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The 2010–2015 Megadrought and its influence on the fire regime in central and south-central Chile

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Abstract. Forest fire activity has increased in recent years in central and south-central Chile. Drought conditions have been associated with the increase of large wildfires, area burned and longer fire seasons. This study examines the influence of drought on fire regimes and discusses landscape management opportunities to decrease fire hazard. Specifically, we investigate the effect of the 2010–2015 Megadrought (MD) compared to 1990–2009 period on fire activity (fire-season length, number of fires and burned area across months, fire sizes, regions and vegetation cover types, simultaneity, and duration of fires) in central and south-central Chile (32°–39° S), using contemporary fire statistics derived from the Chilean Forest Service. For large fire events (>200 ha) the average season length increased by 67 d (44%), comparing 2010–2015 to 1990–2009. Earlier and later ignition dates resulted in extended fire seasons in MD years. During the MD, the number, area burned, simultaneity, and duration of large fires increased significantly compared to the control period, including the unprecedented occurrence of large fires during winter. The burned area in large fires increased in all vegetation types, during the MD compared to the control period, especially in the exotic plantation cover type. The regions that were most affected by fire (i.e., total area burned) during the MD were Maule, Bío-Bío, and Araucanía (35–39° S) that concentrate >75% of forest plantations in Chile. Although both maximum temperatures and precipitation are drivers of fire activity, a simple attribution analysis indicates that the sustained rainfall deficit during 2010–2015 was the most critical factor in the enhanced fire activity. Future climate change predictions indicate more recurrent, intense, and temporally extended droughts for central and south-central Chile. Under this scenario, land-use planning and fire and forest management strategies must promote a more diverse and less flammable landscape mosaic limiting high load, homogenous, and continuous exotic plantations.

Key words: drought; fire regimes; fire-prone vegetation; fire-season length.

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Introduction

Fire activity (i.e., burned area, number, and size of large fires and fire-season length) has increased in recent decades in many regions of the world (Pausas 2004, Kasischke and Turetsky 2006, Westerling et al. 2006). The strong changes in the spatial distribution of fuel across landscape—due to human practices such as agriculture land abandonment, fragmentation and clearing of tropical forests, extensive livestock grazing, fire suppression, and land cover conversion to fast growing exotic plantations—have modified the patterns of wildfire regimes (Moreno et al. 1998, Cochrane and Laurence 2008, Moreira et al. 2011, Carmona et al. 2012, Dennison et al. 2014). On the other hand, the lengthening of the fire season seems to be more associated with climatic factors such as the increasing variability in moisture conditions (wet/dry oscillations promoting biomass growth), drought frequency, and/or warming temperatures (Westerling et al. 2006, Yoon et al. 2015). Recent extreme fire seasons have occurred during drought conditions and global warming is likely one of the causes exacerbating the burned area extent and likelihood of extreme fire risk (Westerling et al. 2006, Jolly et al. 2015, Yoon et al. 2015, Littell et al. 2016, Turco et al. 2017). In the so-called Millennium drought of southeast Australia (2001–2009), fire activity strongly increased, burning large tracts of native, and plantation forests (Van Dijk et al. 2013).

Mediterranean-type climates (MTC; e.g., Southwest Australia, The Cape Town Region, South California, Mediterranean Basin, and Central Chile) harbor ecosystems that are naturally fire-prone because they are subject to a marked seasonality (rainy winters that increase productivity followed by dry summer conditions that turn vegetation flammable) and natural sources of fire ignition (i.e., lightning; Keeley et al. 2012). Central and south-central Chile (32°–39° S) has an archetypical MTC with frequent fires during the dry season, although these mostly are human-caused (at least ~95%; Appendix S1: Fig. S1). Natural fires in Chile are less significant than in other MTC regions due to the infrequent summer convective thunderstorms and associated lightning strikes (Veblen et al. 2008, Keeley et al. 2012, Viale and Garreaud 2015).

Fire occurrence in central and south-central Chile has increased by around 50% in the last 40 yr (González et al. 2011). These fires have consumed vast areas of natural vegetation, grasslands, and forest plantations (54,800 ha/yr in average between 1976 and 2016; Lara et al. 2016), with direct economic losses and firefighting expenditures by public agencies and forest companies exceeding US$100 million in recent years (CORMA 2016). During the recent fire seasons, we witnessed the loss of several human lives, the destruction of hundreds of homes, and damages to natural resources due to wildfire. Starting in 1974, over the regions of Valparaíso to Araucanía, extensive areas have experienced the rapid conversion of large landscape areas to fast growing commercial plantations of *Pinus radiata* and *Eucalyptus* spp. According to the latest official reports, forest plantations cover an area of ~2.5 million ha in the country, of which 60% correspond to the species *P. radiata* and 33% to *Eucalyptus* spp., and ~85% of this planted area is concentrated between Valparaíso and Araucanía (INFOR 2017). Furthermore, the increase of the exotic plantations (afforestation) was relatively insignificant for the period 2010–2015 (<60,000 ha in total between Valparaíso and Araucanía regions; 9967 ha/yr) compared to the precedent period 1990–2009 (increase of 1,059,838 ha of new exotic plantations; 55,781 ha/yr), representing only 2.4% of the total planted area. As a consequence, the increase in fire activity in these regions—including the burnt of rural–urban interfaces of several town and cities—has been closely associated with the accumulation of high, flammable, and continuous fuel load of forest plantations (Peña and Valenzuela 2008, Carmona et al. 2012, Díaz-Hormazábal and González 2016).

Year-to-year variation in wildfire activity in central and south-central Chile is controlled by interannual climate variability, and this climate–fire relationship being modulated by vegetation type and their associated fuel characteristics (Holz et al. 2012). Documentary records and proxy reconstructions (from tree rings) of fire and climate relationships have demonstrated that forest fires are negatively associated with precipitation during the concurrent spring–summer fire season and positively related to winter precipitation in the previous year (González and Veblen 2006, Urrutia-Jalabert et al. 2018). The number of fires and the area burned also increase in response to higher maximum (daytime) air temperatures in late-spring and summer (Urrutia-Jalabert et al. 2018). El Niño–Southern Oscillation is also a dominant driver of fire activity in central Chile through wetter conditions caused by El Niño during the year preceding the fire (González et al. 2011, Urrutia-Jalabert et al. 2018). Moreover, in Mediterranean sclerophyllous forests and shrublands in central Chile, fire activity increases following wet autumns during negative Southern Annular Mode (SAM); however, at mid-latitude (37°–42° S), coinciding with temperate forests, fire is positively correlated with reduced spring precipitation during positive phases of SAM (Holz et al. 2012).

Central Chile and south-central Chile have experienced an uninterrupted dry period since 2010 that given its exceptional duration and extent have been termed the central Chile Megadrought (MD; Garreaud et al. 2017). During this extended drought, the region has experienced exceptional forest fire activity as notably shown by the most recent fire season (2016–2017), in which ~600,000 ha burned—10-fold greater than the historic average since mid-1970s—and which has been recognized as a catastrophe unprecedented in the last 40 yr (CONAF 2017, Martínez-Harms et al. 2017). This suggests that the MD and the concomitant alteration of the fire regime in this region might have a cause–effect relationship.

