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Recent wildfires in Central Chile: Detecting links between burned areas and population exposure in the wildland urban interface

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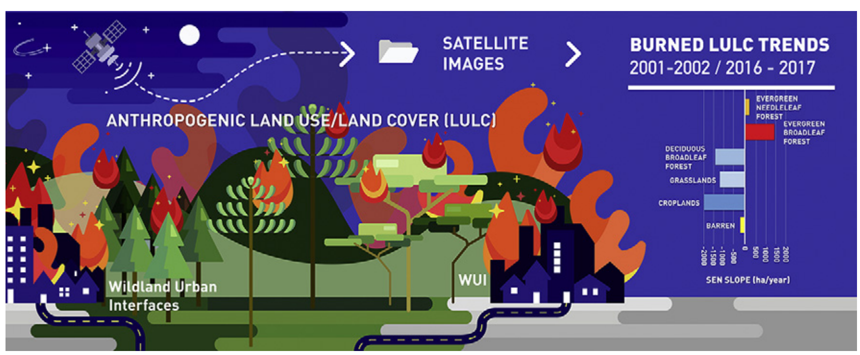
HIGHLIGHTS

- Three million people live in flammable wildland-urban interfaces in Central Chile.
- Wildfires in Central Chile show hotspots and high spatiotemporal variability.
- Land covers most frequently affected by wildfires were human-produced ecosystems.
- Evergreen forests (i.e. plantations) showed a positive trend with the burned area.
- MODIS imagery allowed to identify wildland-urban interfaces and wildfires.

GRAPHICAL ABSTRACT



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ABSTRACT

Wildfires are gaining importance in the Mediterranean regions owing to climate change and landscape changes due to the increasing closeness between urban areas and forests prone to wildfires. We analysed the dry season wildfire occurrences in the Mediterranean region of Central Chile (32°S–39°30′ S) between 2000 and 2017, using satellite images to detect burned areas, their landscape metrics and the land use and covers (vegetal) pre-wildfire, in order to determine the population living in areas that may be affected by wildfires. The existing regulations in western Mediterranean countries (Portugal, Spain, France, and Italy) were used to identify and define the wildland-urban interface (WUI) areas, quantifying the people inhabiting them and estimating the population affected by burned areas from 2001 to 2017. We used the Google Earth Engine to process MODIS products and extract both burned areas and land covers. We detected that 25% of the urban population inhabits WUI areas (i.e. Biobío, Araucanía and Valparaíso regions) where the urban population exposed to burned areas exceeds 40%. Most of the land use and land covers affected by wildfires are anthropogenic land covers, classified as

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savannas, croplands, evergreen broadleaf forests and woody savannas, representing >70% of the burned areas. Urban areas show only 0.6% of the burned surface from 2001 to 2017. We estimate that 55,680 people are potentially affected by wildfires, and 50% of them are in just one administrative region. These results show the imperative need for public policies as a regulating force for establishing WUI areas with the purpose of identifying wildfire risk in urban areas, such as establishing prevention methods as firewalls and prescribed fires.

1. Introduction

Wildfires are a global problem Krawchuk et al. 2009; Bowman et al. 2011; Gill et al. 2013). They affect increasingly pressured and complex landscapes due to the world's high urbanisation rates and the expansion of other land uses such as agriculture or livestock. The global warming experienced since the 19th century has increased the fire probability regarding to climate change (Liu et al. 2010; Sun et al. 2019), due to the increment of the recurrence of extreme events as drought and heat waves. Although temperatures have increased throughout the planet, rainfall has shown annual amounts increasing in some regions and decreasing in others. In the case of areas with reduced rainfall, it is possible that dryness also implies a greater probability of wildfires (Turco et al. 2014; Stephens et al. 2018).

Wildfires can be quantified as burned areas (Donovan et al. 2017), which are inserted in diverse geographical contexts, ranging from close to human settlements and other land uses and land covers (LULC) such as crops, grazing or wetlands. Another common way to quantify wildfires is by number, as the annual or seasonal events counted (Westerling et al. 2006; Westerling 2016). According to the management perspective, both the burned area and the number of wildfires are important, not only from the ecological and environmental damage point of view, but also because of the impact of the human settlements, whose most representative indicator is the burned area (Tymstra et al. 2019). In addition, there are many other specific indicators, such as the effects on soil properties, the characteristics of the burned forests, the affected homes and even the human or wildlife lives.

