 10%, and 3%, respectively. In the case of maximum temperature, three components were also obtained across the latitudinal gradient (North, 31°–35.4° S; Central, 35.4°–37.7° S; and South, 37.7°–43.6° S), accounting for 50%, 14%, and 8% of the variance, respectively. Note the overlap of regions defined by the mean precipitation and maximum temperature. Broadly, the northern climatic region encompassed Valparaíso, Metropolitana, and Bernardo O'Higgins administrative regions. The central climatic region encompassed part of the
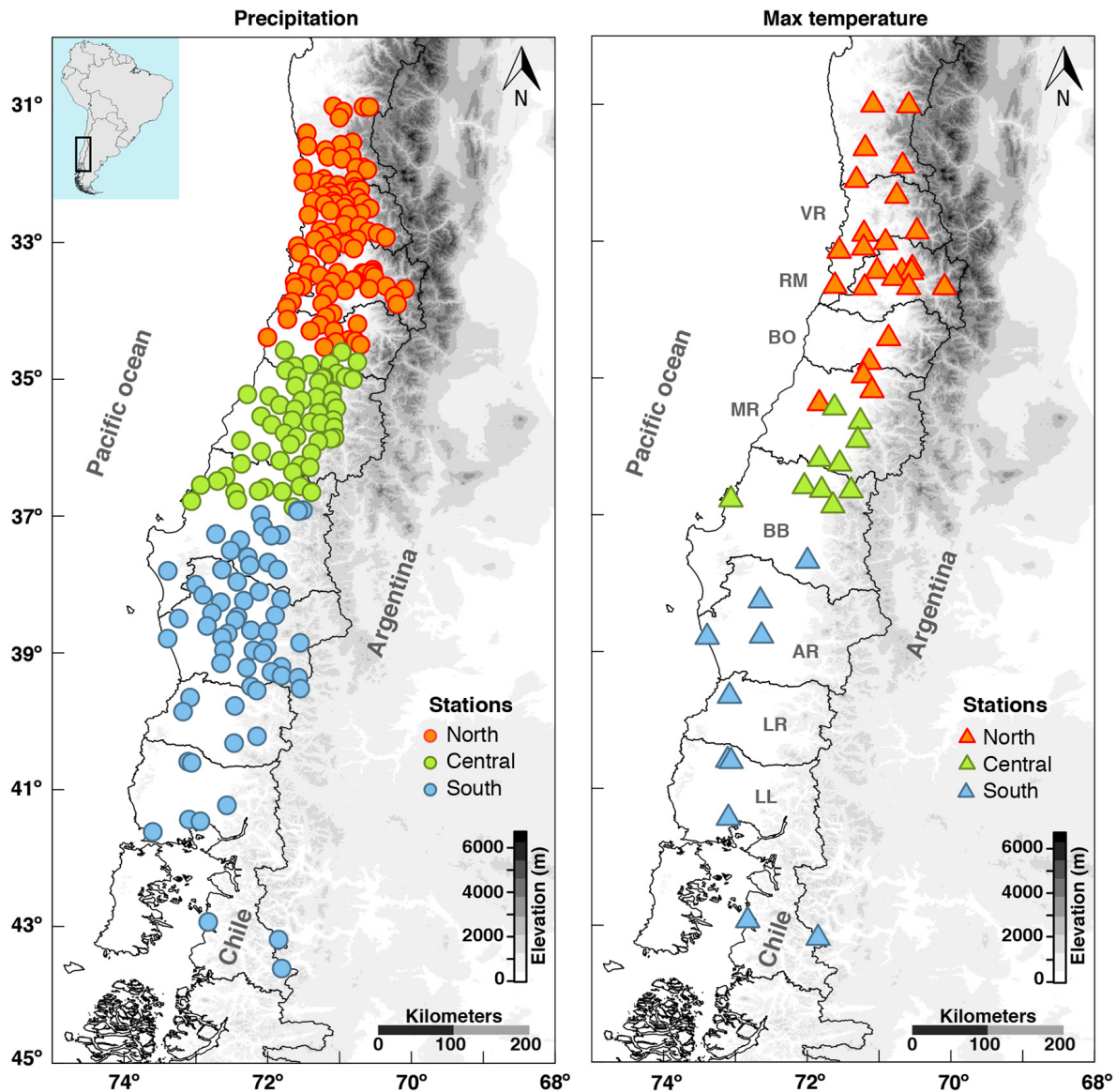
Fig. 2. Precipitation and maximum temperature records throughout the study area, used to generate the regional means. The three groups formed per variable were named North, Central, and South. Administrative regions: VR, Valparaíso; RM, Metropolitana; BO, Libertador Bernardo O'Higgins; MR, Maule; BB, Bío Bío; AR, Araucanía; LR, Los Ríos; LL, Los Lagos.

O'Higgins, Maule, and part of the Bío Bío region. The southern climatic region encompassed part of the Bío Bío as well as the Araucania, Los Ríos, and Los Lagos administrative regions (Fig. 2).