The present study documents the increase in fire activity during the central Chile MD, explores the causes of these changes and discusses forest landscape planning, and management strategies that can be adopted to design landscapes with lower fire hazard (degree of ease of ignition and the resistance to control). The specific goal of this study was to assess whether fire activity (fire-season length, number of fires and burned area distributed per month and fire size, burned area of distinct vegetation cover type, simultaneity, and duration of forest fires) has increased consistently during the MD period compared to the last twenty years (1990–2009), and whether these changes varied systematically across time (months and seasons), administrative regions, and different vegetation cover types in central and south-central Chile. We expect that fire activity will increase during the MD period compared with previous years and that these effects (i.e., from drought conditions) will be stronger and/or amplified in areas characterized by the widespread presence of high fuel load and fire-prone vegetation dominated by industrial tree plantations.

Methods

Study region

This study was developed in central and south-central Chile (32°–39° S) and includes six administrative regions (Valparaíso, Metropolitana, O'Higgins, Maule, Bío-Bío, and Araucanía; Fig. 1). This area is located in a MTC characterized by a pattern of winter rains under mild temperatures and summer droughts (Keeley et al. 2012). The MTC varies from semiarid conditions in the north to more mesic and humid conditions in the south; with precipitation ranging from 200 to 1200 mm/yr (Fig. 1a) and a summer dry period varying from 8 to 2 months in the northern and southern edges, respectively (Garreaud et al. 2017).

The historical land cover of the MTC area of Chile has been heavily modified and largely converted to pastures, agricultural lands, and commercial tree plantations (Fig. 1b). The characteristic vegetation types in the study area are sclerophyllous shrublands (called *matorral*, in a broad sense) and woodlands with a gradual transition to temperate forests toward the south (Donoso 1982, Keeley et al. 2012). The matorral and sclerophyll woodland transition to a savanna-like community known as *espinal* (dominated by the thorny tree *Acacia caven*; Mol. (Mol.)) in human-disturbed areas of the central depression and eastern slopes of the coastal cordillera from about the Choapa River (32° S) to the Laja River (36° S; Donoso 1982). Dry equator-facing slopes in the matorral contain species well adapted to xeric conditions (e.g., arborescent cactus *Echinopsis chiloensis* (Colla) Friedrich & G.D. Rowley, *Puya* spp., *Trevoa trinervis* Miers, *Lithraea caustica* (Molina) Hook. Et Arn., *Kageneckia oblonga* Ruiz & Pav., *Colliguaya odorifera* Mol., among others; Donoso 1982, Keeley et al. 2012). Sclerophyllous woodlands are mostly located on mesic pole-facing slopes with stands dominated by trees such as *Quillaja saponaria* (Mol.), *Cryptocaria alba* (Mol.) Looser., *Beilschmiedia miersii* (Gay) Kosterm, and *Peumus boldus* (Molina) Johnston (Donoso 1982, Keeley et al. 2012). On more mesic areas at higher altitude (commonly above 1000 m a.s.l.) in the coastal and Andes ranges (~34° S) or central valley (~37° S, from Malleco River), the matorral and sclerophyllous forests give way to temperate deciduous forests dominated by pure or mixed *Nothofagus* species (Donoso 1982). In the overall region, and especially in the coastal range and foothills of the Andes, extensive areas have experienced land-use change and now support large-scale, fire-prone plantation stands of *P. radiata* D. Don and *Eucalyptus globulus* Labill. (Carmona et al. 2012, Nahuelhual et al.

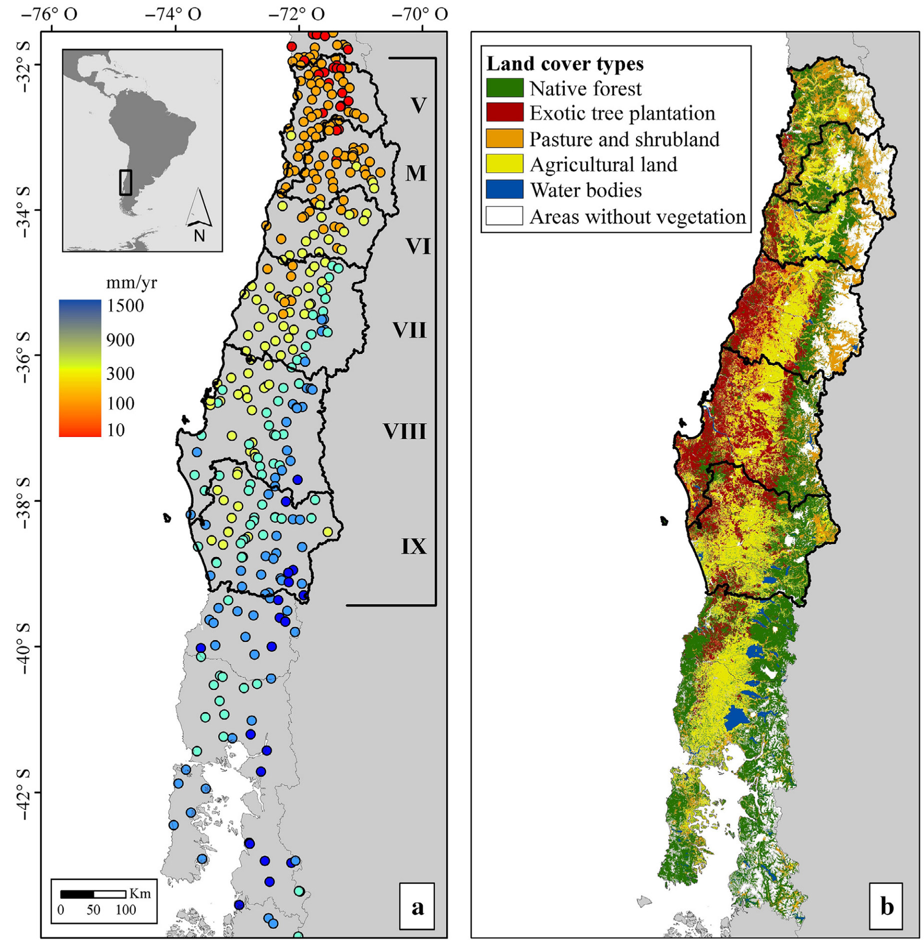
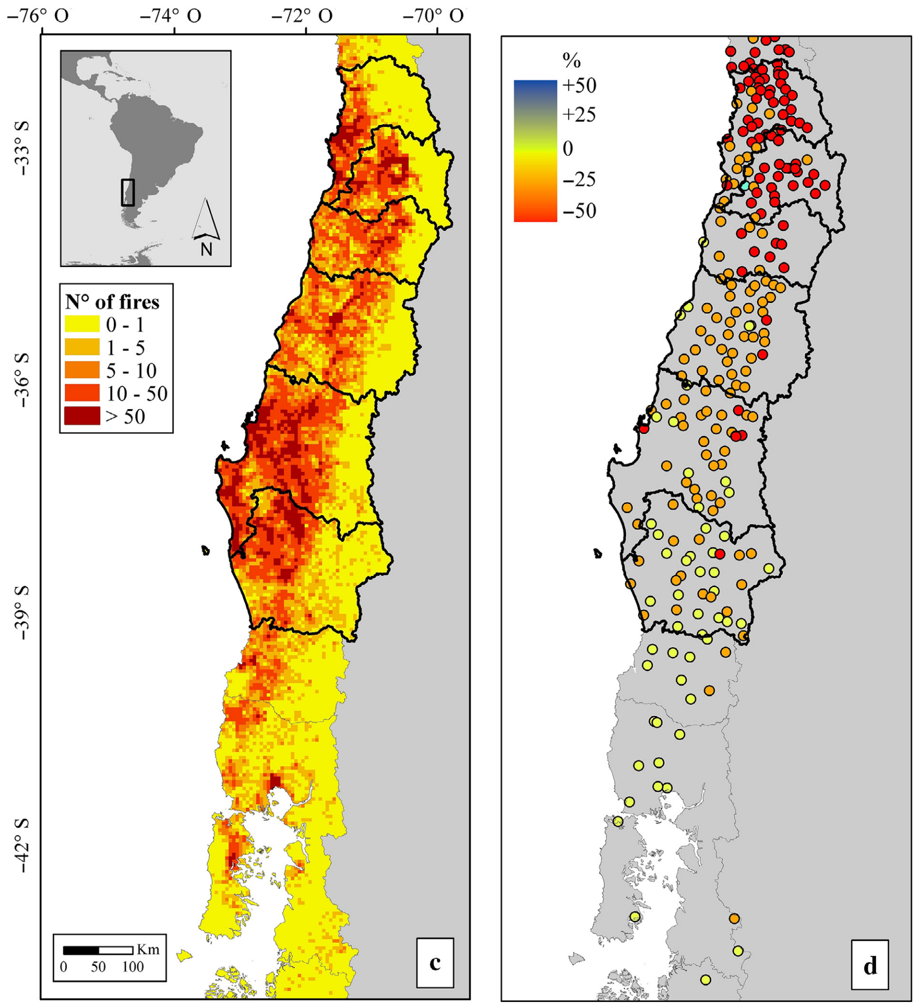