Wildfires have evolved over time, and since the 20th century, they are recognised within six different generations (Costa et al. 2011), from those due to fuel continuity affecting areas between 5000 and 10,000 ha (1st generation) to firestorms that consume hundreds of hectares in a few hours, which correspond to the 6th generation or mega-fires (UE, 2017). Each generation has required different strategies to limit the fire spread, such as linear infrastructures, surveillance networks, fire-resistant constructions or considering fire into forest management through prescribed fires. All of them are complementary, and seek to avoid the involvement of larger areas and the negative ecological and environmental effects. On the other hand, many countries have increased their forest area due to the acquisition of carbon neutrality commitments, which implies an unresolved and uncertain future challenge (Bellassen and Luyssaert 2014). For exemple, according to Van Der Werf et al. (2003), the total emissions of 1 km^2 of burned forest reach 0.44 kT C yr^{-1}.

On a global scale, the subtropical and Mediterranean regions are the most affected areas by forest fires, mainly due to their inter-annual climatic characteristics (simultaneous dry and warm period) and the recent and projected trends of climate change, with increasing temperatures and decreasing precipitation (Giorgi and Lionello 2008; Garreaud et al. 2017; Urrutia-Jalabert et al. 2018). The growth of the urbanisation rates exacerbates the risk, as they make up the so-called wildland-urban interfaces (WUI) (Ubeda and Sarricolea 2016; Curt and Frejaville 2018). WUIs are defined as risk areas, where danger (combustible vegetation) and vulnerability (population, housing, and infrastructure) coexist (Stewart et al. 2007). Therefore, they can be detected and dimensioned in terms of exposed elements. Once a WUI wildfire takes place, it is possible to determine the total of population and housing effectively affected. Thus, WUI wildfires constitute an unresolved and growing problem given population dynamics, climate change and, in some cases, increasing forest areas. Moreover, while the forms of urbanisation have changed in recent decades, due to the greater exposure, the risk has increased in many world's regions (Darques 2015), from urban centres far from the forest, to urbanisation processes of peripheral areas close to the forests or even mixed with forests.

Research on WUIs involves knowing the location of both combustible material (forests and other plant covers that connect them) as well as the potentially affected population, and, based on proximity and mixture criteria, allows the risk quantification. Dimensioning the WUI allows to define planning measures focused on mitigation and adaptation, such as territorial planning, firewalls creation, surveillance systems, housing protection radios, wildfire prevention protocols, and, more recently, prescribed fires.

The most common way to register wildfires is through maps of burned areas, coming from aerial images, field work, satellite images (Hawbaker et al. 2017) or even drones (Tang and Shao 2015). The most economical way is given by satellite images, which through digital processing allow to know the burned areas and even the severity of fires. On a global scale, the best remote sensor for this is MODIS, which has specific products for mapping burned areas (Andela et al. 2019). To obtain these images a decade ago, it was necessary to have large volumes of storage and processing capacity. However, thanks to imagery banks and cloud processing offered by Google Earth Engine (Gorelick et al. 2017), nowadays daily, monthly and multi-temporal scales results of the last 20 years, can be obtained. These results have cadastral quality, for both fires and burned LULCs.

In Chile, wildfires mainly affect the lands located between the Valparaíso and Araucanía regions (Ubeda and Sarricolea 2016; McWethy et al. 2018; Bowman et al. 2019), the area ranging in the Mediterranean climate (32° S–39°30′ S), the most densely populated area of the country. These wildfires have mainly human cause (both accidentally and intentionally) (CONAF 2018). Dry summer conditions propitiate wildfires, and moreover, this area has known an important economic dynamism thanks to the forest industry, with economic incentives to the exploitation of non-native species such as *Pinus radiata* and *Eucalyptus globulus* (Heilmayr et al. 2016; Aliste et al. 2018; Manuschevich et al. 2019).

Chile has proposed to increase the forest area to achieve carbon neutrality goals, although the prediction indicates the same strategies to subsidise the forest industry, which have traditionally led to human conflicts, loss of native forests and a wildfire increase (Durán and Barbosa 2019), will be employed. Hence, if a right strategy is not properly planned, and the increasing urbanisation is added, fires may affect more and more territory and may involve more exposed population, not only to fire but also to air pollution and to other derived processes such as erosion and mass movements during episodes of post-fire precipitation (Abbate et al. 2019).