Time series of the El Niño 3.4 (sea surface temperature anomalies in the central-eastern equatorial Pacific) and the AAO Index were obtained from http://www.esrl.noaa.gov/psd/data/ correlation/nina34.data and http://research.jisao.wa shington.edu/data_sets/aao/slp/, respectively.

Relationships between fires and climate

Correlation analyses (Pearson correlation coefficient) were carried out between fires occurring in each of the eight administrative regions of central and south-central Chile and the regional

series of precipitation and maximum temperatures for the 1976–2013 period.

Given that fires can be driven by (1) drying fuels during the previous and current year (dry hypothesis) and (2) wet conditions during preceding years and dry conditions during the current year (wet hypothesis, Westerling et al. 2003, Biondi et al. 2011), we considered climate conditions occurring up to two years before the fire season for the correlation analyses.

Correlations were calculated between all possible combinations of months for the regional climate series (up to 12 months) and fire statistics per administrative region. A multi-region aggregation of fire statistics based on proximity and similar biogeographic/climatic conditions was carried out to test whether groupings of regions gave a better correlation with climate. Logarithmic transformations were used when data did not comply with a normal distribution and in the case of significant positive trends in maximum temperatures, AAO and the number of fires in some regions, a high-pass cubic filter (20-year) was applied to the records to avoid the effect of trends in correlations. Moreover, these series were also tested for autocorrelation and when present, residuals of a lag-1 autoregressive model were used for the correlation analysis. In this work, only the highest correlations between regional climate series and fires (found among collocated administrative regions (fire data) and climate zones) are presented, including a figure depicting that relationship. The set of monthly correlations between climate and fires are presented in Appendix S1: Figs. S1, S2.

The availability and spatial coverage of other climate data that may influence fires in the country (e.g., relative humidity, wind speed) is restricted, so we refrained from conducting multiple regressions in order to assess the combined effect of different climate variables on fire occurrence.

Results

Fires and climate variables

The fire dataset records an annual average of ~47,000 ha burned and >5100 fire events from 1976 to 2013. The number of fires in central and south-central Chile, spanning from Valparaíso to Los Lagos regions, shows a consistent and significant increasing trend (at the 99% confidence

level according to a regression test) during the last three decades (Fig. 3a; González et al. 2011). However, there are no significant trends in the total burned area in the whole region nor in the number and burned area of large events (those burning ≥200 ha; Fig. 3).

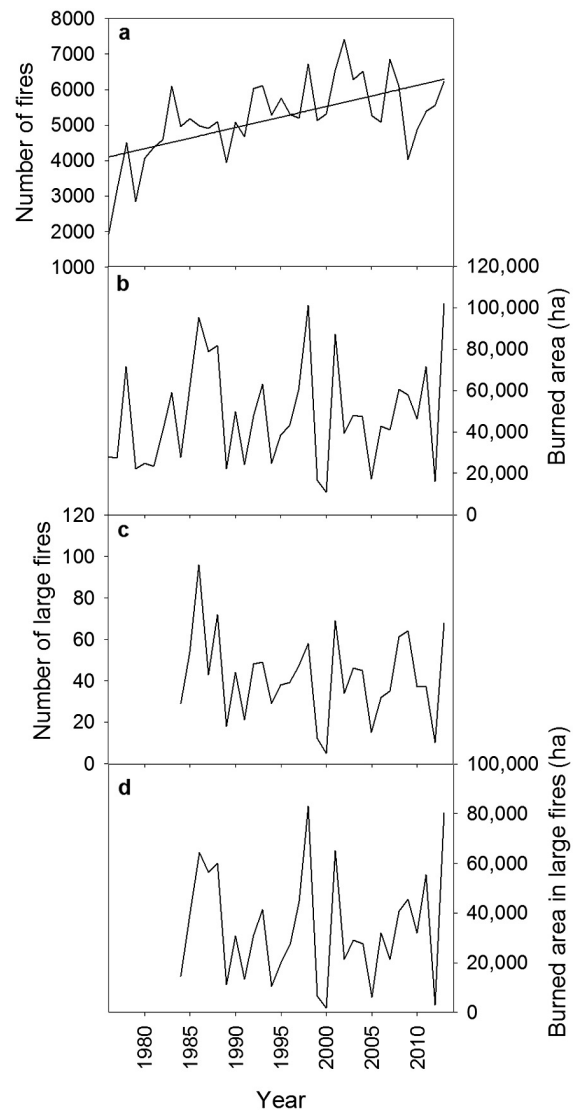The burned area from the Valparaíso to Bío Bío regions was positively correlated with precipitation

Fig. 3. (a) Total number of fires and its increasing trend, (b) total burned area, (c) number of large fires (≥200 ha), and (d) burned area of large fires. All figures are for the area from Valparaíso to Los Lagos regions and for the 1976–2013 period. Source: CONAF http://conaf.cl/proteccion/seccion-estadisticas-historicas.html

during the late fall–winter of the previous year (May–July) in the northern area ($r = 0.56$, $P < 0.05$; Fig. 4a). In addition, the burned area from the O'Higgins to the Bío Bío regions was negatively correlated with precipitation during the concurrent spring–summer (September–January) in the central area ($r = -0.54$, $P < 0.05$; Fig. 4b). Farther south, the burned area from the Bío Bío to Los Lagos regions was more strongly and negatively related to precipitation during summer (December–February) in the southern area ($r = -0.67$, $P < 0.05$; Fig. 4c).