Fig. 1. (a) Annual mean rainfall (mm); (b) geographical distribution of the main land cover types in south-central Chile; (c) total number of fires per grid-cell (5 × 5 km; Projection system WGS84 UTM 19S) during the period 1985–2015; (d) annual rainfall anomalies during the Megadrought (2010–2015) as a percentage of the historical norm (1980–2009). The administrative regions considered in the study indicated in c: Valparaíso (V), Metropolitana (M), O'Higgins (VI), Maule (VII), Bío-Bío (VIII), and Araucanía (IX).

2012, Lara et al. 2016). In the study area at present, approximately 23.3% of land cover corresponds to native forests, 18.2% to exotic plantations, 21% to pastures and shrublands, and 21% to agriculture lands (Fig. 1b). For the period 1985–2015, these administrative regions account for 92% and 88% of the cumulative fire occurrence and burned area of the country, respectively (Fig. 1c).

The central Chile Megadrought

Since 2010, the Chilean territory between the administrative regions of Coquimbo and Araucanía (31°–39° S) has suffered a rainfall deficit ranging from 20% to 40% (Fig. 1d), coinciding with the warmest decade of the last 100 yr (Boisier et al. 2016, Garreaud et al. 2017). Although 1- or 2-yr severe droughts are not infrequent in central Chile's climate, the temporal persistence (six uninterrupted years) and southward extent (reaching 39° S) of the current event are extraordinary in the century-long historical records, with an estimated return period of 200 yr (Garreaud et al. 2017). Furthermore, few analogs have been found in a tree-ring-based millennial reconstruction of regional precipitation (Christie et al. 2011), and consequently, the current dry period has been termed the Central Chile MD (Garreaud et al. 2017). In absolute terms, the rainfall



(Fig. 1. *Continued*)

deficit was larger in the drier northern portion of central Chile (30°–33° S), but using a standardized precipitation index the MD magnitude and continuity increased southward (Garreaud et al. 2017). For many stations between 35° and 38° S, the MD duration and severity is unprecedented considering the records during the second half of 20th century. The rain and snow deficit led to a concomitant decline in annual mean river flow and reservoir storage across Central Chile and in the adjacent foothills east of the Andes ranges in Argentina (Rivera et al. 2017).

During the second half of the 20th century, precipitation over central Chile (30°–35° S) experienced high interannual variability but little long-term trend; the opposite occurred farther south where interannual variability is less marked but sustained drying trend was evident (Quintana and Aceituno 2012). In this context, the MD emerges as an outstanding event in central Chile while augmenting the drying trend farther south (Boisier et al. 2016).

Forest fire database

The forest fire database was provided by the Chilean Forest Service (CONAF) and comprises the period between 1985 and 2015. The fire records include the number of fires and surface burned area assembled in an appropriate time period (month, season, or year) considering the complete study area, disaggregated by regions or vegetation types. Other variables obtained from the fire database were the ignition and extinction dates, size of individual fires, and the area burned per cover type of large fires (>200 ha). From 1985 to 2015, the dataset record comprises a total of ~1.5 million ha of area burned and 162,249 occurrences. Each fire season involves two calendar years, since most fires occur between October and April (spring–summer) with a high frequency peak from December to February (more than 67% of the total number of fires occur during this period). Thus, the fire year was assigned to the year of the end of the fire season (e.g., 2010 represents the fire season 2009–2010). For this study, we mainly focused in large fires (>200 ha), which annually account for more than 70% of the total area burned (TAB; for the period 1985–2015).

Statistical test for epochal differences

To assess the influence of the MD conditions on the fire regimes from Valparaíso to Araucanía regions, we compared several variables describing fire activity between the MD period (2010–2015 fire seasons) and a previous control period (1990–2009) using t tests or Mann–Whitney nonparametric U tests in cases in which normality and/or equal variance tests were not attained (Zar 1996). These comparisons were made across different months, seasons, fire size classes, vegetation cover types (native forest, exotic plantation, shrubland, and pasture), and administrative regions (from Valparaíso to Araucanía). The fire-season length for large fires (>200 ha) was considered as the number of days elapsed between the first fire discovery date and the last fire extinction date (i.e., days between first fire date and last fire extinction date in each fire season). The number of fires and burned area was calculated for each month (fires >200 ha). Moreover, the number of fires and burned area was calculated for different fire size classes (i.e., 25–50 ha, 50–100 ha, 100–200 ha, 200–500 ha, 500–1000 ha and >1000 ha). The variable fire simultaneity considered the maximum number of simultaneous fires reached in a particular month for all fires (any size) and large fires (>200 ha). The duration of fires was defined as the average time (number of days) between discovery and the extinction of individual fires (any size of fire and >200 ha) in each Southern Hemisphere season (fall, MAM; winter, JJA; spring, SON; summer, DJF). Since large fires mostly occur during summer and fall, the analysis was restricted to those seasons. The annual total burned area of large fires by different vegetation covers considered all and separately each vegetation type (native forest, exotic plantation, shrubland, pasture) across regions.

