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Megafires in Chile 2017: Monitoring multiscale environmental impacts of burned ecosystems

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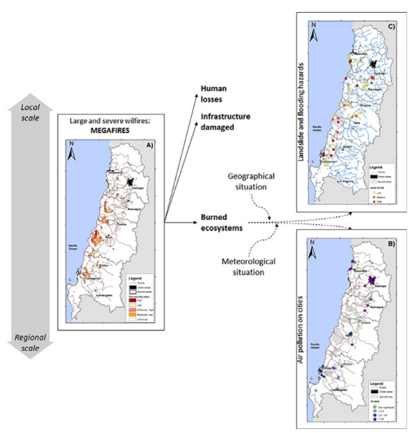
HIGHLIGHTS

- Megafires in South-Central Chile caused negative consequences on environment.
- There are cities located very close to severely burned ecosystems.
- Significant impacts on air quality in close and distant cities were detected.
- Cities close to burned ecosystems are exposed to new landslide and flooding hazards.

GRAPHICAL ABSTRACT



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ABSTRACT

During the summer of 2017, several megafires in South-Central Chile burned down forest plantations, native forests, shrublands and human settlements. National authorities identified the relevant effects of the wildfires on infrastructure and ecosystems. However, other indirect effects such as the risk of flooding or, increased air pollution were not assessed. The present study assesses: i) the geographic characterization of wildfires, ii) amount of damage to ecosystems and the severity of wildfires, iii) the effects of megafires on air quality in nearby and distant urban areas, and iv) identification of cities potentially exposed to landslides and flooding. We ran remote sensing analyses based on the Normalized Burn Ratio taken from Landsat imagery, “active fires” from MODIS, and ASTER GDEM. The particulate matter (PM_{10} and $PM_{2.5}$) levels measured on 34 Chilean's municipalities were correlated with the burning area/distance ratio by Spearman correlation. Socionatural hazards were evaluated using multi-criteria analyses combining proximity to burned areas, severity, potential flow of water and sediments as indicated by the Digital Elevation Model, drainage networks and the location of human settlements. 91 burned areas were identified, covering 529,794 ha. The most affected ecosystems were forest plantations and native shrublands. We found significant correlations between burned area/distance ratios and $PM_{2.5}$ and PM_{10} levels, leading to increased levels over the Chilean air quality standard in the most populated cities. 37 human settlements were at increased risk of landslides and flooding hazards after fires and eleven could now be

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characterized as dangerously exposed. The 2017 wildfires in Chile have had an impact at both a small and large scale, with far-reaching air pollutants dispersing and affecting >74% of the Chilean population. The impact of the wildfires was also extended over time, creating future potential for landslides and flooding, with the risk increasing in rainy seasons.

1. Introduction

Wildfires play a fundamental role in Earth life, having strong ecological consequences on landscape and ecosystem patterns and dynamics (Úbeda and Sarricolea, 2016; North et al., 2015; Pausas and Keely, 2009). Among many positive effects, wildfires help to keep the fuel complex resistant to severe burning by naturally managing vertical and horizontal structures of forests (Rocca et al., 2014; Hurteau et al., 2014). They also can increase on plant diversity when native seeds are dominant and accelerate the nutrient cycle, enriching biotically and abiotically the ecosystems (Hurteau et al., 2014; Thonicke et al., 2001). Carbon sequestered by forest can be return to the atmosphere by biomass decomposition and by emissions caused by fires, however after fires carbon can be rapidly resequestered by forest grown in fire-adapted systems, helping to reduce atmospheric carbon dioxide concentration (Hurteau et al., 2014). Most of these positive effects depend on the natural fire regime of biomes and the occurrence of low-severity wildfires. When fire regime change or severity of fires increases, the consequences are different. Climate change induces modifications on both features, for example if the pattern of precipitation changes, it affects the forest structure and wildfires could reach higher severities in the short term, having effects on the ecosystem services provided (Lee et al., 2015; Rocca et al., 2014). In addition, the increase of dryness in some biomes converts potential fuels to available fuels, increasing severity of fire (Pausas and Keely, 2009). Fire management alternatives include no active management, fire suppression, prescribed fires, and mechanical treatments (e.g. thinning); decision makers need to decide when and where to apply each of them to avoid damages on human settlements, ecosystem recovery, ecosystem services and sustainability of resources (Lee et al., 2015; Rocca et al., 2014; Pausas and Keely, 2009).

Despite of the natural importance of wildfires to model landscape patterns and ecosystem processes, there is an extensive literature about the diversity and magnitude of damages produced by them when fire management is unable to control the propagation of fires, especially in short and medium term (Alexandre et al., 2015; Moritz et al., 2014; Milne et al., 2014; Newman et al., 2014; Yell, 2010). Large scale and severe forest fires cover broad areas and produce significant consequences to land and territory (Salis et al., 2014; Gill et al., 2013; Carmona et al., 2012). They also have considerable social impact on large-populated areas located close to landscapes modified by large fires (Hendrychová and Kabrna, 2016; Weng, 2007; Vitousek et al., 1997). In fact, megafires can modify in the short and medium term the local climate, ecosystems processes, nutrient cycles, and the emission rate of gases and particulate matter, depending on the extension and severity of fires (Rocca et al., 2014; Hurteau et al., 2014; Adams, 2013; Tansey et al., 2002; Chuvieco and Martin, 1994). The direct impact of large-scale forest fires (> 10,000 ha) and megafires (>40,000 ha) are diverse ranging from tragic human loss, damaged homes, the loss of ecosystem and fundamental changes of their characteristics (Alexandre et al., 2015; Moritz et al., 2014; Milne et al., 2014; Newman et al., 2014; Yell, 2010). Also, as a consequence of land cover change derived from large-scale fires there are losses of ecosystem services provided by the lands before the fire, being especially critical when said fires reach urban areas or extensively populated areas (Moritz et al., 2014; Adams, 2013; Parise and Cannon, 2012).

Native forests, forest plantations and all types of vegetated areas store carbon, acting as an ecosystem service of global and local relevance. When these areas catch fire, they release not only carbon – in the form of CO_2 or CO – into the atmosphere, but also PM_{10}, $PM_{2.5}$, O_3, etc., cancelling the positive effects of the ecosystem services they provide (Cuchiara et al., 2017; Rubio et al., 2015; Price et al., 2012). The plume of smoke and air contaminants can be easily seen and reported, and it disperses particulate matter over hundreds of kilometers, eventually reaching populated areas and dramatically increasing mortality and morbidity rates, making it an important public health problem (Cuchiara et al., 2017; Alman et al., 2016; Rubio et al., 2015; Johnston et al., 2014; Finlay et al., 2012; Price et al., 2012; Fowler, 2003). In addition to accumulating carbon and preventing the release of air pollutants, densely vegetated ecosystems provide ecosystem services linked to the regulation of hydrological flows, preventing the landslides and flooding; so when said vegetation is destroyed in a fire, the land beneath becomes exposed and prone to these phenomena, especially in periods of intense precipitation (Moody et al., 2008).