Likewise, the number of fires in Valparaíso, Metropolitana, and O'Higgins regions was positively correlated with precipitation in the northern area during fall–winter (March–July; $r = 0.51$, $P < 0.05$; Fig. 4d). In contrast, the number of fires from the O'Higgins to the Bío Bío regions was negatively correlated with spring–summer precipitation (September–March) in the central area ($r = -0.47$, $P < 0.05$; Fig. 4e). A negative relationship was also found between summer precipitation (November–February) in the southern area and the number of fires from the Bío Bío to Los
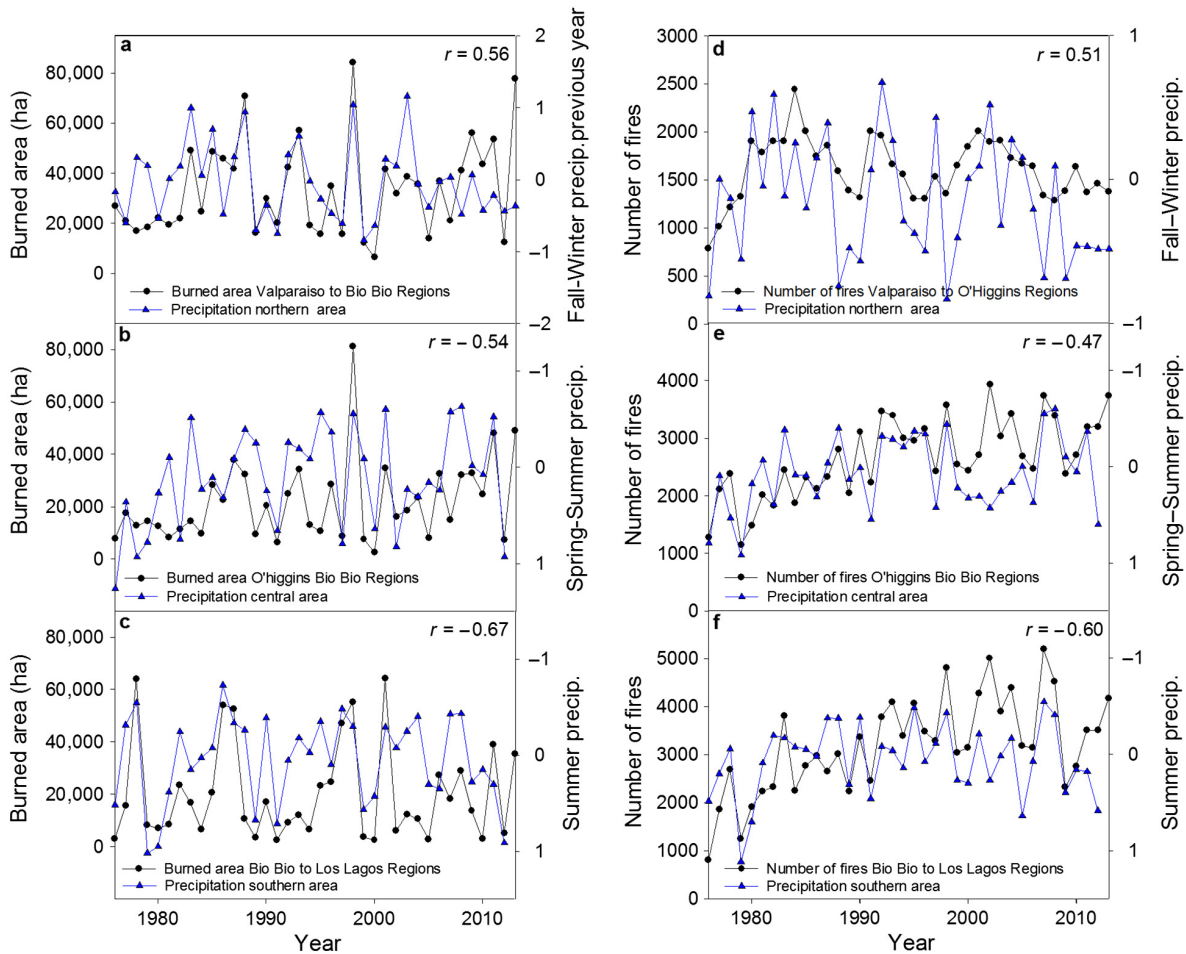

Fig. 4. (a–c) Relationships between the burned area in different regions (in black) and seasonal precipitation (Z values) from the northern, central, and southern areas, respectively (in blue), for the period 1976–2013. (d–f) The same as (a–c) but considering the number of fires (in black). The seasons in each figure correspond to (a) May–July, (b) September–January, (c) December–February, (d) March–July, (e) September–March, and (f) November–February. Significant correlations shown in the upper right corner of each plot were calculated using the natural logarithm of the burned area and the detrended number of fires. The right axes in (b, c, e, and f) have been inverted for a better visualization of their relationship with fires.