Attribution analysis

We developed a simple attribution analysis of the causes behind the increase in fire activity during the period 2010–2015. Our starting point are the works by Holz et al. (2012) and Urrutia-Jalabert et al. (2018) that link climate drivers (precipitation and temperature anomalies) with different metrics of fire activity along central and southern Chile. Those works have established climate–fire association at monthly and subregional scales; here, by the contrary, we used two simple climate indices to quantify that relationship aggregated both in time and space. We first defined the TAB considering all fires between November (year 0) to March (year +1), from Valparaíso to the Araucanía regions (32°–39° S). The annual precipitation anomaly (January to December of year 0) is defined as the median of the rainfall anomalies in five stations between 33 and 38° S (Appendix S2: Table S1). The station time series were previously normalized by their long-term mean (that increases significantly from north to south). This simple index of precipitation is reasonable given the Mediterranean climate of the region and the high degree of spatial homogeneity of year-to-year rainfall fluctuations along central Chile (Garreaud et al. 2017). For the temperature, we first calculated the summer-mean (December 0 to February +1) average of daily maximum values in six stations in central Chile (Appendix S2: Table S1). The maximum temperature index is then calculated as the median of the station values. The three time series (TAB, precipitation anomaly and temperature index) are available for 39 fire seasons from 1976/1977 to 2014/2015. The last five fire seasons occurred during the MD period (2010–2015).

We also used the period 1976–2009 to calibrate univariate models of the type PAB = $aY + b$, where PAB is the predicted area burned, Y is the predictor (either the precipitation anomaly or the temperature index), and $\{a,b\}$ are the regression coefficients obtained from a least square method, including their 95% confidence interval (Wilks 2005).

Results

Fire-season length and monthly distribution of number and burned area of large fires

The length of the fire season increased significantly during the MD (2010–2015) in relation to the previous control period (1990–2009; U statistic = 25; $P = 0.036$). The season length for large fires (>200 ha) extended on average 67 d (44%) when comparing 2010–2015 to 1990–2009 (Fig. 2). Nearly 40% of that increase was due to earlier ignitions (27 d), and 60% to later extinction (40 d). Later extinction dates were probably due to later ignition dates, which in average increased by 32 d (54%).

Furthermore, during the MD period the number of large fires and their burned area increased during late-spring and summer (from December to March) compared to the period 1990–2009, although differences were statistically significant only in December (number of fires, $t = -3.21$; $P = 0.004$ and area burned, U statistic = 25; $P = 0.036$; Fig. 3a, b). The occurrence of large fires during the months of June and July (winter) was unprecedented considering the previous period (Fig. 3).

Simultaneity and duration of fires

During the MD period, simultaneous fires tended to increase when compared to the control period through all months of the fire season (Fig. 4). Considering all fire events, the maximum number of fires occurring simultaneously was significantly higher in spring and early summer (September, U statistic = 12, $P = 0.002$; November, $t = -2.957$, $P = 0.007$; December, $t = -3.535$, $P = 0.002$) and winter (May, U statistic = 24.5, $P = 0.031$ and June, U statistic = 19.5, $P = 0.003$), compared to the previous period (Fig. 4a). In the case of large fires, during the MD period, the maximum number of simultaneous fires was significantly higher in summer (December, U statistic = 25, $P = 0.030$ and January, $t = -2.119$, $P = 0.045$; Fig. 4b).

During the MD period, fire duration increased in all months compared to the control period (Fig. 5). However, the largest and significant increases were found during spring and winter for all fires (Fig. 5a; spring, U statistic = 25; $P = 0.036$ and winter, $t = -2.3$; $P = 0.029$) and during fall for large fires (Fig. 5b, U statistic = 22, $P = 0.022$). During the MD, the duration of large fires in fall doubled the number of days

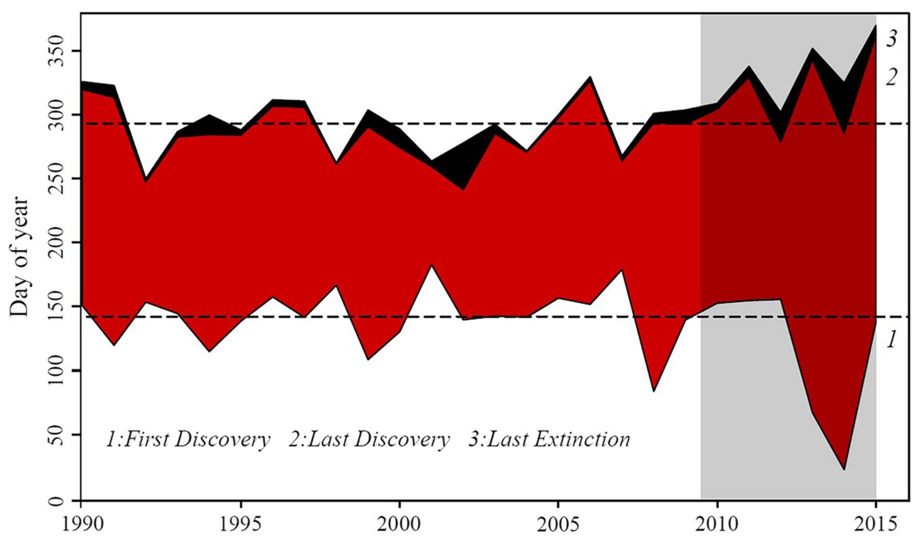


Fig. 2. Fire-season length for large fires (>200 ha) in central and south-central Chile (from Valparaíso to Araucanía regions). The period of Megadrought (2010–2015; gray shading) compared with the previous 20 yr (1990–2009). Segmented lines indicate the average start and end of the fire season for the period 1990–2009 (start: day 142 corresponds to the third week of November; end: day 293 corresponds to the third week of April). In the Y axis, the day = 0 (first day of the fire season) starts 1st of July and the day = 365 (last day of the fire season of the following year) is 30th of June. X axis indicates the year of the end of the season (e.g., 2015 corresponds to the fire season 2014–2015).

compared to the control period (MD = 10 vs. control = 4.3 d). Similarly, for the complete fire season, the average time between discovery and extinction increased significantly from 4.9 to 9.2 d for large fires (>200 ha) comparing the MD to the control period ($t = -2.991$; $P = 0.006$).

Number of fires and area burned by fire size classes

During the MD, the number of fires and burned area increased in all fire size categories with respect to the previous period (1990–2009; Fig. 6a, c). In the case of fires of greater magnitude, the mean annual burned area significantly increased (fire >200 ha, $t = -2.4$; $P = 0.025$ and fire >1000 ha, $t = -2.46$; $P = 0.021$). Overall, the mean number and burned area of large fires (>200 ha), which annually account for more than 70% of the total burned area, increased 58% and 100%, respectively (Fig. 6b, d).