During the austral summer of 2017, the central-southern region of Chile suffered the biggest forest wildfires in the country's history. The intensity of some of these fires led the authorities to call them “fire storms” given they set a record for the highest amount of energy released in a wildfire in the world, and added an entirely new level to the scale used to classify forest fires (CONAF, 2017). Chilean authorities officially acknowledged that a total of 518 thousand hectares of land was burned in the wildfires between January 11th and February 18th, where forest plantations were the most affected ecosystems. Public expenditure to combat fires was more than US$ 370 million (CONAF, 2017) and the toll in the aftermath of the fires came to: at least 11 deceased and 3000 houses lost, and many changes to several ecosystems and sensitive species living in them.

Megafires are infrequent phenomena, but they not only reached Chile, they also impacted other countries during the last decades, for example: Portugal (2003 and 2005), Greece (2007), Australia (2009 and 2013) and the USA (2007 and 2013; (San-Miguel-Ayanz et al., 2013). The summer of 1985 was especially hard in Spain, tens of wildfires exceeded 500 ha and the reported total of burned land was over 450 thousand ha (Bento-Gonçalves et al., 2015). Portugal 2003 was an extreme case, where 218,047 ha were burned in only 9 days, an amount 2.7 times the European average (European Commission, 2004). In Greece 2007 set a historical record with 195 thousand ha burned by the end of summer (European Commission, 2008).

Mediterranean landscapes are prone to wildfires, especially when meteorological conditions favour them (high winds, high temperature and low humidity; Turco et al., 2014; CONAF, 2017), and when dominant land cover is highly combustible, homogeneous and includes pyrophyte vegetation (Levin et al., 2016; Darques, 2015; Salis et al., 2014; Gill et al., 2013; Carmona et al., 2012; Bajocco and Ricotta, 2008). Although wildfires are frequent phenomena in Chile and its austral Mediterranean landscape, megafires are not (Úbeda and Sarricolea, 2016). It is possible that the intensive transformation of natural landscapes of native forests, shrublands and grasslands into massive exotic pyrophyte forest plantations (pine and eucalyptus trees; Heilmayr et al., 2016) could have an effect on the magnitude of wildfires and their recurrence. It is becoming critical to assess the consequences of megafires in this type of landscapes.

During this critical episode, reports issued by the Chilean authorities mainly focused on the number of wildfires (locations), their extension, the affected ecosystems (percentage of total burned area), the number of fatalities directly caused by wildfires, the number of households lost, and the protected natural areas threatened by fires. The event caught the attention of not only national but also international press (e.g. http://www.bbc.com/news/world-latin-america-38713019). Weeks and months after the wildfires the discussion turned to identifying their causes, in particular the extension of exotic pyrophyte plantations and the inadequate maintenance of overhead power lines (e.g. http://www.biobiochile.cl/noticias/nacional/region-del-maule/2017/10/05/imputan-a-tres-ejecutivos-de-la-cge-por-incendios-forestales-del-verano-en-el-maule.shtml). Yet there is still very little or no information on the secondary consequences or other primary consequences.

With this study our first objective is to specify the data for the spatial extension and daily temporal evolution of the burned area, characterizing the affected areas by severity and types of ecosystems. Secondly, we aim to report on some of the environmental consequences of wildfires, assessing their effects on air quality and foresee the appearance of new hazards, specifically landslides and flooding in cities at the vicinity of these fires.

2. Methodology

Wildfires in Chile generally occur between parallel 33 and 42 S, in other words the South-Central region. The majority of them are concentrated in certain administrative areas of the Chilean territory; these areas include Valparaiso, Metropolitan Santiago, O'Higgins, Maule and Bio-Bio regions (Úbeda and Sarricolea, 2016). This area is characterized by extensive monocultures of exotic forest plantations and human activity (Martinez-Harms et al., 2017) (Fig. 1) both of which have changed the landscape in just a few decades, replacing agricultural lands, grasslands and native shrublands and forests (Heilmayr et al., 2016; Schulz et al., 2010). This area is home to 12.8 million inhabitants, 74% of the country's population. We calculated the area affected by wildfires in this region in two months of the summer of 2017, from January 1st to February 28th, evaluating their effects on human settlements located in the aforementioned regions.

As the aim of the study is to show the impact of wildfires and not to try to explain their mechanisms, the statistical tool used for air pollution impacts was Spearman correlation and for landslides and flooding impacts we applied a GIS multicriteria analysis. They serve to get a causal significance and not a predictive model.

2.1. Geographic characterization of wildfires

Burned areas and severity of the fires were determined using multispectral satellite images taken before and after each fire. Corrected Landsat imagery (L8 OLI-TIRS) and Aster digital elevation models (both with a spatial resolution of 30 m) were downloaded from https://earthexplorer.usgs.gov. The difference between the pre and post-fire Normalized Burn Ratio index (resulting in the dNBR) was calculated to identify the burned areas and the degree of severity using infrared bands. The dNBR was calculated by creating two mosaics with nine scenes in each one (path: 233; rows: 82,83,84,85,86,87/path: 01; rows: 85,86,87), each image with either no clouds or with <10% cloud cover. The first mosaic represented pre-fire circumstances; there were

