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RESEARCH ARTICLE

# Human–environmental drivers and impacts of the globally extreme 2017 Chilean fires

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**Abstract** In January 2017, hundreds of fires in Mediterranean Chile burnt more than 5000 $km^2$, an area nearly 14 times the 40-year mean. We contextualize these fires in terms of estimates of global fire intensity using MODIS satellite record, and provide an overview of the climatic factors and recent changes in land use that led to the active fire season and estimate the impact of fire emissions to human health. The primary fire activity in late January coincided with extreme fire weather conditions including all-time (1979–2017) daily records for the Fire Weather Index (FWI) and maximum temperature, producing some of the most energetically intense fire events on Earth in the last 15-years. Fire activity was further enabled by a warm moist growing season in 2016 that interrupted an intense drought that started in 2010. The land cover in this region had been extensively modified, with less than 20% of the original native vegetation remaining, and extensive plantations of highly flammable exotic *Pinus* and *Eucalyptus* species established since the 1970s. These plantations were disproportionally burnt (44% of the burned area) in 2017, and associated with the highest fire severities, as part of an increasing trend of fire extent in plantations over the past three decades. Smoke from the fires exposed over 9.5 million people to increased concentrations of particulate air pollution, causing an estimated 76 premature deaths and 209 additional admissions to hospital for respiratory and cardiovascular conditions. This study highlights that Mediterranean biogeographic regions with expansive *Pinus* and *Eucalyptus* plantations and associated rural depopulation are vulnerable to intense wildfires with wide ranging social, economic, and environmental impacts, which are likely to become more frequent due to longer and more extreme wildfire seasons.

**Keywords** Fire weather · Forest plantations · Land cover change · Mediterranean climate · Smoke pollution · Wildfire

**Electronic supplementary material** The online version of this article (https://doi.org/10.1007/s13280-018-1084-1) contains supplementary material, which is available to authorized users.

## INTRODUCTION

Wildfires are increasingly recognized as a natural hazard that can cause significant social, economic, and environmental harms. Settlement patterns and land management actions affect the magnitude of wildfire impacts, which are showing signs of being exacerbated by anthropogenic global climate change. Analysis of global meteorological data shows that wildfire seasons are becoming longer and characterized by more extreme fire weather (Jolly et al. 2015). Some studies have demonstrated that anthropogenic climate change has contributed to increased vegetation dryness, longer fire seasons, and increased incidence of extreme fire danger in parts of the globe (Abatzoglou and Williams 2016). Globe-scale satellite analyses have also shown that extremely energetic and destructive fire events have been linked to extreme fire weather conditions and promoting economically disastrous fire (Bowman et al. 2017).

Partitioning the relative effects of inherent ecology, human actions, and climate change is difficult. Wildfire is not exclusively a climate phenomenon; it has biological and human dimensions. Some plants and vegetation types (e.g., tall grasses, *Eucalyptus*) are inherently more flammable than others and human ignitions, fire suppression, and land uses (e.g., plantations, urbanization) affect the



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likelihood of fires by altering patterns of landscape fire hazard (Bowman et al. 2011). Collectively, the spatial occurrence and extent, behavior (intensity and rate of spread), and biological impacts are the result of a complex amalgam of climatic, biological, and human influences. Nonetheless, humans can profoundly positively and negatively influence fire activity. For instance, the Maori colonization of New Zealand resulted in a dramatic increase in fires (McWethy et al. 2010); by contrast, in the western USA there has been an effective program of fire suppression since the beginning of the 20th century (Marlon et al. 2012). Given the complex direct and indirect drivers of fire activity, it is crucial to consider the respective roles of climate, biogeography, land use, and fire management in affecting fire activity, which necessarily demands a transdisciplinary approach and analysis of specific fire events.

In this context, we consider a major fire event that occurred in the austral summer of 2016/17 in Central Chile (32–38° S, 70–73° W), a densely populated region with a Mediterranean climate. Between January 1 and February 10, 2017, large areas of Central Chile were affected by historically unprecedented wildfires that have collectively become known as *'tormenta de fuego'* (in English, 'the fire storm'). Hundreds of individual fires burned more than 5000 $km^2$, threatening densely populated areas and destroying extensive forestry plantations, small agricultural holdings, and several rural villages, with 11 confirmed fatalities. Although this fire event was widely reported in the media and has been the subject of brief commentaries in global scientific literature considering the ecological consequences (Martinez-Harms et al. 2017), policy dimensions (Gómez-González et al. 2018), and possible linkages with climate change (Anonymous 2017; Holz et al. 2017), there are yet no detailed pyrogeographic analyses that holistically consider the biophysical aspects of the fires and the health impacts of the smoke.

Rigorous post-mortem analysis of significant fire events is crucial to provide insight on key ingredients that contributed to fire risk, occurrence, and growth rates and the identification of a host of potential drivers. We acknowledge that such a case study approach is necessarily opportunistic, and constrained by available, and often imperfect, data from a variety of sources. Here we (a) use historical records to contextualize the extent of the fires and their association with different land cover types, (b) assess the severity of the fires at a regional and global scale using satellite imagery analysis, (c) identify climatic trends and meteorological conditions that preceded and occurred during the fire, and (d) make a first approximation of the magnitude of the health impacts of the smoke generated from this event. Finally, we discuss both the value of the transdisciplinary case study approach taken here, and canvas the broad implications of this fire event for other landscapes with Mediterranean climates.

## MATERIALS AND METHODS

### Fire severity and extent

We determined interannual variability of the area burned and number of ignitions for five administrative regions of central Chile from 1985–2017 to contextualize the 2016-2017 fire season. Fire data (burned area and ignitions) were acquired from Corporación Nacional Forestal online data (CONAF 2017). We compared burned area in *Pinus* and *Eucalyptus* plantations with non-plantation areas (comprised grasslands, shrublands, and woodlands) for each fire year (July - June) from 1984/85 through 2015/16. We conducted a spatial overlay analysis from the 2017 fire perimeters reported by Corporación Nacional Forestal (CONAF 2017) with land cover from Zhao et al. (2016) to quantify the relative proportions of land cover type burnt and determine if these proportions were greater than expected. We applied a Chi-Square test to determine if the area of plantations burnt was significantly greater than expected.