Lagos regions ($r = -0.60$, $P < 0.05$; Fig. 4f). Note that correlations were generally stronger between precipitation and the burned area than between precipitation and the number of fires.

Variability in maximum air temperatures also impacts the fire regime across the region, with mostly significant and positive correlations. The burned area from the O'Higgins to the Bío Bío regions was well correlated with winter–spring maximum temperatures (August–December) in the north ($r = 0.44$, $P < 0.05$; Fig. 5a). The burned area in the Bío Bío and Araucanía regions exhibited a strong correlation with summer (December–January) maximum temperatures in the central region ($r = 0.59$, $P < 0.05$; Fig. 5b), while the burned area in the Araucanía to Los Lagos regions was more strongly correlated with summer maximum temperatures (December–February) in the southern area ($r = 0.67$, $P < 0.05$; Fig. 5c). Considering relationships with the number of fires, correlations were again positive with maximum temperatures during spring (September–November) in the northern area (O'Higgins to Bío Bío regions, $r = 0.47$, $P < 0.05$;
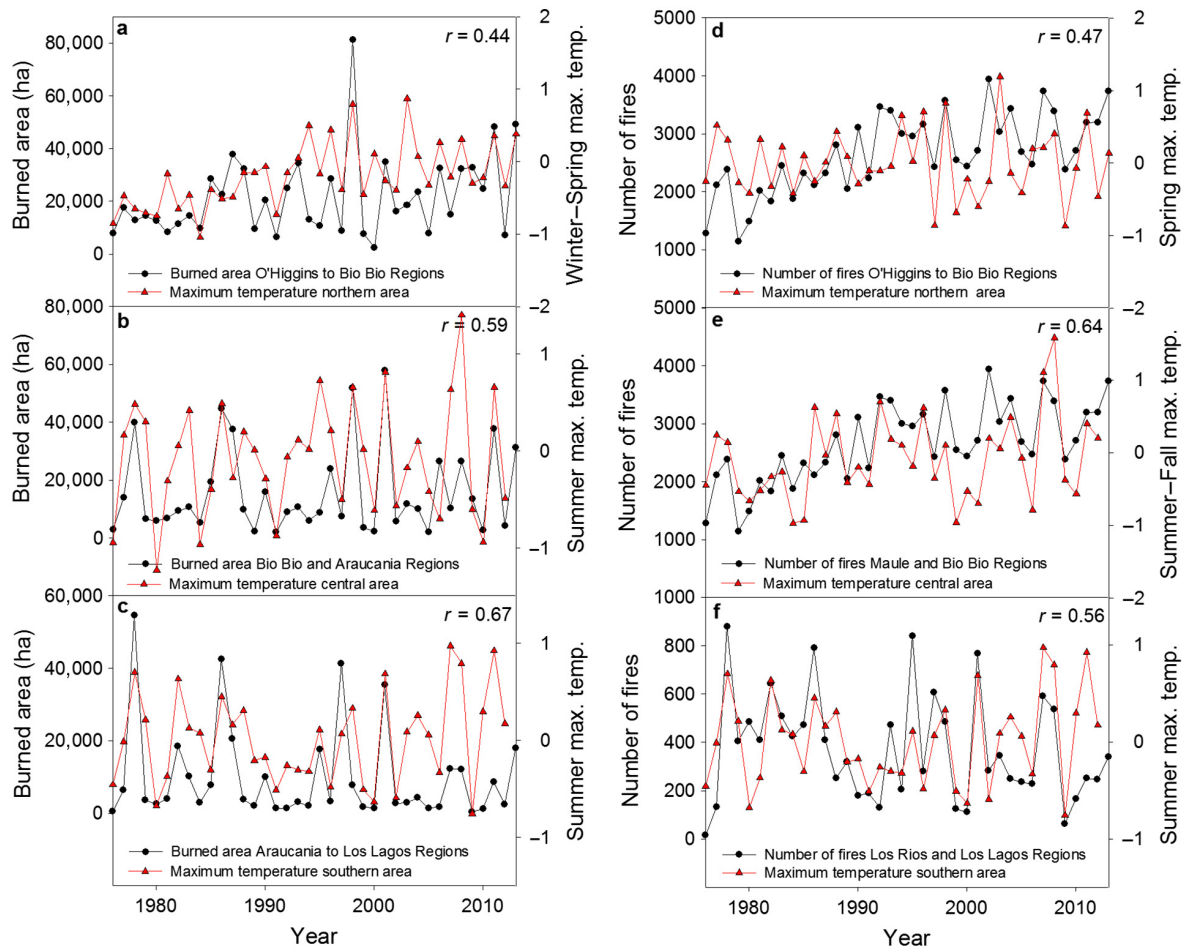