Total burned area of large fires by different vegetation covers across regions

During the MD period, the total burned area of large fires (>200 ha) increased across all regions compared with the previous 20 yr,

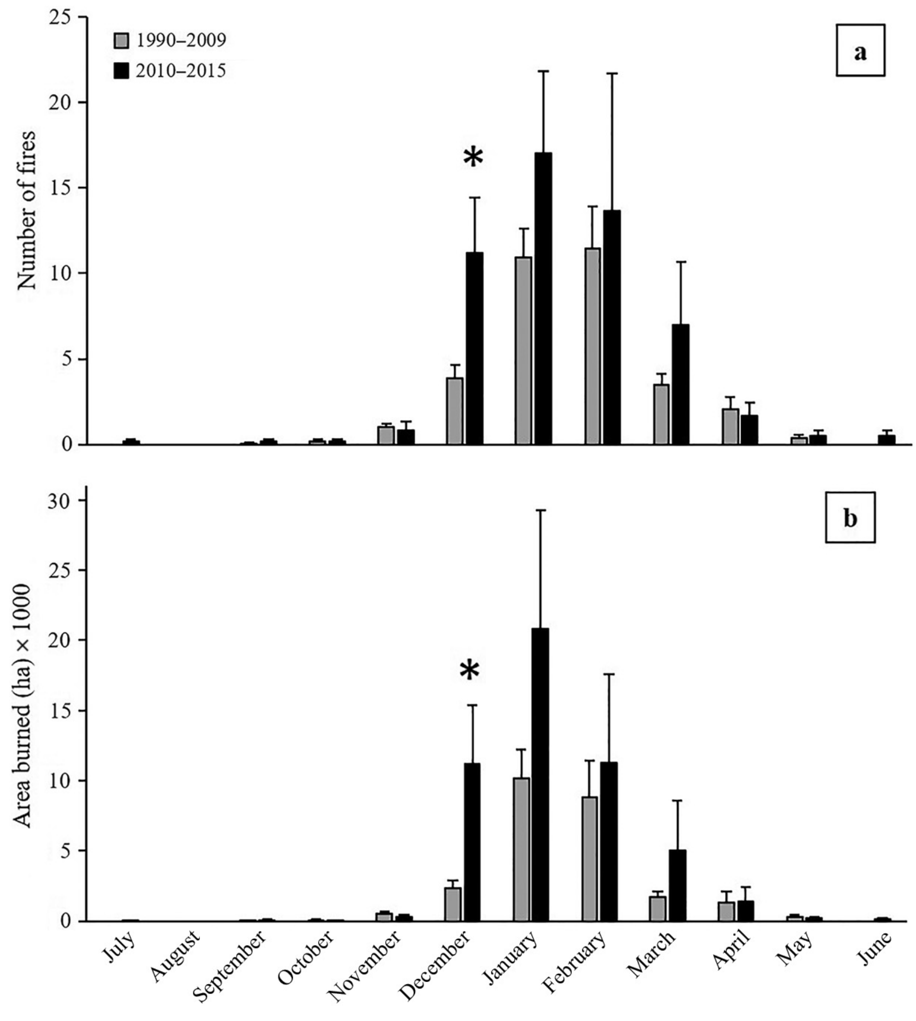


Fig. 3. Mean monthly distribution of (a) number of fires and (b) burned area, both for large fires (>200 ha) from Valparaíso to Araucanía regions. Megadrought period (2010–2015; black bars) is compared with the control period (1990–2009; gray bars). Lines on bars indicate standard errors. Statistically significant differences between study periods ($P < 0.05$) using t or U tests are indicated by asterisks.

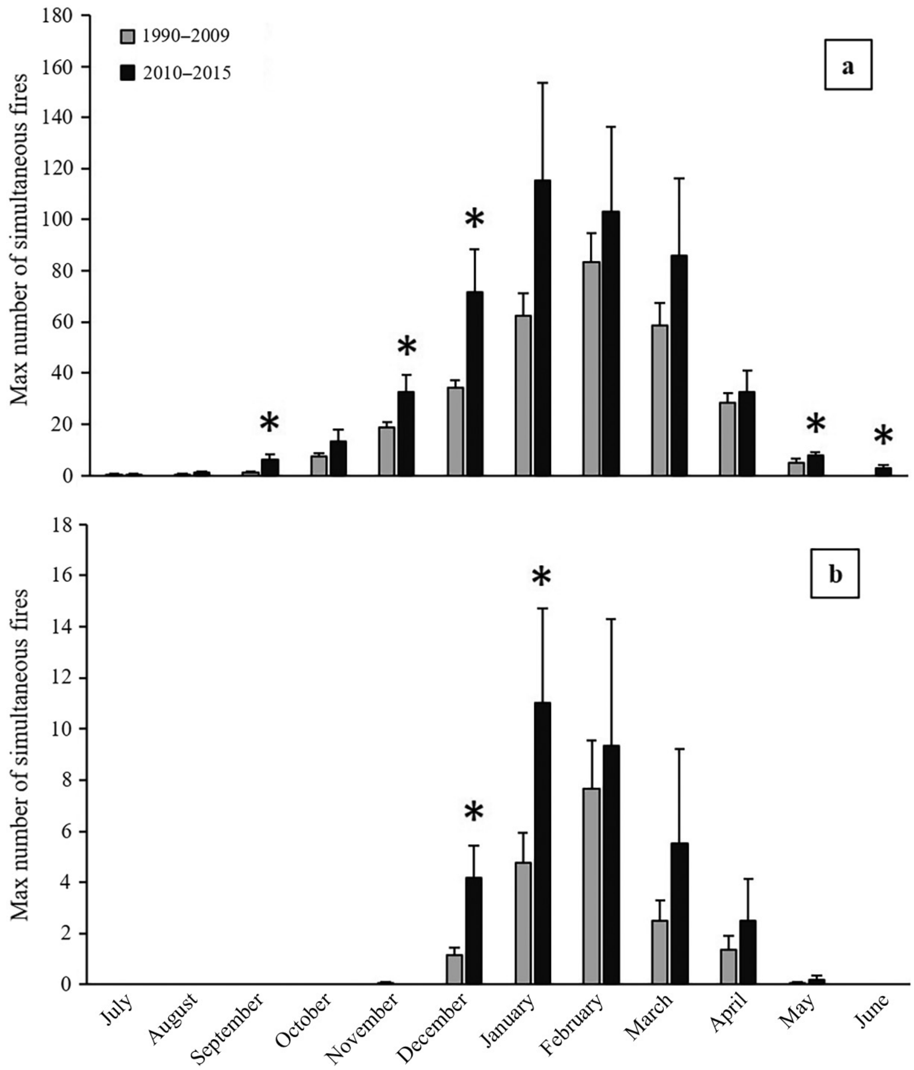


Fig. 4. Mean maximum number of simultaneous fires per month for (a) all fires and (b) large fires (>200 ha). Black bars represent the mean values for the Megadrought period (2010–2015) and gray bars are the mean for the control period (1990–2009). Lines on bars indicate standard errors. Statistically significant differences between study periods ($P < 0.05$) using t or U tests are indicated by asterisks.

independently of the vegetation type cover (Fig. 7; Appendix S3: Table S1). During the MD, the total burned area of all (pooled) vegetation covers in the Maule region increased significantly (VII; 394% of increase, U statistic = 17, $P = 0.01$; Fig. 7a). Overall, the average of the total surface burned (all regions and vegetation types pooled) by large fires in central and south-central Chile significantly increased by 100% during the MD period compared to the control ($t = -2.399$, $P = 0.03$; Fig. 7b).