Despite the research carried out to date, there is a little knowledge in Chile about wildfires and WUI. Therefore, different questions arise: have there been changes in the burned LULCs over time? Is it possible to recognise regular or changing patterns in the geometric attributes of wildfires? Is it possible to delimit the WUI to size the potential affected population?

To fill this lack of knowledge, we adopt a simple and operational WUI definition, considering the possible future inclusion in public policies. We use the definition proposed by Modugno et al. (2016), which indicates that WUI corresponds to the intersection of urban areas (with a 200 m buffer) and vegetable fuel areas (with a 400 m buffer) based on the regulations applied in Europe, regarding to the topographical, climatic (mainly Mediterranean) and population density similarities. However, in Chile, there exist a difference with the European case since houses are built from combustible material.

For a deeper understanding, we adopt the strategy of McWethy et al. (2018) for land use identification. This model compared the burned areas declared by CONAF and the MODIS MCD64A1 product within the period 2001–2017, showing coincidences in the burned areas in Mediterranean Chile. Wildfires also showed a great interannual variability, with no trends in the mentioned period. MODIS products allow us to identify different LULCs affected by wildfires, making possible to recongnise any temporary trend for each LULC, as well. In this framework, the global work of Andela et al. (2019) classifies a large part of forest fires in Central Chile as savannahs, farmland and temperate forests. However, despite the fact that the landscape structure is strongly associated with the risk of wildfires (Ryu et al. 2007), there is a lack of knowledge of wildfires in Chile regarding the geographical characterisation of the landscapes affected. According to many studies, the wildfire risk increases when the distance between fuel patches decreases (Prato et al. 2008; Li et al. 2015; Volokitina 2017; Vallejo-Villalta et al. 2019).

The main objectives of this work are: 1) quantify and characterise the burned areas in terms of location, wildfire occurrence and recurrence, 2) explore relationships between wildfires different land uses and land covers through their temporal trends in 2002–2003 to 2016–2017 periods and 3) map WUI areas in central Chile (32°S to 39°S) to detect the affected and potentially exposed population.

2. Methods

2.1. Study area

The study area is located from 32°S to 39°S representing the area known as Central Chile, delimited by the 7 administrative regions comprised of between Valparaíso and Araucania regions, both inclusive, and coinciding with the main extent of the Mediterranean climate (Sarricolea et al. 2017) (Fig. 1). This area allocates 78.9% of the total population of the country (INE, 2018) and concentrates agroforestry activities with 85% of annual crops and 88% of forest plantations (Censo Agropecuario 2007). Mediterranean climate prevails in most of the region (Fig. 1a), with a lower representation of semi-arid, marine west coast and tundra climates (Sarricolea et al. 2017). Central Chile has being recognised as a global hotspot of biodiversity, however is also strongly urbanised containing the largest Chilean cities (Valparaíso, Santiago and Concepción) (Fig. 1a). It is also a landscape producer of raw materials being covered by agricultural lands in the central valley and forest plantations in the coastal mountain range (Fig. 1b and c).

2.2. Data and methods

We analised data taken from 4 different sources: 1) Monthly burned areas at 500 m spatial resolution from the MODIS product MCD45A1 between 2000 and 2017 (see Google Earth Engine Code in ANNEX 1 Supplementary material); 2) Annual Land Use/Land Cover (LULC) at 500 m spatial resolution from the MODIS product MCD12Q1 between 2000 and 2017; 3) LULC of the year 2014 at 30 m spatial resolution (Zhao et al. 2016) and 4) census blocks and population data from INE (2018). The MCD45A1 product (Roy et al. 2008) has been widely used for detection of burned areas (Ruiz et al. 2014; De Araújo and Ferreira, 2015; Chuvieco et al. 2019; Marcos et al. 2019), along with the MCD12Q1 product (Pisek et al. 2018; Weiss et al. 2018; Chen et al.