Fig. 5. (a–c) Relationships between the burned area in different regions (in black) and seasonal maximum temperatures (Z values) from the northern, central, and southern areas, respectively (in red), for the period 1976–2013. (d–f) The same as (a–c), but considering the number of fires (in black). The seasons in each figure correspond to (a) August–December, (b) December–January, (c) December–February, (d) September–November, (e) January–April, and (f) December–February. Significant correlations shown in the upper right corner of each plot were calculated using the natural logarithm of the burned area and the detrended number of fires and maximum temperatures in the case of figures (a, d, and e).

Fig. 5d) and positive with summer–fall temperatures (January–April) in the central (Maule and Bío Bío regions, $r = 0.64$, $P < 0.05$) and with summer temperatures (December–February) in the southern regions (Los Ríos and Los Lagos regions, $r = 0.56$, $P < 0.05$; Fig. 5e, f).

Fires and climate modes

A positive relationship was found between sea surface temperatures in the El Niño 3.4 region during winter (July–August) and the burned area not in the immediate, but in the following fire season in central Chile (Valparaíso to Bío Bío regions, $r = 0.43$, $P < 0.05$; Fig. 6a). This is in agreement with the positive correlation between precipitation in winter of the previous year and the burned area in the same regions presented above (Fig. 4a). When considering the number of fires the relationship was essentially the same ($r = 0.49$, $P < 0.05$; Fig. 6b), reinforcing the effect that ENSO has on fires in the northern half of the study area with a one-year lag.

Considering the influence of the AAO on fires, correlations were positive between its index during winter–spring (July–December) and the burned area in the central area (O'Higgins to Bío Bío regions, $r = 0.44$, $P < 0.05$; Fig. 6c) and also between its index in summer and the number of fires in the Araucanía to Los Lagos regions ($r = 0.47$, $P < 0.05$; Fig. 6d). The effects of ENSO and AAO on fire activity are mediated by both rainfall- and temperature-related anomalies (Appendix S1: Fig. S3).

DISCUSSION

The physical link between climate and fire activity

Climate variability plays an important role in shaping fire activity patterns in central and south-central Chile, as summarized in Fig. 7 for their correlation with burned area. Overall, there is a general negative and strong relationship between precipitation during spring and summer and fire activity (that concentrates in summer) from the
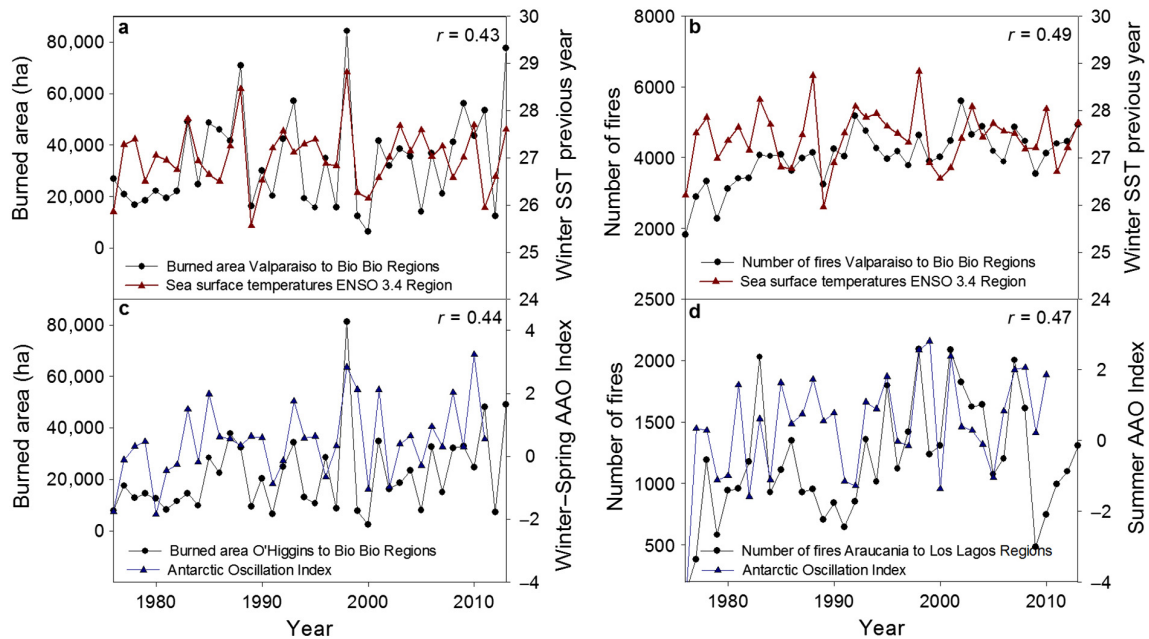