To quantify wildfire effects on vegetation productivity, we mapped contemporaneous biomass loss as quantified by the 16-day Enhanced Vegetation Index (EVI) product (MOD13Q1) from MODIS (Huete et al. 2010). Data were pre-processed using the quality assessment bands, and by eliminating pixels corresponding to snow, water, clouds, cloud-shadows, and high level of aerosols. For each pixel in central Chile, we calculated an anomaly for the wildfire season by first developing a probability curve of a given EVI value occurring on a given day during the primary growing season from the first 16 years of the EVI data (i.e., excluding the 2016–2017 growing season). We then calculated the cumulative anomaly (difference between baseline and post-fire EVI values) for a given pixel for the 2016–2017 growing season up to January 1, the final EVI scene before the wildfires began, to account for pre-fire impacts of the severe drought and heat on vegetation. Finally, we calculated the fire-induced EVI anomaly as the difference between the EVI observed on March 6, 2017 (the start of post-fire recovery) and the expected (modeled) EVI, minus the 2016–2017 growing season anomaly up to January 1. These phenological reconstructions and anomaly calculations were performed using the software R and the package *npphen* (Chávez et al. 2017). We then randomly sampled 10,000 points from within the burnt areas and attributed both pre-fire land cover and post-fire EVI anomaly for each point. A Kolmogorov–Smirnov test (Lilliefors 1967) was applied to the EVI anomaly distributions to test for significant differences in the distribution of biomass loss between plantation and non-plantation sites (Parks et al. 2014). To assess the fires by intensity against the MODIS-derived global extreme events, we used the database developed by Bowman et al. (2017), we updated this database through April 30, 2017, and then re-ranked the events based on the new years of data.

### Climatic context and fire weather conditions

To assess meteorological conditions during the fire event and the climatic context for the fires, we acquired daily data output from the ERA-Interim reanalysis at a 0.75° spatial resolution from 1979 to 2017. Daily precipitation data from the Multi-Source Weighted-Ensemble Precipitation (MSWEP) product (Beck et al. 2017) at 0.5° spatial resolution were prioritized over ERA-Interim precipitation given its incorporation of gauge-based precipitation data. Daily accumulation precipitation from MSWEP was interpolated to the ERA-Interim grid for compatibility following Abatzoglou et al. (2018). These data were used to compute a suite of bioclimatic variables that have been linked to wildfire activity in global studies including vapor pressure deficit (VPD), climate water balance, and the Fire Weather Index (FWI) from the Canadian Forest Fire Danger Rating System (van Wagner 1987).

All calculations were performed at the native resolution of the data and then aggregated to cover the geographic extent of central Chile excluding non-land pixels. Daily mean wind speed, maximum temperature, and FWI were examined for Austral summer (DJF) 2016–2017. In addition to examining daily near-surface fire weather data for December 2016–February 2017, we computed climatological statistics to contextualize conditions. This was done by calculating the median, interquartile range, and 95th percentile range of daily data using a 21-day-centered moving window of historical daily data from 1979-2016. Finally, to provide longer-term context for drought conditions across the region leading up to the fire event, we acquired gridded monthly self-calibrated Palmer Drought Severity (sc-PDSI) indices from the Climatic Research Unit dataset for the study region (Osborn et al. 2017). Whereas we make no attempt to explicitly model burned area extent during the 2017 firestorm, we provide a climatic context for the event by calculating linear climate-burned area correlations for the study area excluding the 2017 fire season. This was done separately for the base-10 logarithm of fire season (Dec-Mar) burned area, as well as for burned area in plantation and non-plantation areas. We considered interannual correlations to climate variables concurrent to the core fire season (e.g., temperature, VPD, occurrence of extreme fire danger days defined as FWI exceeding the 95th percentile) as well as precipitation antecedent to the fire season-given relationships reported in prior studies (e.g., Urrutia-Jalabert et al. 2018).

### Air quality and health impacts

We followed the approach of Broome et al. (2016), who evaluated a period of severe pollution from landscape burning in Sydney, Australia. The details of this analysis are provided in the electronic supplementary material. We obtained hourly measurements of particulate matter less than 2.5 micrometers in diameter ($PM_{2.5}$) per cubic meter of air from the Chilean National Air Quality Information System (Sistema de Información Nacional de Calidad del Aire (SINCA) 2017) (Table S1). We included all monitors in regions affected by the fire as follows: Valparaiso, Metropolitan, O'Higgins, Maule, and Biobio. The difference between the historical mean $PM_{2.5}$ for January and February 2012–2016, and the measured $PM_{2.5}$ during the fire period was calculated to estimate the excess pollution attributable to the fires. Mortality and hospital discharge records for 2011–2015 were obtained from the Department of Statistics and Health Information of the Ministry of Health (Departamento de Información y Estadísticas de Salud Ministerio de Salud (DEIS) 2017) and population data from the 2017 National Census (Instituto Nacional de Estadística (INE) 2017) (Table S2). We calculated the baseline average daily incidence of all-cause mortality, and hospital admissions for respiratory and cardiovascular conditions during the summer months of January and February by region (Table S2). We then applied standard concentration–response functions for $PM_{2.5}$ developed by the World Health Organization (WHO 2013), to estimate the number and 95% confidence intervals (95% CI) of premature deaths, respiratory, and cardiovascular hospital admissions attributable to increased $PM_{2.5}$ from the fires (Table S3).