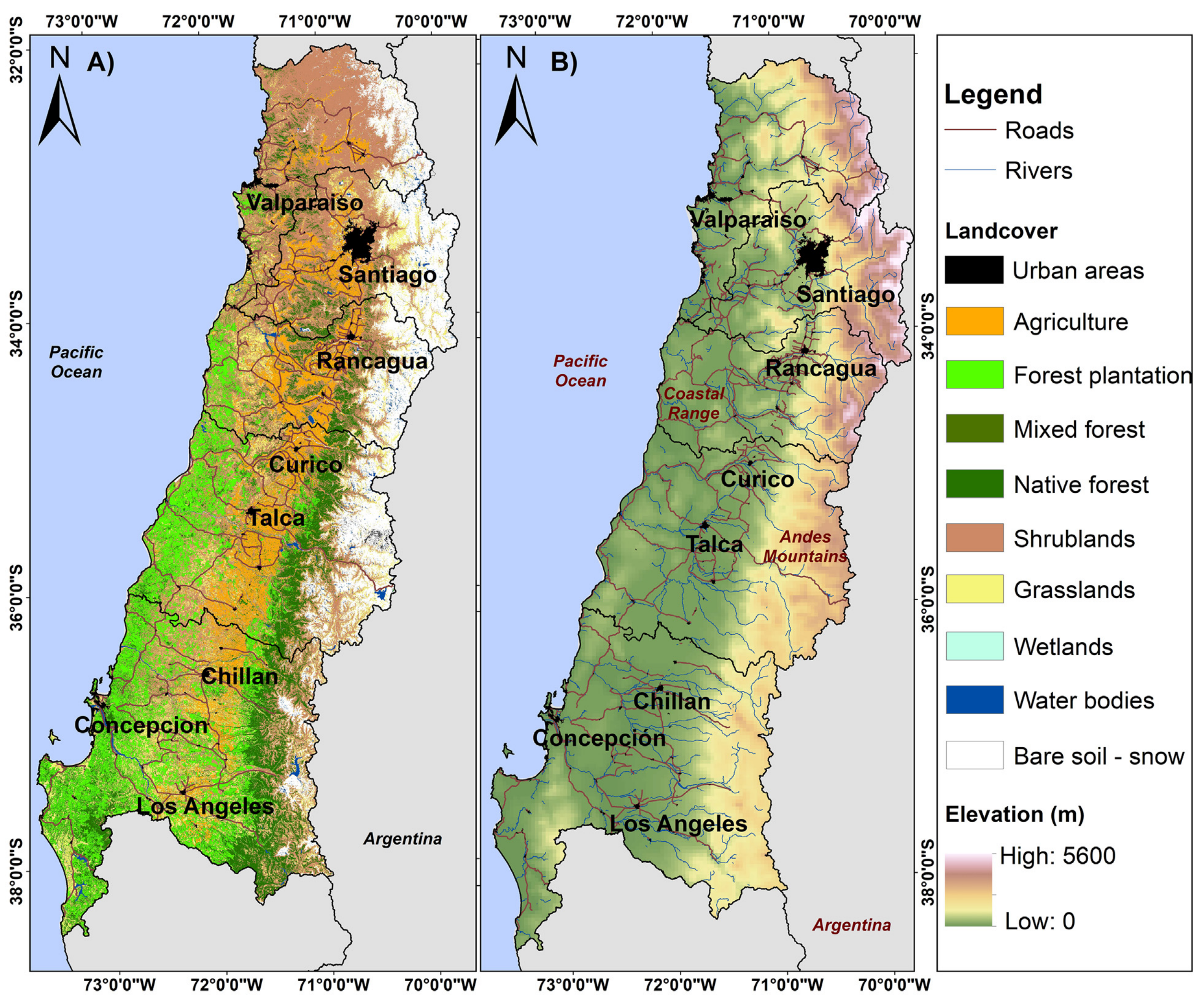

Fig. 1. South-Central Chile. Study area including main land covers, roads, water bodies and elevations. Maps based on Hernández et al., 2016.

8 images taken on January 1st, 2017 scenes depicted in the mosaic, and two images dated December 7th, 2016 for the coastal areas of the Bio-Bio region. The second mosaic was representative of post-fire circumstances and it included scenes from March 6th, 2017 and February 25th, 2017 (scenes from the coast of the Region of Bio-Bio). After obtaining the dNBR, we categorized the degrees of severity of the fires and then digitalized the limits of the burned areas which were visited to verify in the field the occurrence of the fire and the severity calculated through images. We categorized the fires into six degrees of burn severity using the dNBR: i) high, ii) moderate-high, iii) moderate-low, iv) low, v) area without fire (not burned), and vi) burned areas with signs of low and high regrowth. The results yielded the number of wildfires (burned units) and the total burned area for each independent fire. The calculation took into consideration both planimetric surfaces (2D) and relief (3D). To obtain the 3D area we used an ASTER digital elevation model (spatial resolution 30 m) and used this method to quantify the difference between 2D and 3D areas.

To calculate the daily burned area, two parallel independent processes were used. First, we estimated how many days each fire was active by comparing the products from Landsat imagery with MODIS data (MCD64A1) using a web-based platform (https://worldview.earthdata.nasa.gov). Then, we divided the total area of each burned units by the days that unit showed an active behaviour to get the result. Secondly, we combined two MODIS products (MCD64A1 and MOD14A2) and calculated the total area affected by wildfires in a refined daily scale and a moderate spatial scale (1000 m), processing the data in GIS software accordingly (Giglio et al., 2016).

2.2. Impact on ecosystems

To assess the ecosystem changes caused by wildfires we calculated the loss of area and the severity of the fire in each burned unit. First, we obtained the data for land covers (considering them the equivalent of ecosystems) in the entire area based on data freely provided by Hernández et al. (2016), using the information to represent the situation prior to the fires. Working with the burned units already mapped, we then evaluated the land cover of each ecosystem, quantifying the absolute area and relative area (proportion of the landscape) of each ecosystem affected by the fires. The entire study area and each territorial region was analyzed. We also identified the most spatially dominant ecosystem in each burned unit (e.g. native forest, forest plantation), and we compared the 2D and 3D areas to calculate the how much of the area is not taken into consideration as a result of not factoring in relief in each ecosystem.

2.3. Air pollution; data and statistics

We evaluated the impact of particulate matter released from the wildfires on air quality of 34 Chilean municipalities. We used Spearman correlation (at 95% confidence interval) between the concentration of two different size of particulate matter (PM_{10} and $PM_{2.5}$) with the daily burned area/distance^2 ratio and burned area/distance ratio. The statistical parameters were Spearman's rho and its corresponding *p*-value. We used the PM_{10} and $PM_{2.5}$ data available from the National Air Quality Information System (http://sinca.mma.gob.cl/index.php/). We studied the levels of $PM_{2.5}$ from 36 air quality monitoring stations located in 34 municipalities; and for PM_{10} we used data collected at 42 monitoring stations located in 34 municipalities. The identification of the monitoring stations and the Chilean geographical administration are listed in Supplementary Table 1.

The meteorological data of seven of the most populated cities in the researched area were studied to identify the predominant wind directions and correlations of six meteorological parameters with $PM_{2.5}$. The meteorological parameters were: relativity humidity, temperature, wind speed, wind direction, and precipitation which are available in the National Air Quality Information System (http://sinca.mma.gob.cl/index.php/).

2.4. Landslide and flooding hazards

To identify the human settlements that, as a result of the fires, are highly exposed to the risk of landslides and/or flooding we used a multicriteria approach. First, we listed all the human settlements in local administrative units that were affected by the latest wildfires. Secondly, we selected only those located down-stream of burned units in the same watershed and that have main water courses close to burned units, i.e. human settlements that could be exposed to mass flows from areas that lost the vegetation cover. Later, we analyzed the characteristics of the above-mentioned burned units, selecting only human settlement associated to burned units that experienced fires of high or medium-high degree of severity, and reached extensions over 500 ha. Thus, we considered that the finally selected human settlement have an increment of their risks to experience these types of hazards. Additionally, we tested these results by comparing them with flooding events reported by local authorities during the 2017 austral winter (after summer and wildfires), looking for links between areas that experienced flooding and the human settlements we previously identified as at risk of landslides and flooding.

3. Results

3.1. Geographic characterization of wildfires

3.1.1. Spatial and temporal distribution

Ninety-one burned units were identified in Chile over two summer months in 2017 dispersed through five Chilean administrative regions, and mostly near to the coast. The total burned area was 529,974 ha, and for wildfires were characterized as megafires (burned area > 40,000 ha), and one of them burned >100,000 ha. The aforementioned total of 529,794 ha was based on the supposition that the affected area was flat, an assumption that is not entirely correct in large-scale fires. Taking relief into consideration the total burned area increased to 555,381 ha, an increase of 4.8% or 25,587 ha. Severity of the fires was correlated with size of the burned units; the larger the burned units, the more severe the fires.

Calculations made using MODIS products yielded a smaller total burn area (475,075 ha) compared to Landsat analysis (555,381 ha). This is partially explained by lower spatial resolution (500 m) compared to Landsat imagery (30 m) and different temporal resolution. A comparison between Landsat and MODIS results showed the same temporal pattern but lower extremes (Spearman rho 0.88 and *p* value 6.17 $\times 10^{-21}$). Both analyses were used to determine and then compare the daily burned area and showed a high concentration of the daily burned units during the last 15 days of January. Those burned daily units concentrated 90% of the total burned area during the 2017 summer of 2017 (Fig. 2). The largest burned area was on January 26th when >100,000 ha burned, decreasing drastically during the first week of February (Fig. 2).