Fig. 6. (a–b) Relationships between sea surface temperatures (SST) in the ENSO 3.4 region during the previous winter (July–August in [a] and June–July in [b]) and the burned area and number of fires in different regions, respectively (period 1976–2013). (c–d) Relationships between the Antarctic Oscillation (AAO) Index during winter–spring (July–December) and summer (November–January) and the burned area and number of fires in different regions, respectively (period 1976–2011). Significant correlations shown in the upper right corner of each plot were calculated using the natural logarithm of the burned area and the detrended number of fires and the AAO Index in the case of figures (b, c, and d).
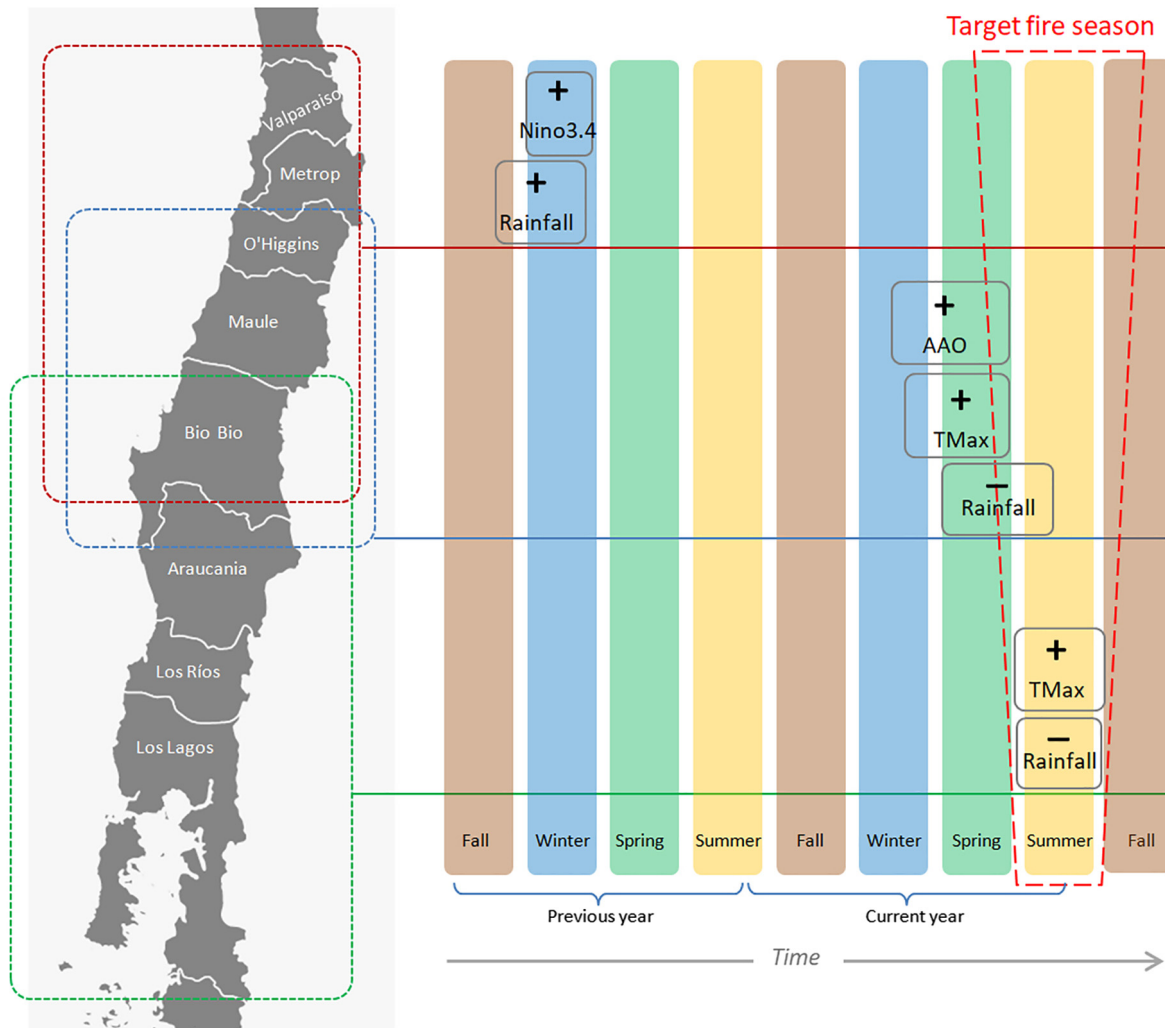
Fig. 7. Schematic figure showing the leading climatic drivers of the burned area along central-southern Chile. The fire activity in each administrative region (indicated in the map to the left) was grouped into a northern (red box), central (blue box), and southern (green box) areas. The calendar to the right indicates when a given driver (rainfall, maximum temperature, El Niño–Southern Oscillation, or Antarctic Oscillation [AAO]) has its largest impact on the fire activity during the target fire season (typically from late spring to early fall).