The average total burned area of native forests increased universally throughout all study regions during the MD period compared to the control, varying from 20% (O'Higgins) to 269% (Maule), and being significant in the Maule region (Fig. 7c; U statistic = 23, $P = 0.03$). Similarly, in the case of the plantation and shrubland cover types, the total average burned area increased significantly in the Maule region (U statistic = 17, $P = 0.01$ and U statistic = 13, $P = 0.01$) with a 911% and 356% increases,

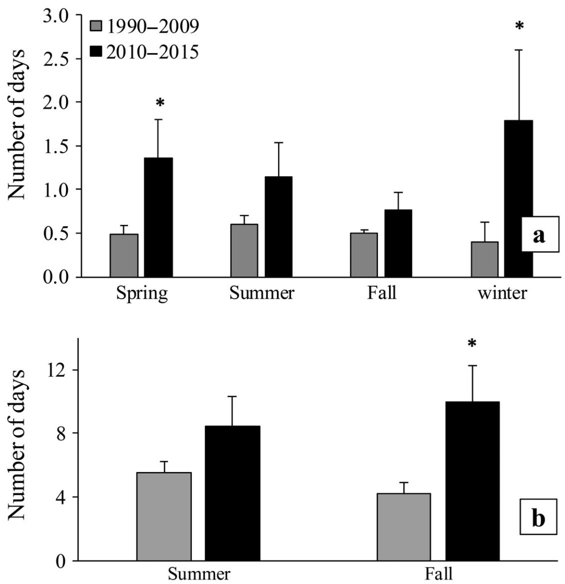


Fig. 5. Mean duration of (a) all fires and (b) large fires (>200 ha) in each season. For large fires (b), only data for summer and fall seasons were available (*Methods*). Lines on bars indicate standard errors. Statistically significant differences between study periods ($P < 0.05$) using t or U tests are indicated by asterisks.

respectively (Fig. 7e, g). In the case of pastures, the total average burned area increased significantly in the RM region (Fig. 7i; $t = -2.838$, $P = 0.01$). When considering all regions combined in each vegetation type (Fig. 7d, f, h, j), the MD increased significantly the annual total burned area of plantations by 161% (Fig. 7f; $t = -2.572$, $P = 0.02$), without significant effects on the other vegetation type covers (Fig. 7d, h, j).

Attribution to climate drivers

Consistent with the previous works, the annual precipitation anomalies in central Chile are negatively correlated with the TAB (Pearson correlation coefficient $r = -0.34$ ($P < 0.01$). On the other hand, the maximum temperature index is positively correlated with the TAB (Pearson correlation coefficient $r = 0.58$; $P < 0.005$). Varying the window for rainfall accumulation or temperature average does not change the correlations significantly. The climate–fire associations are summarized in Fig. 8 by the scatter plot between the temperature index and the total burned area. The full dataset shows that contemporaneous temperatures exert a stronger control on fire activity. For instance, a cold summer restrain fire activity, even if precedent precipitation was low (i.e., data points to the left of the mean temperature, dry anomaly, and low TAB), whereas a hot summer is conducive of large fires even if precedent rainfall was slightly wetter (i.e., data points to the right of the mean temperature, wet anomaly, and high TAB).

The fire seasons within the MD (2010–2011 to 2014–2015) are highlighted (Fig. 8). Three seasons were truly extraordinary (i.e., 2011–2012, 2013–2014, 2014–2015) with burned areas outside the historical interquartile range, featuring dry and significantly warmer conditions. The other two seasons (2010–2011, 2012–2013) had burned areas near or below average, featuring conditions as dry as before but with temperatures colder than average. The average area burned reached ~70,000 ha, well outside the historical interquartile range. All the years in this period were dry, with an average regional precipitation deficit of 30% which is outside the historical interquartile range (see also Garreaud et al. 2017). By the contrary, the MD-average temperature index (28.6°C) was warmer than normal but within its historical range.

To make a more quantitative attribution, we use the univariate linear regressions linking the TAB with precipitation and temperature. The climate-congruent average area burned during the 2010–2015 period was obtained using the MD average values of precipitation anomalies and maximum temperature (pink rectangles at the right of Fig. 8). The model based on temperature predicts a burned area of $49 \pm 5 \times 10^4$ ha, not too far from the historical average of the burned area, suggesting that the slightly warmer conditions between 2010 and 2015 were not the leading climate forcing of the large area burned in that period. The model based on precipitation predicts a burned area of $60 \pm 9 \times 10^4$ ha, still lower than observed but well above the historical mean, indicating that the protracted dry conditions between 2010 and 2014 were the key climate driver for the large area burned in that period. We also develop a multivariate model $\text{PAB} = aT + bP + c$. Using the MD-average values of temperature and precipitation anomalies slightly increased the predicted area burned relative to the model based on precipitation only, because the two climate drivers are not fully independent.

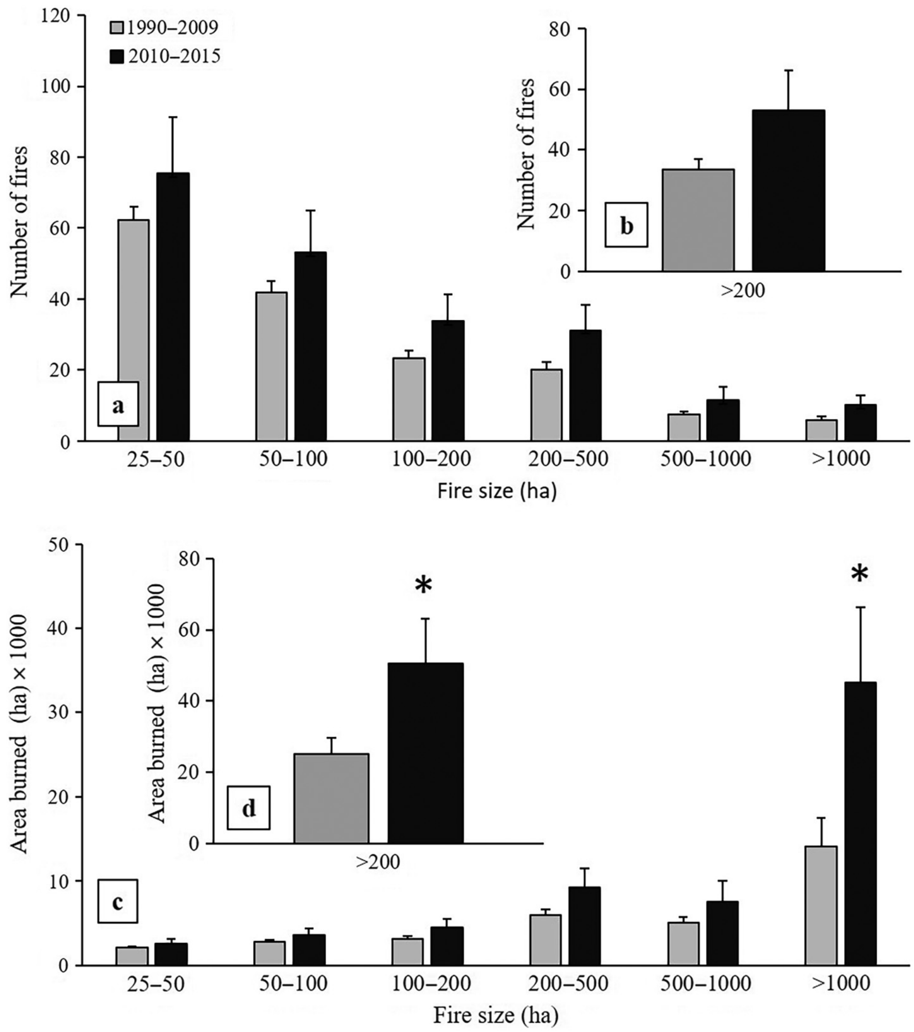


Fig. 6. Mean number of fires and burned area per year for different fire size classes (a, c) and for large fires (>200 ha, b, d). Black bars represent the mean values for the Megadrought period (2010–2015), and gray bars are the mean for the control period (1990–2009). Lines on bars indicate standard errors. Statistically significant differences between study periods ($P < 0.05$) using t or U tests are indicated by asterisks.