## RESULTS

The *'tormenta de fuego'* event involved hundreds of fires that burned a total of 5132 sq. km (Fig. 1). The extent of these fires was 5.7 times the area burned in the next largest fire year on record (1998–1999) and 13.6 times the 32-year mean (excluding the 2016–2017 fire season) for the five administrative regions comprising central Chile (Fig. 1). This extreme anomaly, however, occurred despite a normal number of documented ignitions (CONAF 2017) (Fig. 1). The predominant vegetation types burnt were *Pinus* (31%) and *Eucalyptus* (12%) plantations and grass/shrub rangelands (44%), with a substantially smaller proportion (11%) of natural forests (Fig. 2). As plantations only comprise

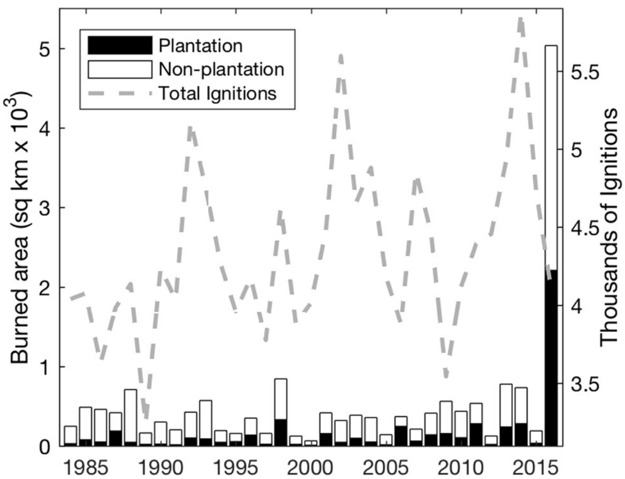


**Fig. 1** Trends in area burned (broken down by plantation and non-plantation land cover types) and number of ignitions for five regions in central Chile from Corporación National Forestal (CONAF 2017) that show a > 500% increase in area burnt in the 2017 event despite a typical number of ignitions. Over the 33-year period—475,000 of plantations burned, and excluding 2017 at total of 12,000 ha was burned

14% of the landscape of central Chile, the fires burned at a significantly higher rate than expected in this human-engineered land cover type (d.f. = 1, $p < 0.0001$). The disproportionate amount of fire in plantations in 2016–17 is consistent with a significant increase in plantation burned area over the 33-year record. For example, approximately 40% of the burned area from fire seasons 2005/06 to 2016/17 occurred in plantations compared to 21% of the burned area for fire seasons from 1984/85 to 2004/05.

Plantations also burned more severely than non-plantation land cover types with greater loss of biomass (Fig. 2). The median EVI negative anomaly (i.e., departure from normal vegetative greenness) for plantations was 0.19, compared to a median negative anomaly of 0.14 for other land cover types, where the range of values for all points was 0.07 (lowest severity) to 0.38 (highest severity). While other land cover types displayed a near-normal distribution of EVI anomaly as a proxy for burn severity, the EVI distribution for plantations was skewed towards more severe (Fig. 3). The K–S test confirmed that fire effects in plantations were significantly more severe than in other land cover types ($\alpha < 0.0001$).

During the fires, daily regional FWI was high with several days above the 95% distribution (including the all-time highest value in the 1979–2017 period on 25 January) that were coincident with the largest growth rate of reported fires (Fig. 4). High daily maximum temperatures contributed to extreme fire weather (Fig. 4). During the latter half of January 2017, 7 days fell above the 95% distribution, including the warmest region-wide daily mean

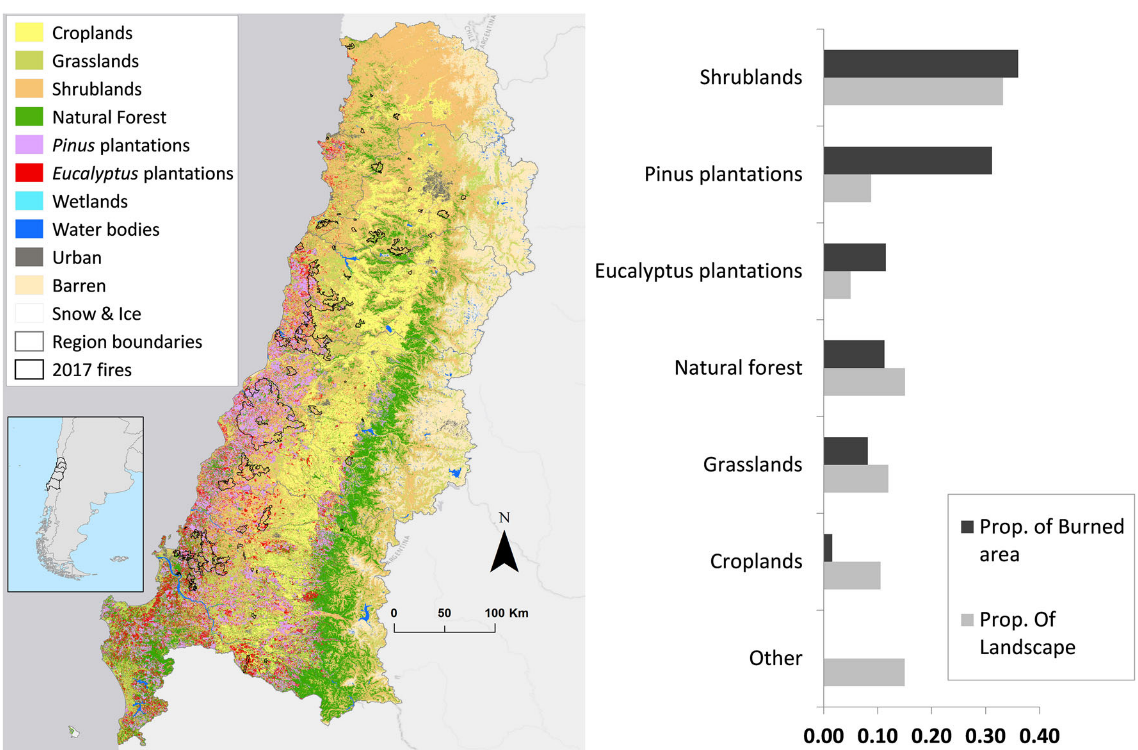


**Fig. 2** Land cover from Zhao et al. (2016) and 2017 fire perimeters from CONAF (2017) demonstrating that the fires were concentrated in plantations (left panel). Proportion of burned area versus proportion of central Chile landscape for each land cover type demonstrating expected versus observed proportions for each class (right panel)