O'Higgins region to the south. A plausible mechanism behind this relationship is that low precipitation—and possibly high evapotranspiration—reduce fuel moisture, increasing the probability of ignition and the potential for fire spread (Littell et al. 2009). Within this area, relationships were stronger when considering spring conditions in the northern part (O'Higgins to Bío Bío), but summer conditions toward the south (from Bío Bío to Los Lagos), consistent with the more Mediterranean climate in the former sector. The relationships were

stronger toward wetter areas where less precipitation during summer makes a significant difference in terms of the combustibility of fuels (Veblen et al. 1999). These results are in agreement with findings by De Torres Curth et al. (2008) and Littell et al. (2009), who also found that dry conditions just before or during the fire season were related to an increased burned area in forested ecosystems in northern Patagonia (Argentina) and most eco-provinces of western United States, respectively. Littell et al. (2009) found that toward northern

ecoprovinces in western United States (wetter conditions), low precipitation during the fire season (summer) had the greatest influence on fires, while toward the south (drier conditions), low precipitation during a longer window from the winter immediately preceding fire through the fire season had the greatest influence on the burned area.

The burned area in the northern portion of the study area (from Metropolitana to Bío Bío regions) was positively correlated with precipitation during winter of the previous year, pointing to an effect of biomass and fine fuel accumulation (annual grasses and forbs), which may burn approximately one and half year later during the following fire season (Kitzberger et al. 1997, Keeley 2004, Littell et al. 2009). This same effect could explain the positive relationship between the number of fires and concurrent fall–winter precipitation in part of this northern area. Littell et al. (2009) reported that moist conditions during the previous winter (lagged 1-yr correlation) had a positive effect on the burned area in semiarid environments of the western United States being in agreement with our study. Pausas (2004) and Koutsias et al. (2013) on the other hand found that high annual and summer rainfall two years before the fire season may act increasing fuel loads that burn two years later in Mediterranean ecosystems. In the case of Central Chile, previous studies have documented that increased precipitation during fall was positively related to burned area (Holz et al. 2012) and that wet falls, winters, and springs are the ones that positively influence an increase in fire risk in this area (Montenegro et al. 2004).

Holz et al. (2012) also found that burned area, including Mediterranean woody vegetation, was negatively related to spring precipitation, being in accordance with the present study. In terms of the burned area in the temperate zone (37°–43° S), Holz et al. (2012) found a negative correlation with spring precipitation, rather than with summer precipitation.

The differences in terms of fire–climate relationships between the present study and the one of Holz et al. (2012) might be due to (1) the different approach used to group fires, as we considered actual burned area in different regions and not the principal modes of variability across the studied area, (2) the time period that was considered (1976–2013 vs. 1984–2008), and (3) the climate and fire datasets used, since the present study

employed data from weather stations and total forest fires (including all vegetation categories combined) for central and south-central Chile, whereas Holz et al. (2012) considered a gridded climate dataset and fires just affecting native vegetation (woody and herbaceous vegetation separately) from north-central through southernmost Chile.

Regarding the overall effect of temperature on fires, maximum temperatures mostly during spring positively affected the burned area and number of fires from the O'Higgins up to the Bío Bío regions. From Bío Bío to the south, summer maximum temperatures were related to the burned area and number of fires, with the strength of this relation maximizing from Araucanía to the south. Maximum temperatures during spring and summer have commonly been associated with fire activity in Mediterranean and other regions of the world (Piñol et al. 1998, Koutsias et al. 2013, Turco et al. 2013, Dennison et al. 2014). In the case of Holz et al. (2012), they did not find any strong relationship between fires and temperature, probably because they used mean instead of maximum temperatures. Regarding the central Chile mega-fire in January 2017, with the largest burned area on record, this occurred during the warmest summer ever recorded in Central Chile (DMC 2017), but these conditions were also preceded by a relatively warm and dry spring (warmer than the mean) supporting our findings (Appendix S1: Fig. S4).

Different studies have demonstrated that fuel structure and fuel flammability are important factors in determining fire activity changes along productivity gradients (Pausas and Bradstock 2007, Holz et al. 2012, Pausas and Paula 2012). Under Mediterranean climatic conditions, fuel structure (amount and connectivity of biomass) is more relevant in driving fire activity than the frequency of climatic conditions conducive to fire (less drought-driven fire). In contrast, in more mesic temperate and productive regions, fuel is not a limiting factor and fire activity is driven by the frequency with which flammable conditions are attained (more drought-driven fire; Pausas and Paula 2012, Holz et al. 2012). The fire regime in central Chile (from Valparaíso to the Bío Bío region) appears to be intermediate in this gradient, namely one between fuel limited and climate limited, where both fuel structure and flammable conditions play an important role. The fire

regime toward the south, however, would be more climate limited, because the drying of greater amounts of biomass would be the primary mechanism for larger burned areas (Veblen et al. 2008, Holz et al. 2012). It is interesting to note that the Bío Bío region appeared in fire–climate patterns that are characteristic of the northern and southern areas, confirming that this is actually a transition zone from Mediterranean to temperate climate (Holz et al. 2012).