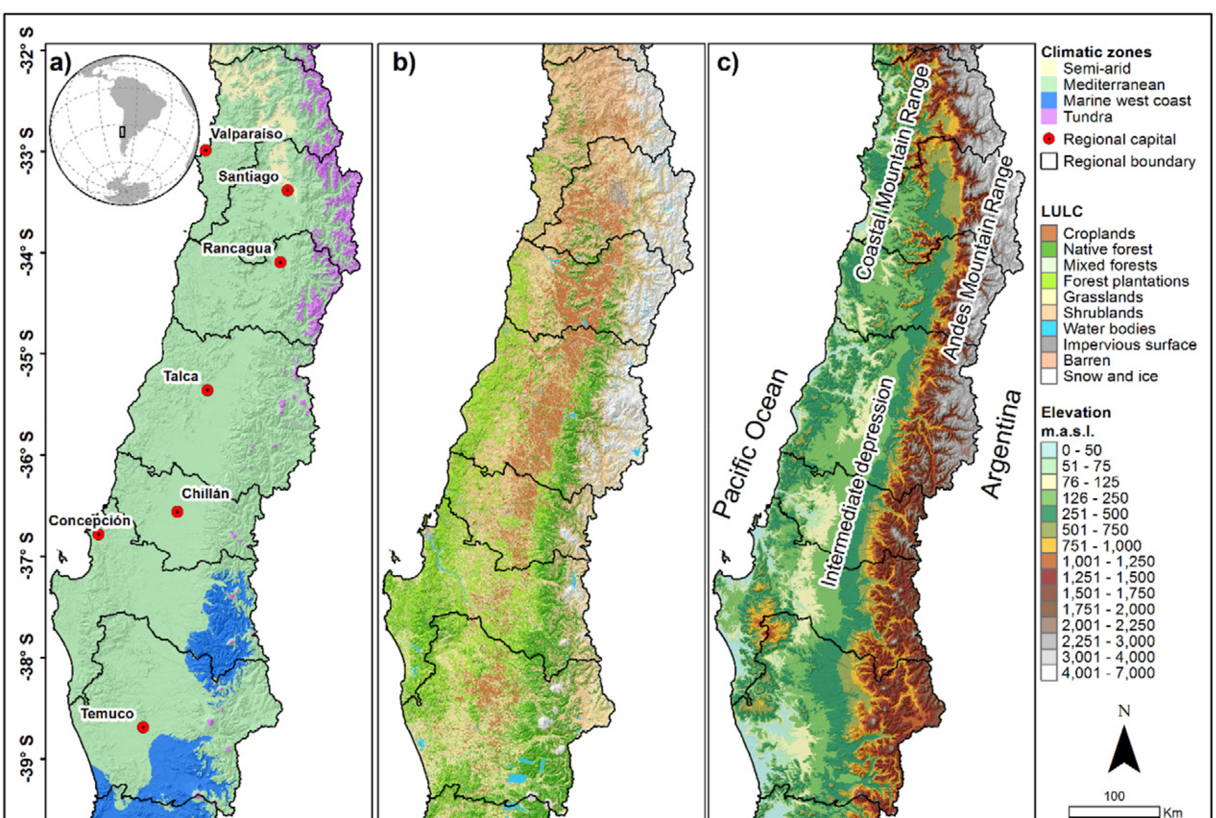

Fig. 1. Study area. a) Climatic zones (Sarricolea et al. 2017). b) Land uses and land covers (LULC) (Zhao et al. 2016). c) Elevation ranges.

2019; Li et al. 2019; Hu and Hu 2019). For this study, we chose the Land Cover Type 1 (Annual International Geosphere-Biosphere Programme (IGBP) classification). It allows to detect the LULC burned area by season and identify patterns in the studied events. The IGBP land uses are described in Table A (Supplementary material).