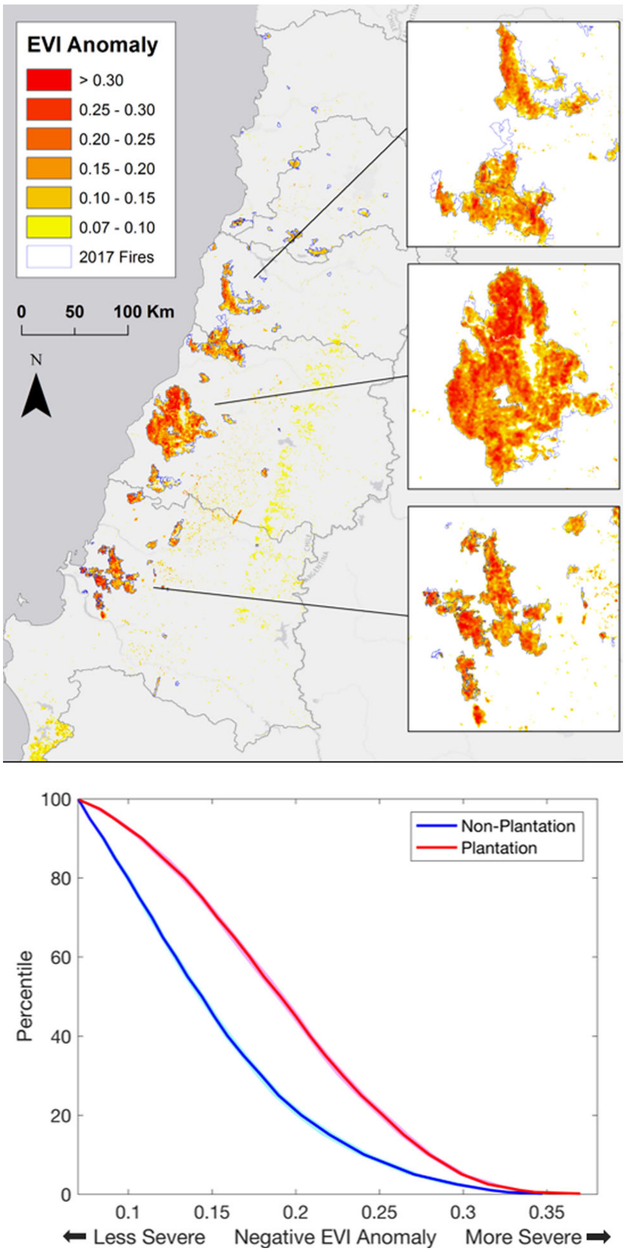


Fig. 3 Map of Enhanced Vegetation Index (EVI) anomaly in central Chile in early 2017 shows where the greatest loss of vegetation occurred relative to expected greenness, due to the wildfires (top panel). Distribution of EVI anomaly values for 10,000 randomly sampled pixels within burnt areas, stratified by whether land cover type was plantation or not, with 95% CI envelope (bottom panel)

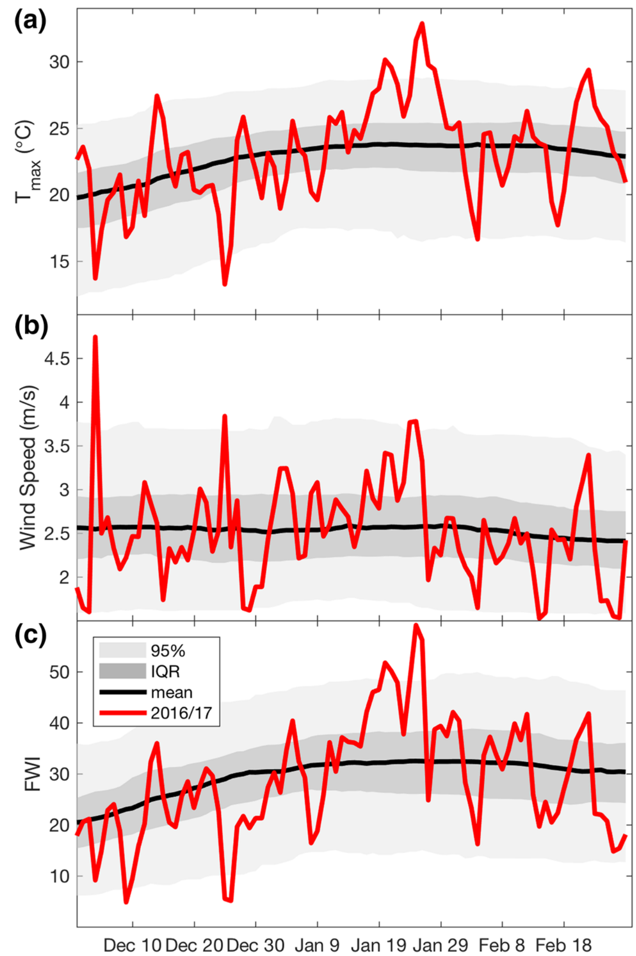


**Fig. 4** Daily **a** maximum temperature, **b** mean wind speed, and **c** Fire Weather Index from December 1, 2016–February 28, 2017 averaged over central Chile. The light and dark gray depict 21-day moving averages of the interquartile range (IQR) and the middle 95% of the data for the period of record (1979–2017), while the bold black line shows the average daily data from 1981–2010

temperature in the ERA-Interim record (1979–2017) and all-time maximum temperatures records set at the two long-term stations in the region: Arturo Merino Benitez International (Station CIM00085574) and Carriel Sur International (Station CIM00085682). Region-wide winds speeds were also above average for the latter half of January 2017, punctuated by a couple of days where winds where above the 95% distribution contributing to fire spread. While summer average temperatures were well above normal, as defined by 1981–2010 averages, summer mean drought stress as realized through VPD was only slightly above average (Fig. 5). The wet warm season and cool season (1-year lag) preceding the fire year moderated the effects of a significant prolonged and historically significant drought from 2008–2015 (sc-PDSI $< -1.5$). Climate–fire relationships excluding the 2016–2017 fire season showed significant positive correlations between burned area extent and summer temperature, VPD, and the number of days with extreme FWI, most notable for burned area in plantations (Table 1). Likewise, burned area extent was weakly negatively correlated to cumulative precipitation the previous winter, but positively correlated to precipitation in the preceding year, suggestive that interannual variability in both fuel abundance and fuel dryness enable fire activity in the region.