3.1.2. Ecosystems affected and severity of wildfires

The ecosystems most affected by the 2017 wildfires were: forest plantations (223,605 ha), native shrublands (187,906 ha) and native forest (60,995 ha) (Fig. 3a). The largest ecosystem burned were in the Maule region (287,027 ha), followed by the Bio-Bio region (118,476 ha). The damages to forest plantations were mainly located in the Maule region with 145,554 ha, followed by the Bio-Bio region with 53,663 ha (Fig. 3a). Meanwhile, the affected shrublands were mainly located in the Maule region with 91,234 ha and O'Higgins with 42,187 ha. The largest native forest burned was in the Maule region with 25.263 ha (Fig. 3a).

A comparison of the percentage of burned land and the total coverage of each ecosystem shows that forest plantations were the most affected ecosystems (14.2%), followed by shrublands (4.9%) (Fig. 3b). 3.5% of native forests were affected by wildfires. Agricultural lands and

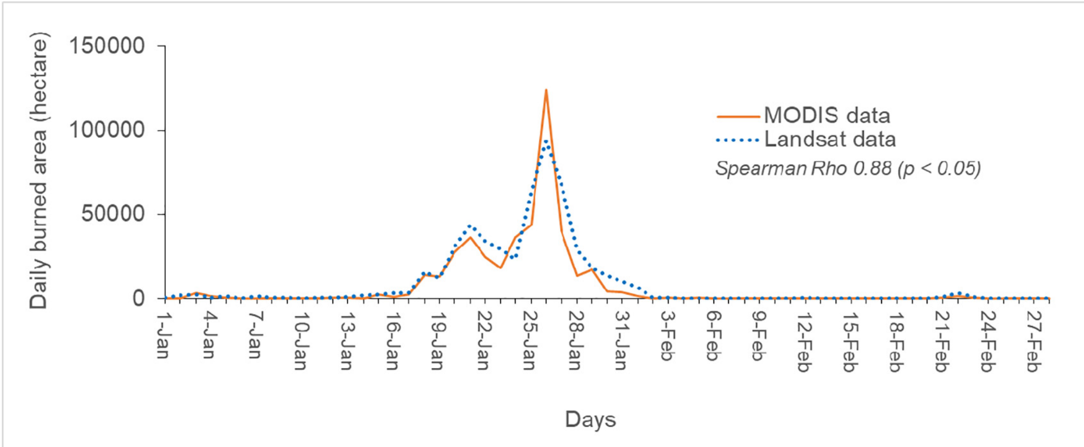

Fig. 2. Daily burned areas in Chile in January and February 2017. Continuous line represents the temporal evolution calculated using Modis and the dashed line using Landsat models.

grasslands were the least damaged ecosystems with wildfires only affecting 0,9% and 1,5% of their coverage respectively. The region with the highest native forest burned was the Metropolitan area of Santiago (8%). Over 20% of forest plantations in Maule (31%) and in O'Higgins (22%) were lost, and also both regions had the largest shrubland burned in Maule (11%) and O'Higgins (8%) (Fig. 3b).

When relief is not taken into account the burned unites areas are underestimated. Considering the relief the native forests ($n = 34$) increased their coverage by 8.9%, shrublands (5.4%) and forest plantations (5.2%). This underestimation could be relevant to the planning and funding of restoration activities.

The severity of the wildfires was different when comparing native and exotic vegetation. Wildfires were most severe in forest plantations, and the severity of the wildfires affecting native forests and shrubland was mostly low to medium-low (Table 1).

3.2. Environmental consequences

3.2.1. Increased air pollution

3.2.1.1. Results for $PM_{2.5}$. Twenty-eight of thirty-six monitoring stations showed significant positive correlations between $PM_{2.5}$ and the burned

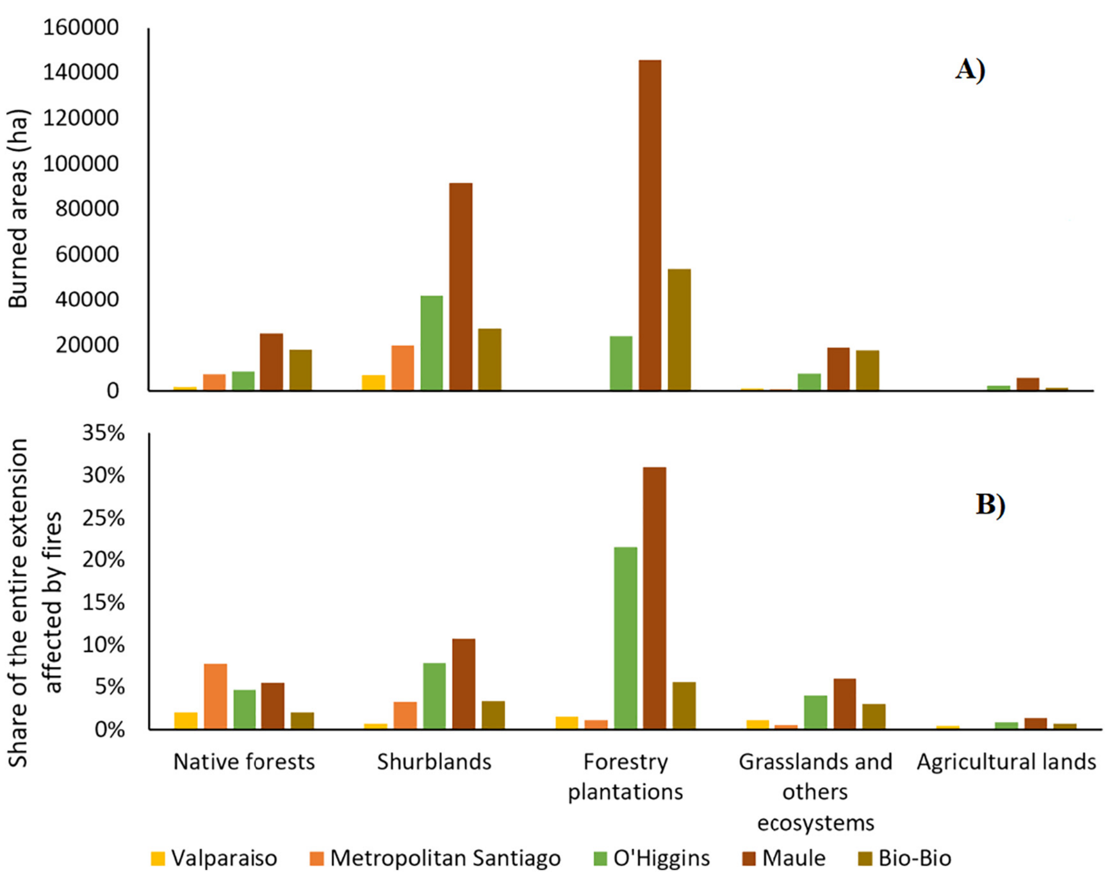

Fig. 3. Total and relative burned area (percentage of the total extension) of ecosystems affected by fires in Chile in January and February 2017.

Table 1
Wildfire severity detected through dNBRI for the main ecosystems in the area affected by fires in Chile in January and February 2017.