The links between the data extracted and results obtained, starting by the geographical characterisation of burned areas from 2001 to 2017, continuing with the associations among wildfires and LULC and finalising by analysing WUI is shown in Fig. 2. To (1) identifiy the burned areas with MCD45A1 during the wildfire season and to obtain the metrics (table with them) Fragstat has been used; (2) to determine the LULC before the wildfire season and overlay with the wildfires we can estimate the burned LULC and calculate its trends; (3) for the determination of LULC in 2014, we make a buffer of 400 m; and (4) a crossing with the 200 m buffer from the cities, which provides the WUI area. According to the detected WUI areas and the 2017 population data, the total exposed population was obtained, and, in addition, the potentially affected population (this means that they are not affected figures, but that could have suffered effects of fires) in the WUI areas burned in the study period. It is important to note that 79% of the national population (13,882,853 inhabitants) live in the study area, with 89% of urban population and 11% of rural population (Fig. 2). To quantify the geometrical attributes of burned areas and their spatial distribution, 12 landscape metrics were calculated for the 2000–2017 period (Table 1) using Fragstats 4.2 (McGarigal et al. 2002). The metrics used in this case were: number of patches (NP), total area (CA), landscape percentage (PLAND, considering the whole study region), mean and standard deviation of the burned area (AREA_MN, AREA_SD), largest patch index (LPI), total edge (TE), edge density (ED), mean and standard deviation of the distance between burned areas (ENN_MN, ENN_SD), aggregation index (AI; increases if the land affected by the wildfire is only one large burned area), and the compacity of the burned patches (NLSI; increases if the burn areas are disaggregated and have irregular shape). PLAND represents the percentage of the burned landscape compared to the surface of the study area. LPI represents the largest burned patch compared to the surface of the study area. TE is the measure of the total length of the burned patches' edge. ED quantifies the burned patches'edge density.

Table 1
Landscape metrics used to describe geometrical attributes of the burned areas.

Variables	Landscape metrics
Quantity of burned patches	Number of patches (NP)
Area affected by wildfires	Class area (CA), Percentage of landscape (PLAND), Mean and Standard Deviation (AREA_MN, AREA_SD), and Largest patch index (LPI)
Interface areas generated by wildfires	Total edge (TE) and Edge density (ED)
Closeness and aggregation of burned areas	Euclidean nearest-neighbour distance (ENN_MN, ENN_SD), Aggregation index (AI) and Normalised Landscape Shape Index (NLSI)

To analyse the trends of the burned LULC, the Mann-Kendall test (MK) (Mann 1945; Kendall 1975) was applied to check their significance and Sen's slope (Sen 1968) to estimate their magnitude. The MK test is a non-parametrical test that evaluates the monotonous behaviour of a data series, and it has been used before in wildfires studies (Jain et al. 2018). In this work, we consider significant trends—those at the $\alpha = 0.05$ signification level. After defining the burned areas, we performed a WUI classification considering the LULC in 2014 (Zhao et al. 2016). We used the same criteria as proposed in Modugno et al. (2016), defining the interface as the intersection between urban areas (and a 200 m buffer) and the fuel areas (and a 400 m buffer), according to the European normative. We also used the population in 2017 (INE, 2018) to define potential risks. Only combustible areas with at least 10,000 m^2 were included in the WUI definition due to the LULC pixel being 30 × 30 m resolution (900 m^2) (Fig. 3).

3. Results

3.1. Seasonal analysis of burned areas

The analysis of the metrics linked to the geometrical attributes of wildfires shows that there were around 175–324 burned areas with a total extension of 45,915–423,335 ha (Fig. 4). The summer wildfires of the 2016–2017 season were remarkably exceptional, not only due to the burned area (CA) but also due to all the other metrics, except for