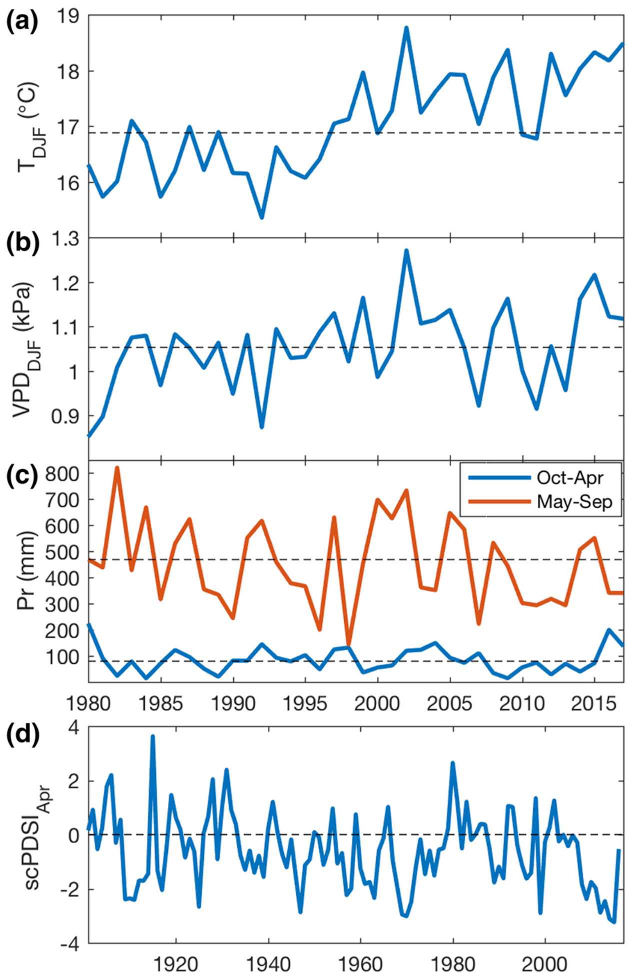


**Fig. 5** Time series of **a** December–February mean temperature, **b** December–February vapor pressure deficit (VPD), **c** cumulative precipitation for the warm season (Oct–Apr) and cool season (May–Sep), and **d** April self-calibrated Palmer Drought Severity Index for central Chile. The horizontal dashed lines depict the 1981–2010 averages in (**a**–**c**)

Reanalysis of the global extreme wildfire events database of Bowman et al. (2017), based on daily Fire Radiative Power (ΣFRP) from the MODIS space-borne sensor summed over 100 $km^2$, highlighted the extreme nature of this fire event globally. A total of 11 of the revised top 500 ΣFRP events (out of a total of more than 30.4 million events in the 2002–2017 MODIS record) occurred in central Chile between 18 and 26 of January 2017, corresponding with the peak in fire activity and extreme fire weather conditions (Fig. 6).

Smoke impacts varied by region (Table S4). The highest daily average $PM_{2.5}$ recorded during the fire period was 739 μg/$m^3$ in the region of Biobio, while in the Metropolitan region, which includes the capital city of Santiago, the peak $PM_{2.5}$ was 93 μg/$m^3$ at Independencia. More than 9.5 million people, representing approximately 54% of the total population of Chile (17.5 million), were exposed to an average increase in $PM_{2.5}$ of 26.8 μg/$m^3$ above historical mean concentrations for a period of 16 days (Fig. 7). The calculated health impacts of the increased air pollution were (N, 95% Confidence interval): 76 (24–132) premature deaths 140 (0–343) respiratory hospital admissions and 69 (15–127) cardiovascular hospital admissions (Table S5).

**Table 1** Pearson's correlation coefficients between the base-10 logarithm of fire season (Dec–Mar) burned area in central Chile and climate variables both concurrent to and antecedent to the fire season. Correlations were computed over a 32-year period from the fire season 1984/85 to 2015/16. Statistically significant correlations at $p < 0.05$ are shown in bold. All climate data were aggregated over land covering 32–38°S, 70–72.5°W

| Variable | All fire | Plantation | Non-plantation |
|---|---|---|---|
| Mean temperature (Dec–Feb, DJF) | **0.32** | **0.45** | 0.22 |
| Precipitation (DJF) | − 0.09 | − 0.03 | − 0.16 |
| Vapor pressure deficit (DJF) | **0.37** | **0.43** | **0.36** |
| Days where the Fire Weather Index > 95th percentile (DJF) | **0.39** | **0.47** | **0.36** |
| Self-calibrated Palmer Drought Severity Index (DJF) | − 0.26 | − **0.34** | − 0.22 |
| Precipitation (previous wet season, May–Sep) | − **0.31** | − **0.30** | − **0.30** |
| Precipitation (previous warm season, Oct–Apr, lag − 1) | **0.46** | **0.39** | **0.46** |
| Precipitation (previous wet season, May–Sep, lag − 1) | **0.41** | **0.41** | **0.35** |

## DISCUSSION

We have shown that the fires that occurred in central Chile in the January 2017 were some of the most intense landscape fires on Earth in this century. Our synthesis of available biophysical information leads us to conclude that area burned (albeit not number of fires) was historically anomalous, driven by extreme climatic conditions. Further, we find that extensive monocultures of highly flammable *Pinus* and *Eucalyptus* plantations played a substantial role in these extreme fires.