Discussion

Megadrought and its influence on fire regimes in central and south-central Chile

Between 2010 and 2015, annual precipitation along central and south-central Chile decreased 20–30% relative to the previous 30 yr. During this MD, the increase in the wildfire-season length represents an important change in fire activity. In western United States, longer fire seasons have been associated with earlier spring runoff and warmer summer whose conditions extend further into fall (Westerling et al. 2006). Under these conditions, vegetation typically becomes ready to burn within weeks. In Chile, the fire season for large fires (>200 ha) between 1990 and 2009 normally ran from late October through mid-April of the following year. Currently, under the MD, the fire season is starting as early as July and ending later in May or June of the next year. Accordingly, the average season length (the time between the first reported fire ignition and last extinction date of large fires) extended by 67 d (44%) during the MD, most of this increase owing to earlier and later ignition dates. Furthermore, during the MD, the number and burned area of large fires

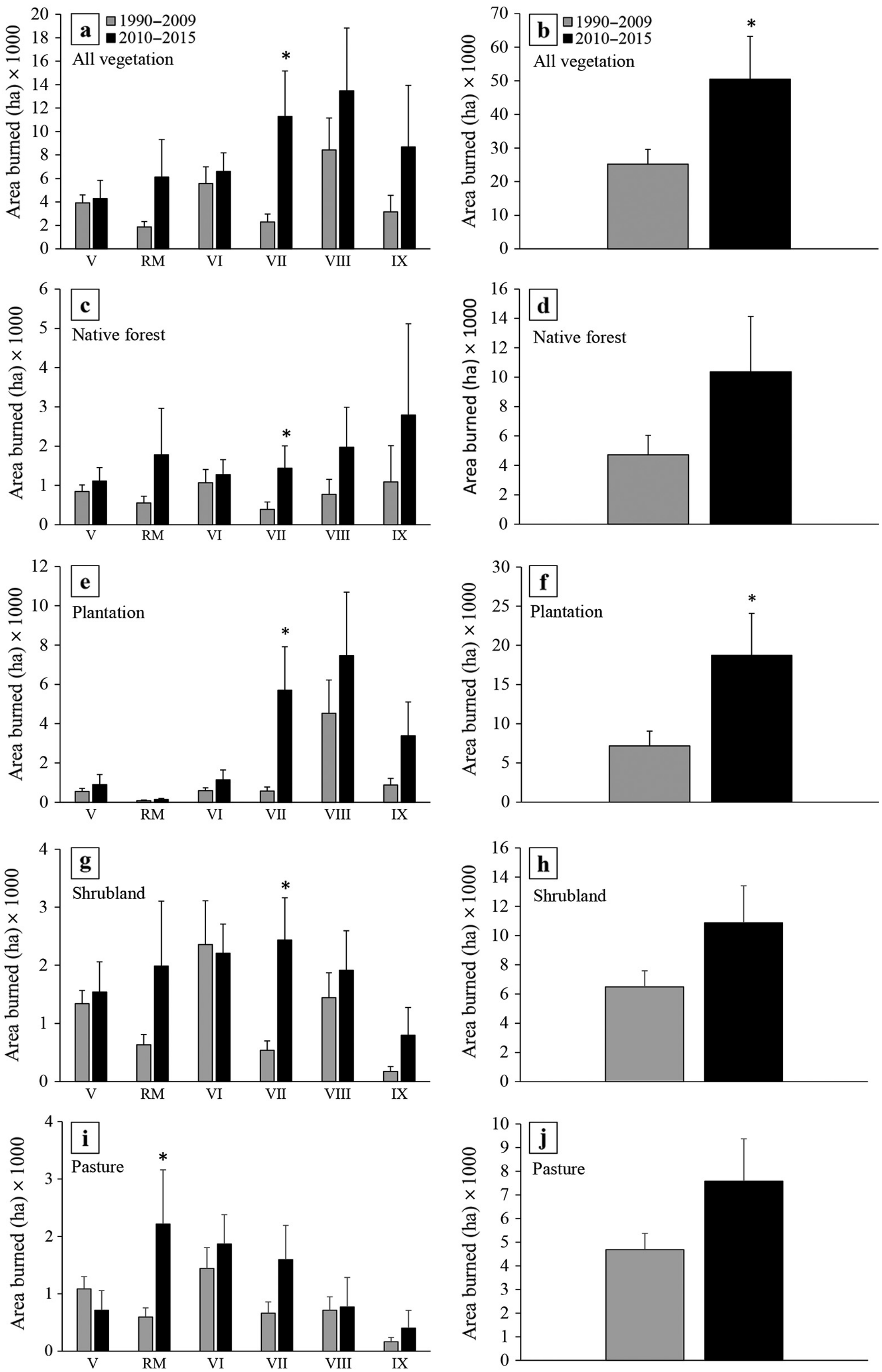


Fig. 7. Average total burned area for large fires (>200 ha) per region (left column) and for all combined regions

(Fig. 7. *Continued*)
(right column) by different vegetation cover types. Black bars correspond to the Megadrought period (2010–2015) and gray bars to the control period (1990–2009). All vegetation covers (a, b); native forest (c, d); plantation (e, f); shrubland (g, h); pasture (i, j). Lines on bars indicate standard errors. Statistically significant differences between study periods ($P < 0.05$) using *t* or *U* tests are indicated by asterisks. Regions: Valparaíso (V), Metropolitana (RM), O'Higgins (VI), Maule (VII), Bío-Bío (VIII), and Araucanía (IX).

increased substantially during late-spring and summer, and also during late fall and early winter, something unprecedented in the previous period (1990–2009).