Impact of climate modes

Our results indicate that ENSO is a dominant driver of fire activity in central Chile, while the AAO exerts its influence throughout the study area. ENSO is the climatic forcing mostly related to fires in central Chile through wetter conditions caused by El Niño during the year preceding the fire. This relationship agrees with what was found by Swetnam and Betancourt (1990, 1998), for the semiarid ecosystems of southwestern United States where increased fire activity was found one year after the occurrence of El Niño (wet conditions).

Although a strong correlation between fires in the southern area and ENSO was not found in the present study, a close correspondence has been reported between the occurrence of strong El Niño years (1982–83, 1986–87, 1997–98) and high burned area in southern Chile (Lara et al. 2003). This relationship is mainly due to the occurrence of dry and warm summers following positive ENSO phases at this latitude (González and Veblen 2006).

The positive correlations between AAO (from winter through summer) and fires (number and burned area) throughout the study area are mainly due to the warmer/drier than normal conditions normally associated with positive values of this index, which trend is unprecedented within the last 600 yr (Lara et al. 2008, Christie et al. 2010, Urrutia et al. 2011, Villalba et al. 2012). According to Holz et al. (2012), spring AAO was the most important large-scale climate driver of fires in the temperate area (37°–43° S), somewhat agreeing with our results.

Fire activity during prolonged droughts

So far we have used correlation analysis between fire activity and climate forcing at individual months/seasons (e.g., rainfall accumulation during winter). Therefore, our results are useful to explain changes in fire activity in a context of

high year-to-year variability; however, climate anomalies of a given sign can prevail for several seasons and even years. Given that fire activity (as per number of fires or burned area) in the more Mediterranean regions (Valparaíso to Bío Bío) is positively correlated with fall–winter precipitation, but negatively correlated with spring–summer precipitation, it is not clear the fire response to an all-season/multi-year drought. The intense multi-year drought that has affected central and part of south-central Chile since 2010 (CR2 2015, Garreaud et al. 2017) offers some perspective on this question. During the 2010–2015 period, a rainfall deficit ranging from 10% to 30% was observed in nearly all seasons between Valparaíso and Araucanía. A preliminary report showed an increase in the number of large fires (≥200 ha) and their affected area by 27% and 69%, respectively, in the 2010–2015 period compared to 1990–2009 (CR2 2015). This indicates that the spring–summer signal (leading to more fire) has completely offset the fall–winter signal (leading to less fire). Probably, the generalized warming during the last decades along the interior valleys of central Chile (Vuille et al. 2015) has further accentuated the tendency for more fire activity during the drought, given the significant relationship between spring–summer mean maximum temperature and fire number/burned area.

Climate change projections indicate a year-round drying and warming of central-southern Chile that may reach up to 40% rainfall reduction and 4°C temperature raise toward the end of the 21st century (Fuenzalida et al. 2007). In this context, protracted droughts like the one occurring since 2010 should become more frequent in the near future (Boisier et al. 2016). Considering our findings related to year-to-year variability and the evidence during the recent multi-year drought, one might expect an increment of the occurrence and area affected by fires (González et al. 2011).

In conclusion, climate, representing mean weather conditions, is undoubtedly related to the occurrence of fires in the study area as it has been demonstrated in this article. However, and under the climate change scenario that we are facing, it is important to also consider the extreme weather events that are more common nowadays. In addition, it is important to consider the dramatic land-use changes occurred due to the massive conversion of native vegetation to exotic pine and

eucalypt plantations. These changes have not only modified the type of fuel and its load, but also the configuration of the landscape, creating large homogenous patches of the same single species, increasing the risk of occurrence and propagation of catastrophic fires (Lara et al. 2003, 2016, González et al. 2011, Martinez-Harms et al. 2017, N.P Group 2017). New legislation that imposes regulations on land use and promotes the restoration of native forests to create more heterogeneous landscapes, would reduce the spread of human-set fires as well as the associated economic, social, and environmental losses. Moreover, active education, public awareness programs, and stronger legislation toward higher sanctions to those starting fires (intentionally or as a negligence) would contribute to reduce the occurrence of human-set fires. The effects of climate change on fires will finally depend on how climate combines with human actions, so national environmental policies should consider the expected fire behavior under climate change to help reducing the risk of forest fires (Westerling et al. 2014).

Acknowledgments

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Supporting Information

Additional Supporting Information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/ecs2.2171/full