Ecosystems	Low	Moderate-low	Moderate-high	High	Unaffected and regrowth	Total
Native forests and shrublands	25%	24%	22%	16%	13%	100%
Forest plantations	18%	22%	22%	26%	11%	100%
Grasslands and other ecosystems	34%	19%	10%	4%	33%	100%
Agricultural lands	32%	21%	11%	3%	33%	100%

area/distance^2 (Fig. 4b and Supplementary Fig. 1). The highest correlations were found in the Metropolitan Region (33.5°S) registering at over 0.6 (Spearman's correlation value) while correlations in the other regions generally were lower, between 0.3 and 0.6. Only seven monitoring stations yielded correlations not statistically significant (Spearman's *p*-value above 0.05): one in the O'Higgins region, three in the Maule region, and three in the Bio-Bio region. All the monitoring stations in both the Valparaiso and Metropolitan regions presented statistically significant correlations (Supplementary Fig. 1). A pairwise comparison between $PM_{2.5}$ and the burned area/distance yielded the same outcomes (Supplementary Fig. 2).

The five Chilean administrative regions analyzed in the present study showed levels of $PM_{2.5}$ above the Chilean standard during the two summer months analyzed in the study. In the Valparaiso region the Viña del Mar (33.0°S) monitoring station registered only 1 day with levels above the standard (Fig. 5). In the Metropolitan region of Santiago (33.5°S) several monitoring stations registered at least one-week of levels above the standard; only one monitoring station did not register excessive levels of $PM_{2.5}$ (Fig. 6). In the O'Higgins region (34.5°S) all the monitoring stations registered levels over the standard with episodes lasting between 4 and 7 days (Fig. 7). All the monitoring stations in the Maule region (36.0°S) registered episodes of poor air quality lasting between 4 and 6 days (Fig. 8). In the Bio-Bio region (37.0°S) eight of the eleven monitoring stations registered levels over the Chilean standard, with one monitoring station registering the highest $PM_{2.5}$ levels recorded in the whole area on the studied period. The city of Chillan (the Puren monitoring station) recorded a severe episode with levels above 700 μg/m^3 (Fig. 9).

3.2.1.2. Results for PM_{10}. Thirty-three of forty-two monitoring stations yielded significant positive correlations between PM_{10} and the burned area/distance^2 (Fig. 4 and Supplementary Fig. 3). Several monitoring stations in the Metropolitan and Bio-Bio regions yielded high correlations (over 0.6) and correlations between 0.3 and 0.6. In the Maule region PM_{10} and burned area/distance^2 correlations were between 0.3 and 0.6. Four monitoring stations presented non-significant correlations, one in Valparaiso, two in O'Higgins, and one in the Bio-Bio region (Supplementary Fig. 3). The pairwise data for PM_{10} and the burned area/(distance) showed similar outcomes (Supplementary Fig. 4).

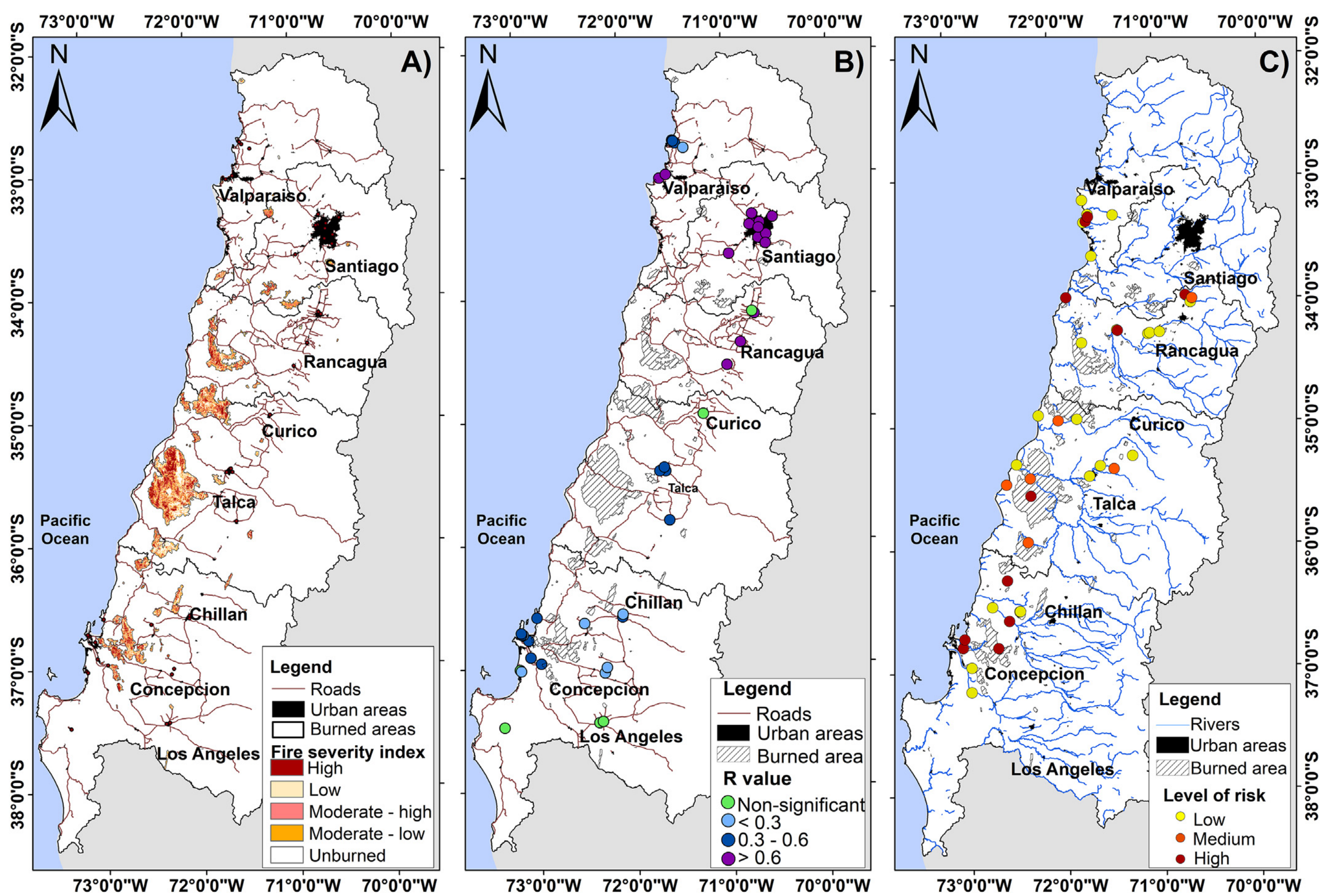

Fig. 4. Geographical distribution of the three types of damages after the 2017 Megafires. A) shows the spatial distribution of the wildfires and their respective severity, B) presents the impact of the wildfires on air quality showing the correlation between $PM_{2.5}$ and the burned-area/distance^2 ratio; each dot represents the location of air quality monitoring stations used in this study, C) shows the level of risk of landslides or flooding of human settlements.