We acknowledge this study is necessarily opportunistic working with the imperfect data, which is an inevitable consequence of investigating an unpredictable event. Although uncommon in environmental sciences, case study approaches are recognized of being of great value in progressing understanding of many fields, such as medicine, astronomy, meteorology, and volcanology, where experimentation is ethically or practically impossible and important phenomenon occur

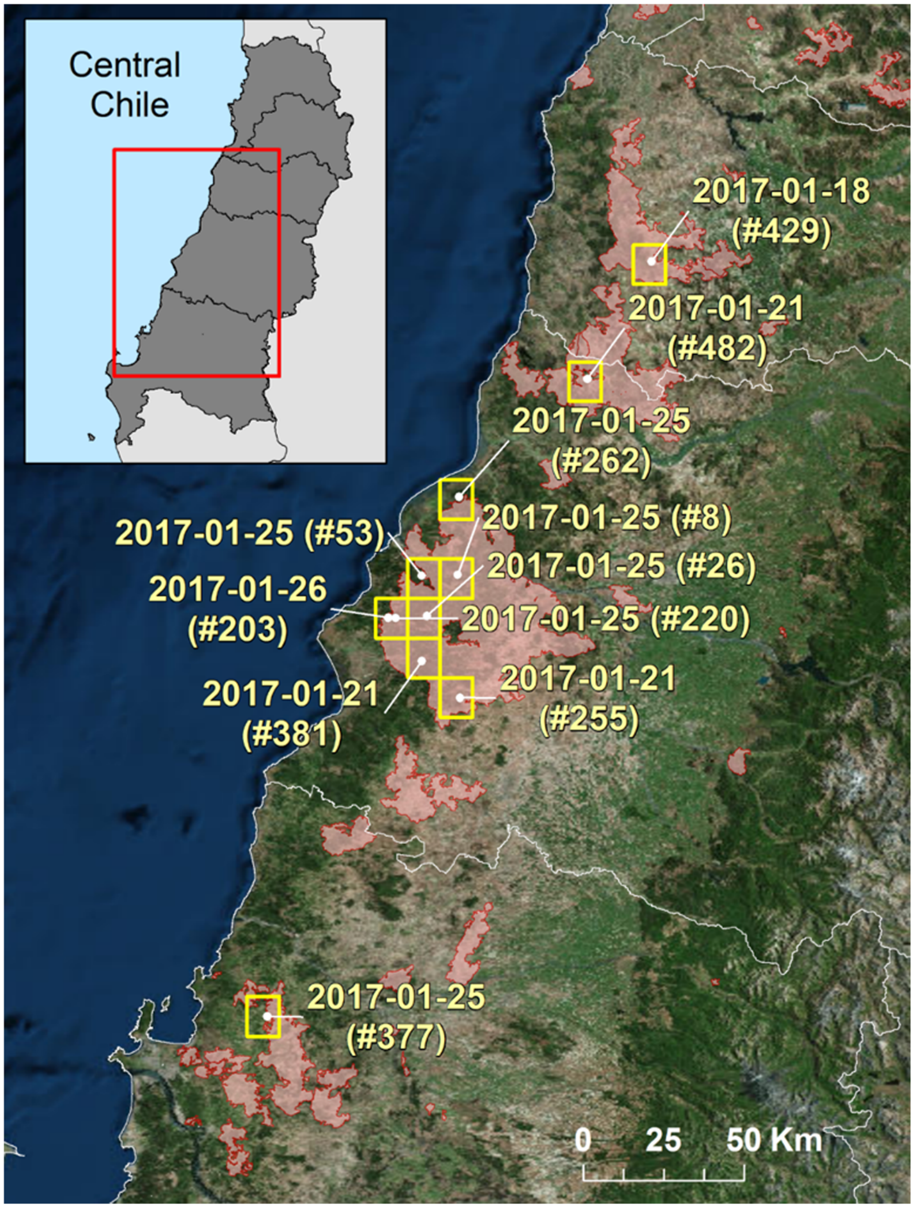


**Fig. 6** Location of pixels ranking in the revised top 500 most extreme global fire events (as defined by MODIS-derived ΣFRP 100 km$^{-2}$). Squares indicate the location, date, and rank (#/500) from 2002 to May 2017 following the methods of Bowman et al. (Bowman et al. 2017), demonstrating that 11 (2%) of the top 500 events occurred in the 2017 fires

unpredictably. There is growing awareness that the synthesis of data to understand extreme fire events is pivotal. Indeed, a recent editorial in *Nature Climate Change* stated 'Earth-monitoring efforts as well as on the ground research seem to be ever more valuable resources as we try to manage the direct and indirect risks that changing wildfires pose to people and the environment' (Anonymous 2017). Below we consider broader implication of our case study for flammable Mediterranean landscapes globally.

The large area burnt, and the extremely intense fires detected by the MODIS satellite, in central Chile, was associated the anomalous meteorological conditions including highest temperatures and FWI in the 39-year reanalysis record. Although meteorological records did not identify particularly windy conditions, the rapid rate of spread, erratic behavior change, and sustained nocturnal intensity reported by fire fighters suggest that the fires were likely creating their own localized wind fields. Additionally, climate variability leading up to the 2016–2017 fire season appears to also have contributed to the high intensity of the fires. Mediterranean climates, including the central Chilean coast plains and ranges, are particularly conducive to wildfires given cool wet winters that favor fuel production and hot dry summers that provide reliable