During the MD, the annual number of fires and area burned increased in all fire size categories compared to the control period (1990–2009). Fires in the largest magnitude category (>1000 ha) doubled their total area with respect to the control period. The total surface burned by large fires (i.e., >200 ha) increased by 100% during the MD compared to the control period, considering all regions and vegetation types pooled together. Forest plantations, as a vegetation cover type (all regions pooled together), experienced the most important change in the total annual burned area during the MD, with a 161% increase compared to the control. The regions that were most affected by fire (i.e., TAB) during the MD were Maule, Bío-Bío, and Araucanía (35°–39° S) that concentrate >75% of forest exotic plantations in Chile (Lara et al. 2016, INFOR 2017). During the MD, ~19,000 ha/yr of forest plantations were burned on average,

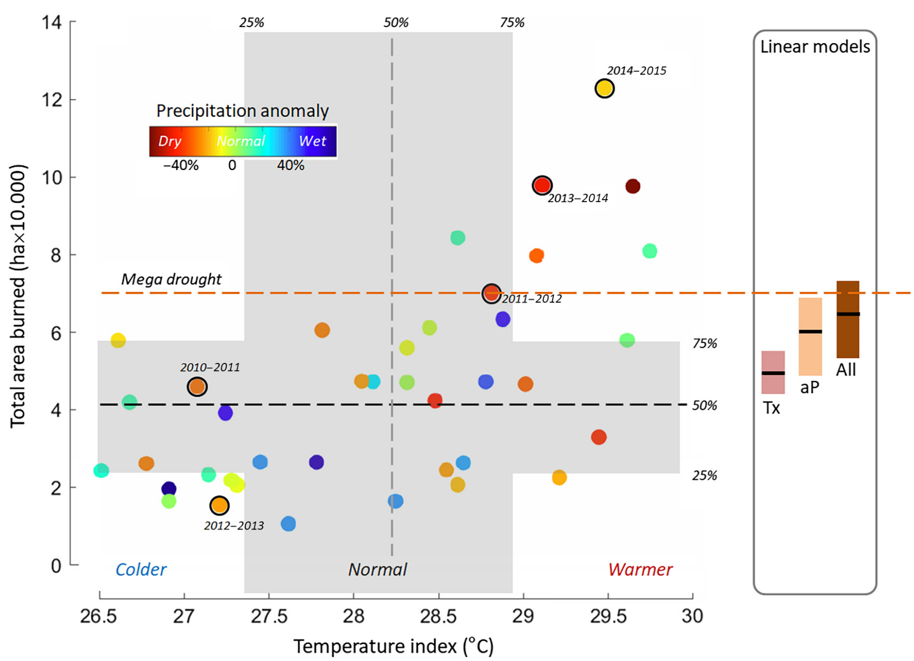


Fig. 8. Scatter plot of the total area burned (TAB) and the maximum temperature index in central-south Chile (See section *Attribution analysis* for the definition of the variables). Each circle represents one fire season, from 1976/1977 to 2014/2015, colored according to the rainfall anomaly during the simultaneous year. The horizontal (vertical) gray bar indicates the interquartile range of the TAB (maximum temperature); the horizontal (vertical) gray dashed line indicates the median of the TAB (maximum temperature). The horizontal, dashed orange line indicates the average TAB during the Megadrought (MD) period, and the individual values are highlighted. The inset to the left shows the climate-congruent TAB during the MD period obtained from linear regressions with the maximum temperature index (Tx), rainfall anomalies (aP), and both variables (All). The predictions (horizontal lines) are obtained by plugging in the MD average values. The boxes indicate the 95% confidence level of each prediction.

which represent nearly 40% of the mean annual area burned by large fires (~47,000 ha/yr).

The number of fires and their simultaneity and duration increased during the MD. In this period, the summer months (December–March) reached the maximum number of simultaneous fires. For example, in January of 2014, there were 286 fires occurring simultaneously, of which 26 were large fires. Simultaneous fire events are an important factor in delaying the prompt response to suppress and extinguish fires because they could overwhelm firefighting efforts making fire suppression less effective (Castellnou et al. 2017). Moreover, out of control fires can become a positive feedback mechanism generating new spot ignitions from firebrands (airborne transport of flaming pieces of fuel; Pagni and Woycheese 2000), which can in turn increase both the number of fires and the area burned.

Results from other MTC regions suggest that changes in fire pattern are likely related to drought conditions, which increased the number of days under fire risk and therefore the probability of fire occurrence (Piñol et al. 1998, Westerling et al. 2006, Jolly et al. 2015, Turco et al. 2017). A simple attribution analysis suggests that this was the case in central and south-central Chile. Although both maximum temperatures and precipitation are drivers of fire activity, the sustained rainfall deficit during 2010–2015 was the most critical factor evaluated in the enhanced fire activity. The rainfall-congruent TAB during this period is well above the historical range but lower than the observed TAB, suggesting other, non-climatic forcing in the marked increase in fire activity that has occurred in the last 5 yr.

By the end of the 21st century, droughts are projected to become more frequent and longer in most MTC regions (IPCC 2013), including central and south-central Chile (Bozkurt et al. 2017), continuing the increment of extreme multiyear drought events unprecedented in the historical record and with few analogs in the last millennium (Christie et al. 2011, Garreaud et al. 2017). These climate trends in combination with land-use changes imply that current increases in fire activity might be the beginning of a longer-lasting trend toward increasingly frequent and widespread fires (Veblen et al. 2008, González et al. 2011). For example, the 2013–2014 and 2014–2015 fire seasons were exceptional in terms of burned area in the country. During these fire seasons, 106,000 and 129,000 ha burned consecutively, exceeding twice the annual average burned (54,800 ha/yr) for the last 40 yr (Lara et al. 2016). And, as mentioned before, the catastrophic 2016–2017 fire season broke these records, with ~600,000 ha burned—10-fold greater than the historic average since mid-1970s (CONAF 2017).

Droughts and fire-prone landscapes: management strategies to cope more frequent and large fires

Fires and their effects on terrestrial ecosystems are highly sensitive to global change. Altered fire regimes resulting from changes in climate conditions are having strong ecological impacts and consequences on biodiversity and ecosystem structure and processes (Cochrane 2003, Lindenmayer et al. 2011). Although climate and humans are the most important drivers of fire occurrence, other factors such as fuel load, arrangement, and continuity are key factors for fire ignition and spread. Landscapes with high load and fuel connectivity are particularly prone to large fires (Veblen et al. 2008, Moreira et al. 2009, 2011, Viedma et al. 2009, Barros and Pereira 2014, Fernandes et al. 2016). In central and south-central Chile, fire hazard has changed associated with the expansion of fire-prone forest plantations of the exotic *Pinus radiata* and *Eucalyptus* spp. (from 250,000 ha in 1974 to near 3 million in 2016). In central Chile, during 1999 and 2009, the expansion of exotic plantations resulted in a fuel load increase between 3 and 40 Mg/ha, contributing to an increase in the wildfire danger area (Carmona et al. 2012).

As a conclusion of this study, the following three superposed drivers and their feedbacks have increased fire occurrence and its impacts: arson and negligent human action, which account for ~95% of the total ignitions during the MD period (Appendix S1: Fig. S1); reduced precipitations and longer droughts; land-use change toward highly homogeneous and fire-prone landscapes dominated by exotic plantations as well as invasive shrubs and trees. The 2016–2017 fire season that affected ~600,000 ha with human casualties and severe impacts on the socio-ecological systems reveals that the extensive landscapes massively dedicated to the monoproduction of timber are no longer sustainable in central and south-central Chile. Recognizing that megafires will be a part of future fire regimes, land-use planning and forest and fuel management are key strategies to reduce landscape vulnerability and their undesired impacts.

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