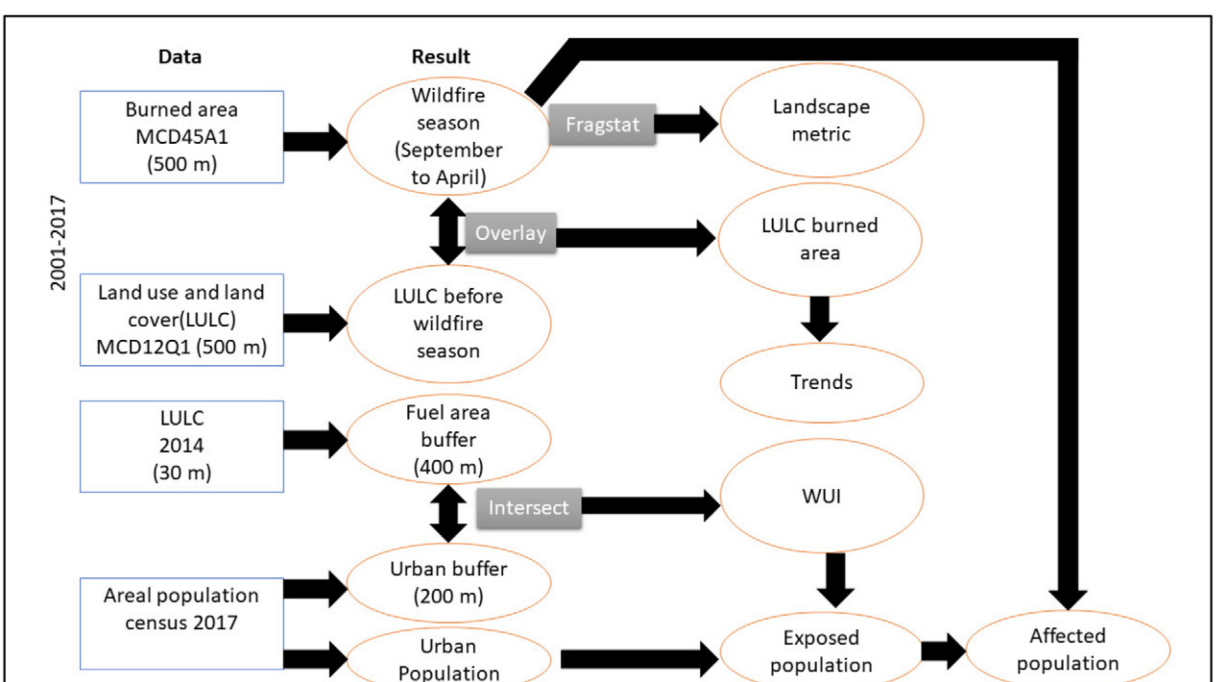

Fig. 2. Sources of information, processes, and resulting products (LULC: Land Use and Land Covers; WUI: Wildland Urban Interface). Grey squares show the specific processes carried out.

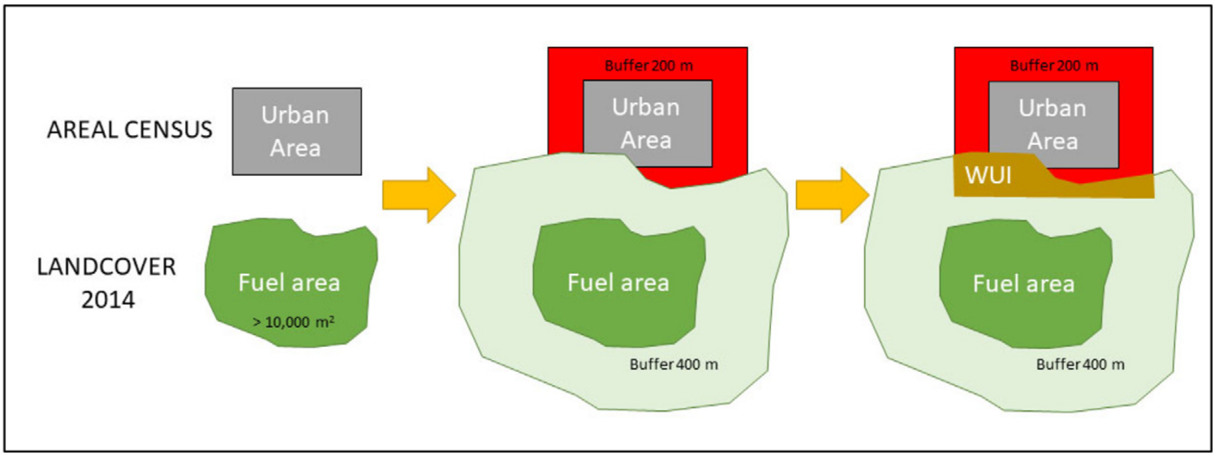

Fig. 3. Graphic representation of GIS analysis to generate the WUI map. Based in Modugno et al. (2016).

the number of patches areas (NP). In addition, the wildfires of the 2000–2001 summer showed 324 burned patches (NP) and a burned area (CA) among the lowest of the whole period (45,915 ha). Regarding the spatial extent of the events, the 2002–2003, 2004–2005, 2011–2012 and 2014–2015 seasons resulted in a higher percentage of affected land (PLAND), CA, NP and larger average burned area (AREA_MN) and dispersion (AREA_SD) (see Table C in Supplementary material). The average area varied between 250 and 480 ha and had larger AREA_SD (approximately 500 ha). The ratio between the largest CA and the total burned area (LPI) showed that, between 2003 and 2004, only one wildfire was responsible for >7% of the total burned area.