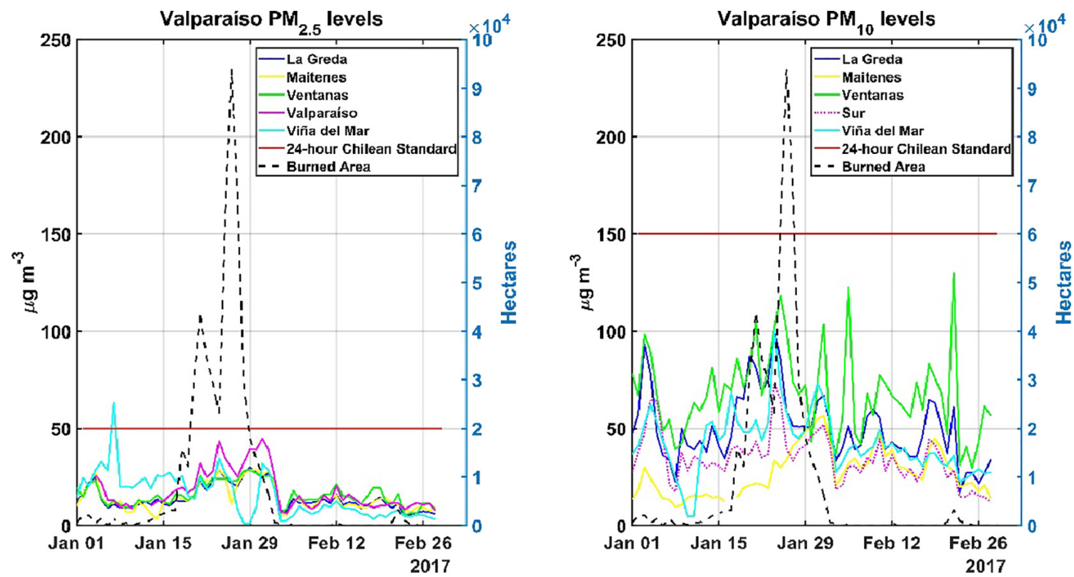

Fig. 5. $PM_{2.5}$ (left) and PM_{10} (right) concentrations registered in the region of Valparaiso on January and February 2017. On both graphs the red lines represent the Chilean standard for each air pollutant and the black dashed lines represent the burned area during the two-month study period. Other colored lines represent the concentration of air pollutants registered by air quality monitoring stations in the region. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Three of the six Chilean administrative regions in this study had episodes over the PM_{10} Chilean standard in the two-month study period. The regions of Valparaiso and O'Higgins had no episodes over the Chilean standard (Figs. 5 and 7). Two monitoring stations in the Metropolitan region of Santiago registered a one-day episode of PM_{10} concentrations over the standard (Fig. 6). All the monitoring stations in the Maule region registered levels over the standard with episodes lasting between 1 and 3 days (Fig. 8). 6 out of 14 monitoring stations in Bio-Bio registered levels over the standard with episodes lasting between 1 and 4 days (Fig. 9).

3.2.2. Meteorological parameters

The meteorological parameters that showed statistical significance were: relative humidity, air temperature and wind speed. Relative humidity had a negative low correlation with the burned area/distance^2 ratio, as well as with the $PM_{2.5}$, mostly in not-coastal cities. Air temperature presented important correlation between burned area/distance^2 ratio and $PM_{2.5}$, being significant mostly in not-coastal cities. Precipitation did not show relevant information, because during the studied period there were not relevant precipitations. Wind roses showed predominant winds from South-West, and South and wind speed was <5 m/s. Valparaiso was the only city that showed important winds from North. Supplementary Figs. 5 to 12 show the wind roses graphs for Valparaíso, Santiago (two stations), Rancagua, Talca, Chillan, Concepción and Los Angeles.

3.2.3. Landslides and flooding hazards

In the aftermath of the megafires human settlements are now exposed to landslides and flooding. Our analysis discovered 37 populated areas that are now newly exposed, 11 of them at high risk of landslides and flooding (Fig. 4c). Of these 37 populated areas there is one settlement with a population larger than 200,000 inhabitants, six areas with

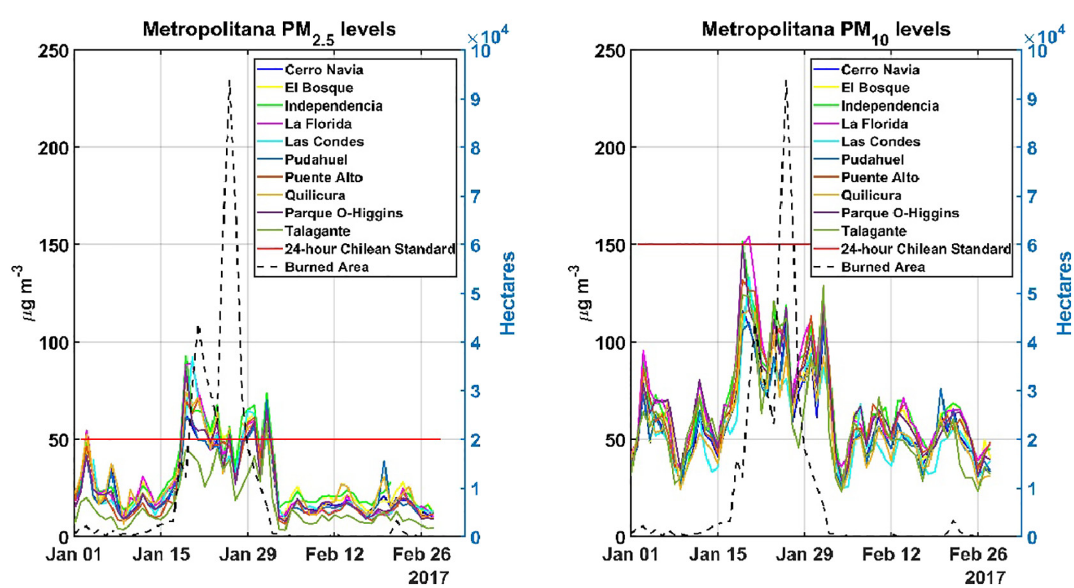

Fig. 6. $PM_{2.5}$ (left) and PM_{10} (right) concentrations registered in Metropolitan Santiago on January and February 2017. On both graphs the red lines represent the Chilean standard for each air pollutant and the black dashed lines represent the burned area during the two-month study period. Other colored lines represent the concentration of air pollutants registered by air quality monitoring stations in the region. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

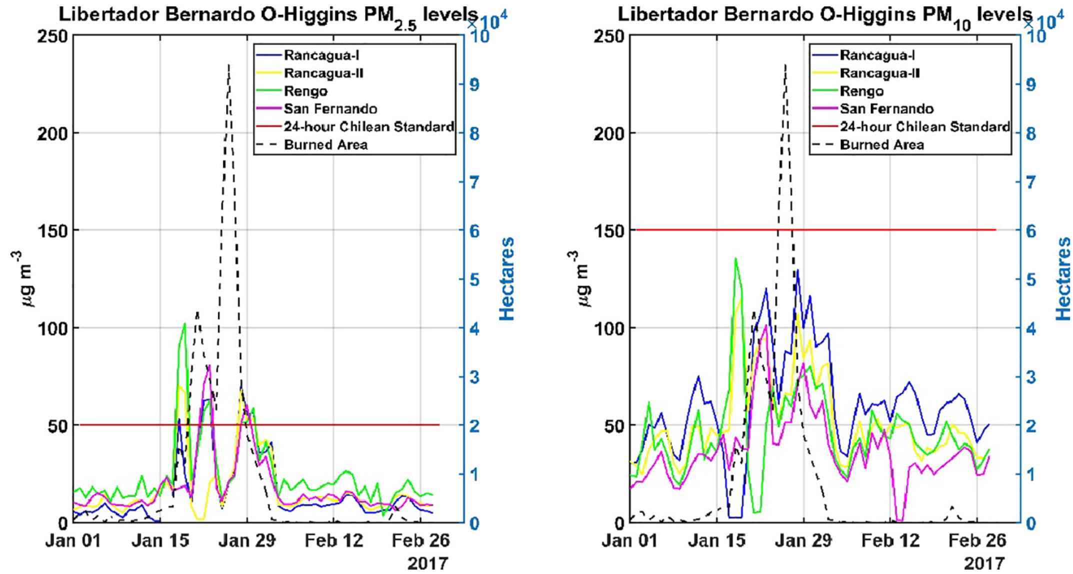

Fig. 7. $PM_{2.5}$ (left) and PM_{10} (right) concentrations registered in O'Higgins on January and February 2017. On both graphs the red lines represent the Chilean standard for each air pollutant and the black dashed lines represent the burned area during the two-month study period. Other colored lines represent the concentration of air pollutants registered by air quality monitoring stations in the region. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