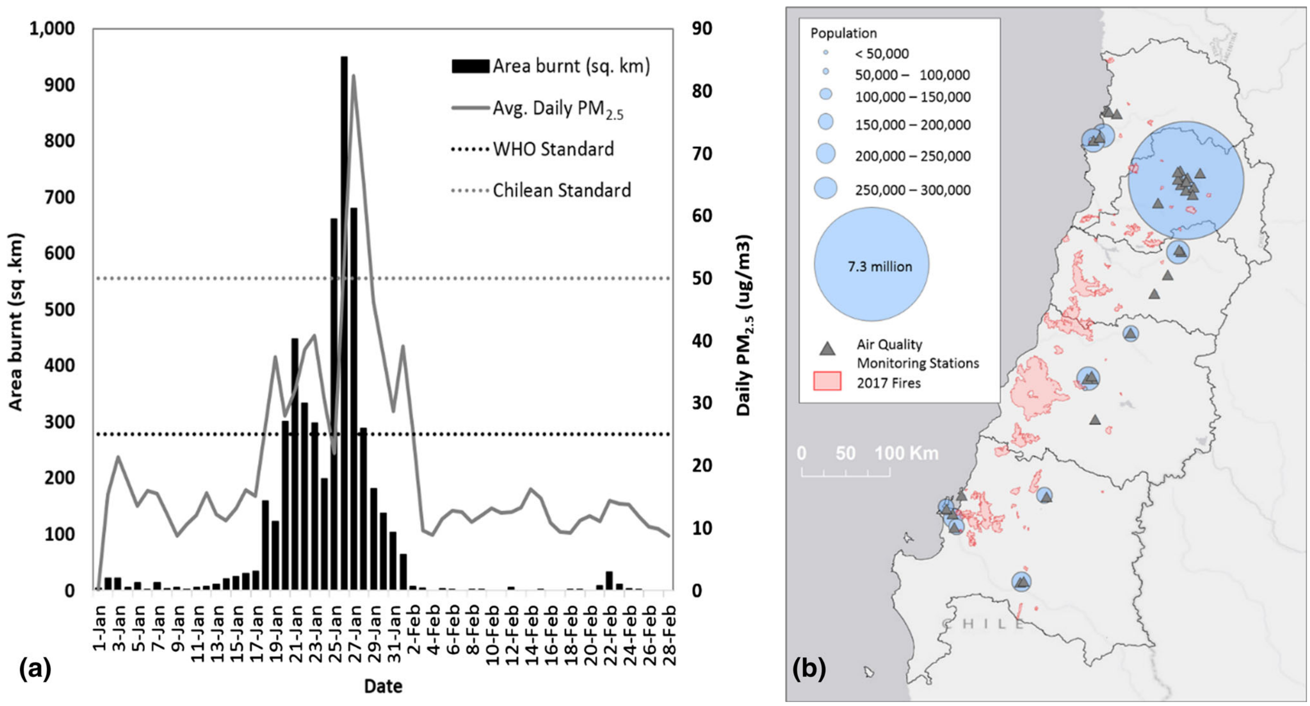


**Fig. 7** Air quality impacts from the 2017 fire event in central Chile both temporally (**a**) and spatially (**b**). Aggregated across the five regions of central Chile, residents were exposed to poor air quality exceeding the WHO (2017) limit of 25 μg/m$^3$ fine particulate matter ($PM_{2.5}$) for a total of 15 days between 18 January and 2 February (**a**), corresponding with the peak of fire consumption (i.e., area burnt) across the region but also resulting in delayed atmospheric clearing after the peak burning period. Over 9.5 million residents were impacted across the fire regions (**b**), most of them in the metropolitan capital region surrounding the capital city of Santiago

fire weather (Cowling et al. 1996, Keeley 2012). Our results, and the results of others (Urrutia-Jalabert et al. 2018; Abatzoglou et al. 2018), suggest that interannual fire activity in central Chile significantly correlates with summer water deficit, and precipitation that occurred in the previous growing season (Table 1). Such antecedent seasonal effects are well-understood features of the pyrogeography of seasonal environments (Bradstock 2010).

Climate variability leading up to the fire season included an antecedent moist growing season associated with El Niño conditions in 2015/16 that result in increased biomass production and hence available fuel. Historical studies have related fire activity in southern South America has also been to the positive phase of the Southern Annular Mode (SAM) due to warmer and drier conditions (Holz et al. 2017; Urrutia-Jalabert et al. 2018), as was the case before the fires. Additionally, the fires occurred after the 2010-2016 drought, which was one of the most extreme droughts in the last millennium (Garreaud et al. 2017). There is evidence that frequency of droughts has been increasing since 1950 (González-Reyes 2016; González-Reyes et al. 2017), possibly in response to climate change (Boisier et al. 2016). In addition, future projections show a decline of precipitation rate in 40% of the total annual amounts over Central Chile for the 21st century (Comisión Nacional del Medio Ambiente (CONAMA) 2006), increasing the severity and frequency of droughts events (Bozkurt et al. 2017). Despite the primacy of climatic conditions in driving the fire intensity and extent of the fires, our study highlights the need to consider additional factors such as land use and vegetation type.

Natural vegetation in Mediterranean regions has adapted to a strongly seasonal climate with a recovery mechanism to both drought and fire disturbance (Cowling et al. 1996; Keeley 2012). However, unlike other Mediterranean regions, natural (lightning) ignitions are rare in Mediterranean Chile. Even though plant species in the *Nothofagus* forests, *Acacia caven* and *Prosopis chilensis* savannas, and sclerophyllous shrublands that characterize central Chile can recover from fire damage via basal and aerial resprouting and soil seed banks, the natural flora is less adapted to fire than other climatically similar regions (Montenegro et al. 2003). This is clearly apparent by the sharply contrasting recovery of burnt *Eucalyptus* trees to native trees (Fig. 8).

Colonization by indigenous people in the early Holocene and European colonization since the 16th century resulted in marked increase in landscape fire and caused a loss of fire-sensitive vegetation (Aravena et al. 2003). In the mid-20th century, much natural vegetation in Central Chile had been converted to small-scale agricultural enterprises (Aronson et al. 1998). Since the 1970s, a massive program of *Pinus radiata* and *Eucalyptus globulus*


**Fig. 8** High mortality induced by extreme fire behavior in *Nothofagus* forest [DMJS Bowman] (**a**); aerial view of the complete destruction of the village of Santa Olga in the Maule region [permission Ministerio de Bienes Nacionales] (**b**); fire effects due to high intensity fire behavior, including rock shattering, whole plant consumption, and hydrophobic soils facilitating erosion [A. Moreira-Muñoz] (**c**), and high burn severity in *Pinus radiata* plantation [DMJS Bowman] (**d**)

plantations has been implemented (Aronson et al. 1998; Klubock 2006; Heilmayr et al. 2016). We found a strong association with area burnt and fire severity with *Pinus* and *Eucalyptus* plantations. Plantations are particularly flammable because of closely dense trees and deep litter beds, which result in sharply increased landscape flammability and, hence the need for fire suppression (Peña-Fernández and Valenzuela-Palma 2005; Carmona et al. 2012; Diaz-Hormazabal and Gonzalez 2016; Úbeda and Sarricolea 2016). Densely stocked regenerating stands of *Eucalyptus* are known to favor high severity fires (Taylor et al. 2014; Bowman et al. 2016). Unlike native vegetation where fire risk increases after periods of above annual rainfall due fuels build up, monocultures of exotic trees are likely to become highly flammable during anomalously dry seasons such as the 2015/16 summer due to leaf shedding and desiccation of fine fuel. Anticipating increasing fire risk due to climate change, Gómez-González et al. (2018) stress the need for fuel management in *Pinus* and *Eucalyptus* plantations to reduce fire hazard.