a population over of 10,000 inhabitants, and nineteen areas located <1 km from areas impacted by fire. Categorized by administrative region the populated areas specifically at an increased risk of landslides and/or flooding are: i) in Metropolitan Santiago: El Canelo and Las Vertientes, ii) in O'Higgins region: Litueche, Copequen, Coinco, Pichidegua, San Vicente de Tagua-Tagua, Alcones, Rinconada de Alcones, Marchigüe, Poblacion, Peralillo and Pumanque iii) in Maule region: Hualañe, Licanten, Curepto, Constitucion, Santa Olga, Empedrado and Cauquenes, and iv) in Bio-Bio region: Portezuelo, Florida, Penco, Concepcion and Hualqui. From this list of populated areas, those at the highest risk are: Poblacion, Pumanque, Hualañe, Constitucion, Santa Olga, Empedrado, Portezuelo, Florida, Penco, Concepcion and Hualqui. Nine of them are adjacent to burned areas and ten settlements are within 1 km of them (Fig. 4c). During winter 2017 authorities reported flooding in 18 of the 37 populated areas identified in this study. These settlements will continue to be at risk in the coming years, decreasing gradually as vegetation grows back.

4. Discussion

4.1. Geographic characterization of latest megafires

Recent wildfires studied here were more severe in areas dominated by large fragments of forest plantations than in fragments dominated by native vegetation. Indeed, the most affected regions lost up to 30% of their total area of forest plantations, compared to <10% of native forests. It cannot be mere coincidence that there are now megafires in Chile when plant species from countries that regularly suffer megafires now dominate the regional landscape in Chile (e.g. Portugal, Greece, Australia, USA; European Commission, 2004; European Commission,

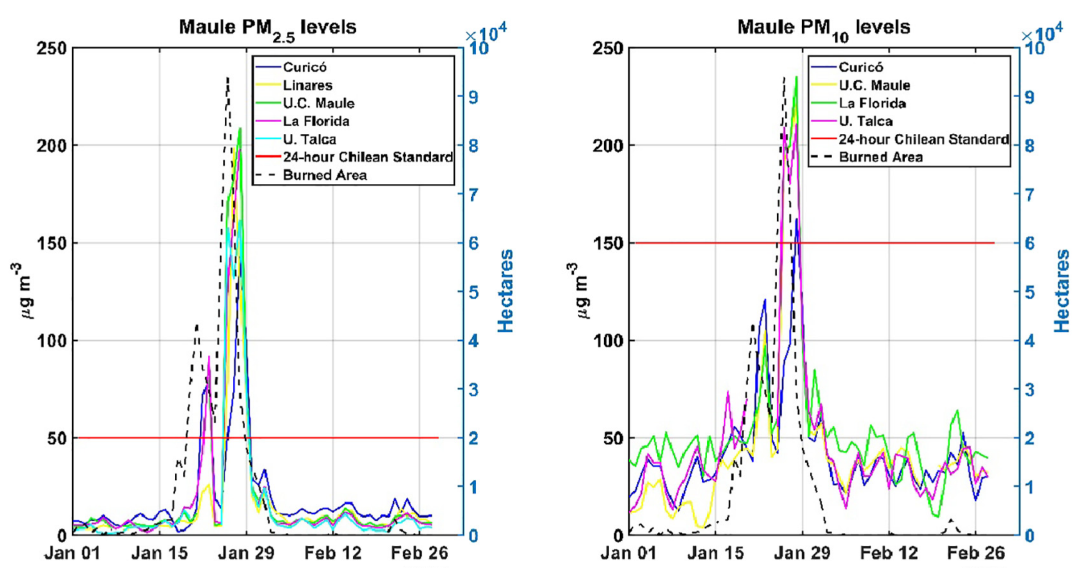

Fig. 8. $PM_{2.5}$ (left) and PM_{10} (right) concentrations registered in the Maule Region on January and February 2017. On both graphs the red lines represent the Chilean standard for each air pollutant and the black dashed lines represent the burned area during the two-month study period. Other colored lines represent the concentration of air pollutants registered by air quality monitoring stations in the region. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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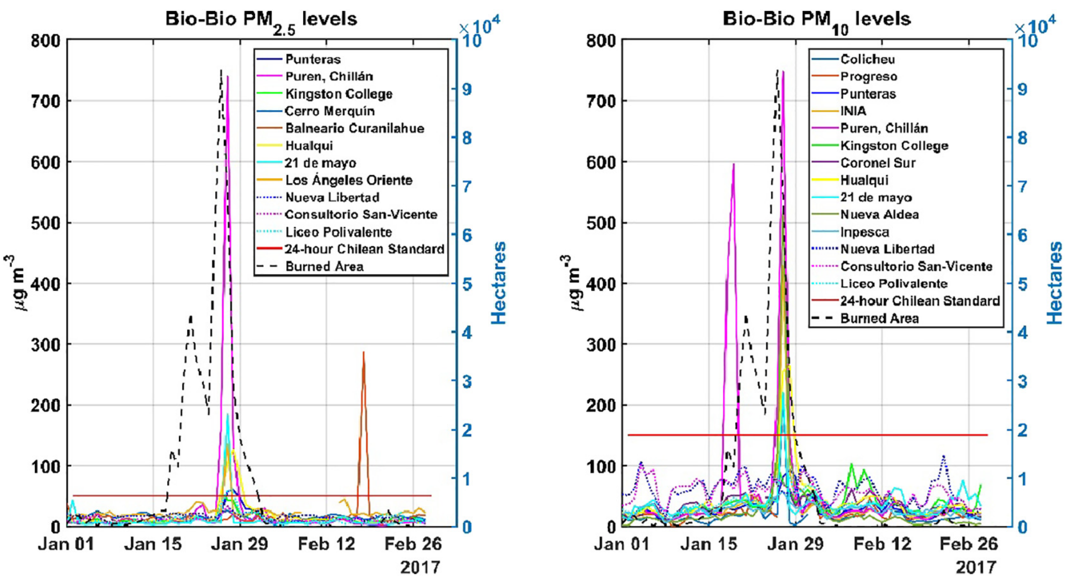

Fig. 9. $PM_{2.5}$ (left) and PM_{10} (right) concentrations registered in the Bio-Bio region in January and February, 2017. On both graphs the red lines represent the Chilean standard for each air pollutant and the black dashed lines represent the burned area during the two-month study period. Other colored lines represent the concentration of air pollutants registered by air quality monitoring stations in the region. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2008; San-Miguel-Ayanz et al., 2013; Bento-Gonçalves et al., 2015). This should constitute a wake-up call for countries with high reforestation rates to understand if it is necessary to put restrictions to extensive forest plantations and how to manage them, especially if they are pyrophyte forest plantations (Meyfroidt and Lambin, 2011; Carle et al., 2002), and more so if their respective climates favour wildfires (e.g. South Africa, New Zealand). Landscapes extensively covered by fire-prone forest plantation requires of sophisticated and mandatory fire management and planning tools, especially in wildland-urban interfaces to avoid negative consequences of megafires and to truly ensure the sustainability of the forestry industry (Gómez-González et al., 2018).