The fire hazard of the plantations is further increased because of a socio-ecological consequence of industrial-scale forestry plantations that lead to widespread rural depopulation and loss of small-scale traditional agricultural enterprises run by poor rural landowners (*campesinos*) (Peña-Fernández and Valenzuela-Palma 2005; Klubock 2006). For example, Curepto commune in Maule region, lost 25% of its population between 1974 and 2015, due to the expansion of forest industry (Aguilera Vivanco 2016). This sociological change has reduced landscape complexity thereby making flammable fuels more continuous. Further, political opposition to industrialized forestry in some regions has been linked to the destruction of plantations by arson (Úbeda and Sarricolea 2016).

Quantification of the direct and indirect economic impacts of the fires, and the insured and uninsured losses, is beyond the scope of this paper, but is likely to be substantial because of the extensive loss of homes (such as the entire Santa Olga village), structures, and damaged large-scale agricultural enterprises such as vineyards and small-scale rural holdings (Fig. 8). The loss of plantations will also have enduring negative economic impacts to the Chilean economy through the destruction of timber resources given the forest industry contributes US$2.8 trillion to the national economy annually, and employs 1.5% of jobs nationwide (Instituto Forestal (INFOR) 2016).

Central Chile is a biodiversity hotspot where nearly all the remaining natural vegetation is on private lands (Pliscoff and Fuentes-Castillo 2011). There is concern that there is little incentive to restore privately owned natural vegetation (Martinez-Harms et al. 2017). Ecosystem services are likely to be severely degraded by the fires due to extensive soil erosion on steep slopes, loss of carbon storage, reduction of biodiversity, and smoke pollution, although there is as yet little quantification of these effects (Fig. 8). It has been estimated that the total emission of the fires was about 30 megatonnes $CO_2$, which would have accounted for 'approximately 8% of the January 2017 total global fire emissions' (Parrington et al. 2017). Our results show that smoke from these fires caused episodes of extremely poor air quality and haze affecting the most densely populated region of Chile and thus about half of the nation's population. Our health assessment suggests that smoke killed seven times as many people as the actual inferno. The link between wildfire smoke exposure and poor health is well established; population exposure to wildfire smoke has been associated with increased mortality, hospital admissions, symptoms, and medication use, especially in people with chronic lung diseases (Reid et al. 2016). Our health impact assessment highlighted the large health burden from wildfire smoke when large populations are affected. There is acknowledged uncertainty around the estimates. However, in available studies, the associations between particulate matter and health outcomes in Chile have shown broadly similar effect size estimates to those used in this assessment (Cifuentes et al. 2000; Sanhueza et al. 2009).

The 2017 Chilean *'tormenta de fuego'* event raises concern about the fire risk of similar catastrophic fire in Mediterranean climate zones. Historically wildfire disasters are concentrated in southern Australia and western North America (Moritz et al. 2014; Bowman et al. 2017), with fewer events in the climatically similar Mediterranean Basin due to high human population densities and different land uses (Bowman et al. 2017). However, socio-ecological trends of rural depopulation and widespread *Pinus* and *Eucalyptus* plantations, combined with a rapidly changing climate, apparently contribute to an increase of fire disasters in southern Europe (Moreira et al. 2011; Pausas and Fernández-Muñoz 2012; Nunes et al. 2016; Oliveira et al. 2017; Gómez-González et al. 2018). This problem was well illustrated by extreme wildfires in Mediterranean Europe during the 2017 boreal summer that caused fatalities and widespread loss of property in Spain and Portugal (Boer et al. 2018; Gómez-González et al. 2018) and those in California in late 2017 (Nauslar et al. 2018).

Our findings have substantial implications for understanding the interplay between climate and land cover change on fire activity, and the likely consequences for fire activity in other flammable landscapes in a warming world. The Chilean fires were extremely difficult to control despite using a well-developed fire suppression force including ground crews (professional fire fighters and local community) and aerial water bombing (including the Boeing 747 Supertanker, the world's biggest aerial fire bomber, which was partially funded by foreign private donors), but little vegetation reduction had occurred locally as a proactive measure to reduce fire hazard. This underscores the urgent need for developing sustainable socio-ecological systems for management of flammable landscapes where the risks of extreme fires are being amplified by climate change (Moreira et al. 2011; Fernandes 2013; Moritz et al. 2014; Fischer et al. 2016; Nunes et al. 2016, Úbeda and Sarricolea 2016; Bowman et al. 2017). In Portugal, landscape analysis has shown that having a mix of agriculture, forestry, and grazing can reduce the occurrence and impact of wildfires (Nunes et al. 2016). Small-scale clearing around structures can also reduce the destructive effects of fire. Under catastrophic fire weather conditions in both Australia and US Mediterranean ecosystems, the probability of houses burning has been reduced where trees and shrubs are removed within 30–40 m of houses (Gibbons et al. 2012; Syphard et al. 2014). It is possible, therefore, that improved landscape planning and design in Mediterranean landscapes can reduce fire hazard (Moreira et al. 2011), including creating mosaics of flammable and less flammable vegetation, planting orchards and vineyards, with an associated increased labor force in flammable landscapes (Otero 2016). It must be acknowledged that sustainably funding such initiatives is more difficult than investing in classical fire-fighting approaches; indeed, there remains unresolved tension between the roles of government and industry (top down) and local community (bottom up) in managing fuels and ignitions (Moreira et al. 2011; Fernandes 2013; Fischer et al. 2016).

## CONCLUSION

We show that the 2017 Chilean fires were globally extreme and historically anomalous. The fires were associated with fire weather conditions unprecedented in the last four decades and an antecedent severe multiannual drought. Further, the establishment of extensive highly flammable *Pinus* and *Eucalyptus* plantations disrupted a form of traditional Mediterranean silvopasture and led to rural depopulation. The fires had substantial effects on air quality and human health, released globally significant amounts of $CO_2$, and impacted a global biodiversity hotspot. The 2017 Chilean fires highlight the vulnerability of this and other Mediterranean settings that are affected by similar land cover and demographic changes, and are prone to experience more extreme fires under anthropogenic climate change. This study highlights the joint effects of climate extremes and land-use practices in contributing to catastrophic wildfires.

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