4.2. Environmental consequences of Chile's latest megafires

As reported throughout the study, during the summer of 2017 there were megafires in unpopulated coastal areas in Chile. However, they had far-reaching consequences affecting distant populated areas (> 100 km) located in valleys and urban areas downstream from burned areas. Our study shows that over 80% of PM_{10} and $PM_{2.5}$ air quality monitoring stations registered significant correlations with the temporal changes of burned areas despite the distance, with the highest correlations in the most populated area of the country. Indeed, weather conditions (e.g. heavy winds) can disperse the pollutant plume from coastal areas to distant cities in the central valley (e.g. Santiago, Rancagua, Talca, Linares). Wind roses showed that several of the most populated cities are located wind up of the fires and with enough wind speed to disperse the $PM_{2.5}$ plume that could be released by fires. Other meteorological parameters as lack of precipitation or low relative humidity contribute to increase the residing time of the particulate matter in the cities. Cities located in central valleys as Santiago and Rancagua that are surrounded mountain ranges, as the Andes and the Coastal range, have a topography that reduce the ventilation of air pollutants. In addition, oxidative conditions in main urban cities, especially in Santiago, could help to increase the secondary formation of aerosols as reported in previous studies (Cuchiara et al., 2017; Rubio et al., 2015).

Our results suggest that a lot of populated areas are now exposed to landslides and flooding hazards. The level of risk of these new hazards is dependent on the severity of wildfires (how much vegetation survived), forest regeneration, storm intensity in the following rainy seasons, and topographic characteristics of the area (Rengers et al., 2016; Moody et al., 2008). In the winter of 2017 national authorities reported no landslides, in populated areas but flooding events were reported in large municipalities, coinciding at 49% with the projected locations. The latter is in conjunction with evaluations demonstrating that floods and landslides are between 3.3 and 5.6 times more likely to happen (Diakakis et al., 2017).

Chilean authorities reported the impact on infrastructure, human lives, the size of the areas affected by fires and natural protected areas. In this study we added an assessment of two unreported consequences; the increase in air pollution and the increased risk of landslides or flooding. However, based on international experience, other important direct and indirect consequences of megafires are still non-studied in Chile and will likely continue to remain unreported. Some of those consequences are: economic losses in the timber industry, job losses, damage to agriculture and its effect on production and machinery, stalled tourism, drop in family incomes, disrupted livelihoods and cultural activities, etc. (Tedim et al., 2013).

4.3. Revisiting planning and management during and in the aftermath of megafires

Megafires have adverse events and come at a tangible cost to property and human life, but they also affect the natural environment (Martin et al., 2016). Authorities should not only be concerned with protecting human lives in the vicinity of these wildfires; but should also be concerned that the air pollution from wildfires can travel hundreds of kilometers from the point of origin, and can impact on the human health of people living in distant cities (Cuchiara et al., 2017; Price et al., 2012). Fire-fighting strategies that prioritize preventing the destruction of households and valuable species and ecosystems, should be redesigned to consider the effects on human health during the wildfires, and the increased risk of landslides and flooding in the seasons after wildfires, as additional impacts on populated areas (Hendrychová and Kabrna, 2016, Moritz et al., 2014, Parise and Cannon, 2012, Weng, 2007, Vitousek et al., 1997).

Greater efforts need to be made to calculate how much land is affected taking into consideration relief, especially when extensive areas are affected; efforts should also focus on fire-fighting management to prevent large-scale spatial impacts, and on reporting the impacts of wildfires in full. According to our methodological approach and results, relief was an important factor, with significant differences categorized by ecosystem type using freely available high spatial resolution DEM (30 m). Similarly, the MODIS web-based platform (https://worldview.

earthdata.nasa.gov) proved to be useful in monitoring the extension of large wildfires, consisting in easy-to-manage open data that provides high temporal resolution and two wildfire-oriented products (MCD64A1 and MOD14A2). For most sophisticated analyses, data from MODIS can be combined with dNBR index data from Landsat imagery, or other high or very-high spatial resolution imagery. The dNBR index provided detailed results and it is frequently used in international literature (Alves and Pérez-Cabello, 2017; Zhu et al., 2017; González-De Vega et al., 2016) but it requires certain expertise to interpret the data and to perform post-classification processes on GIS software or directly online using Google Earth Engine (e.g. Soulard et al., 2016).

Better calculations, maps and the inclusion of links between affected lands and their impact on people living nearby, will help to design restoration plans and to calculate the required financial resources. They will also mitigate the negative impact on ecosystems services. In regard to the impact on human health it should be taken into account the significant correlations between wildfires and two harmful air pollutants able to cause several health problems, which cannot be ignored, especially because of the respiratory diseases that may be caused by wildfires (Alman et al., 2016; Dockery et al., 1993; Johnston et al., 2014). In the present study we found that >70% of the Chilean population were exposed $PM_{2.5}$ and PM_{10} levels over the 24-h World Health Organization guidelines (WHO, 2005) and the Chilean air quality standard (MMA, 2012) for episodes extending over several days.

Lastly, spatial planning and regulations need to reflect on the role of intensive monoculture plantations in the occurrence of megafires. Forest plantations have a role to play in preventing megafires and in additional economic, social, environmental and ecological objectives (Heilmayr, 2014; Paquette & Messier, 2010).

5. Conclusion

Recent fires in Chile were classified as megafires (affecting a total of 529,974 ha with four individual fires burning over 40,000 ha of land). They were far more serious than any of the fires previously recorded in Chile and stand out among the largest and most severe in the world. The dNBR index proved useful and easy to calculate based on freely accessible Landsat imagery, as well as the fire products provided by MODIS platforms. Including relief was relevant in calculating the areas affected by fire (increasing the affected area by 5%), especially in steep mountainous areas usually dominated by natural ecosystems where area underestimations became 9%. 2017 wildfires were unique in unusual extension and severity for the austral Mediterranean regions affecting large extensions of exotic forest plantations with high severity fires and of native forest and shrubland with low and medium-low severity fires. Two environmental consequences were analyzed: i) impacts of the particulate matter released from fires increase the particulate matter over near and distant cities, and ii) new and increased risk of landslides and flooding in populated areas located downstream of burned areas. These consequences can be calculated using dNBR data, freely available data from 44 air quality monitoring stations allowing to get daily comparison between distant burning areas and PM_{10} and $PM_{2.5}$ concentration without the need of dispersion models. and information of distances and potential mass flows provided by geographical data (e.g. DEM). Megafires could continue to happen in the near future, especially if the combination of unfavorable meteorological conditions and inadequate planning and regulations of intensive exotic forest plantations are present. As further analysis, scientists and the authorities should consider monitoring all environmental impacts derived from fires, not only those occurring within the burned areas.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.05.119.

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