The average burned extent for the 2001–2017 period is 106,008 ha/year, with the largest in 2017. Excluding this year, the average is 86,112 ha/year. The number of burned areas varies from 175 to 324 without any clear trend in the period, being the 2016–2017 summer season 1 of the 3 with less burned patches, evidencing the large spatial burned continuities (Table C in Supplementary material).

Landscape metrics used to describe the spatial distribution of burned areas indicate that the average distance among wildfires (ENN_MN) and their standard deviations (ENN_SD) are similar all seasons (7–8 km, see Table 2). Aggregation is higher for seasons with larger wildfires as the NLSI, i.e. larger burn areas affect the expression of these indices.

The correlation analysis between the 12 metrics highlight that NP only has a significant correlation with ENN_MN, being negative, which indicates that the number of burned areas is not a good metric for their spatial characterisation (Fig. 5). NLSI had significant and negative correlation with all other metrics, indicating that seasons with numerous, larger and closer wildfires are associated to extensive and compact-shape wildfires occurring in few places. Landscape metrics for 2017 wildfires were strongly different from those presented in the previous seasons. LPI reach 0.44, i.e. a 44% of the entire territory was affected by 1 wildfire (see Table C in Supplementary material). The total edge almost duplicated the extension of new area of contact among burned areas and other LULC. Metrics of spatial distribution are also different for the 2017 season, reaching the highest value of AI and the lowest NLSI which is explained by a few extremely large burned areas (Table 2). It is appreciated that in a period of 17 seasons, wildfires do not repeat in the same area, except some exceptions. The areas with the highest occurrence (up to 11 times in 17 seasons) are the Araucanía and Ñuble regions in the southern part of the study area (Fig. 6).

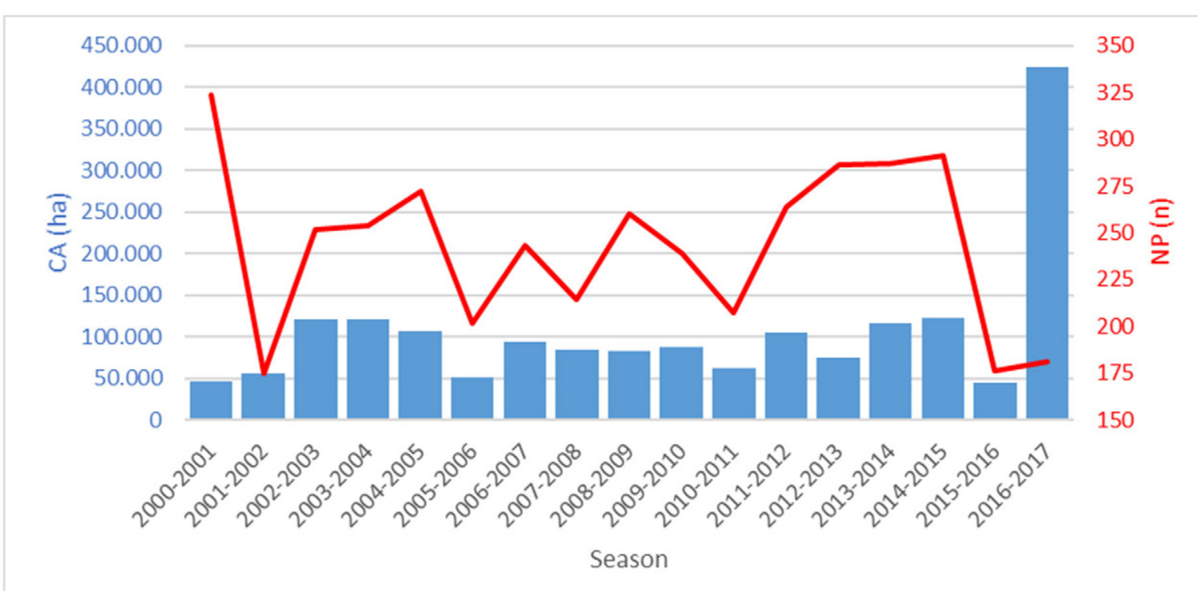

Fig. 4. Temporal behaviour of the burned area (CA) and number of burned patched (NP) between the 2000–2001 and the 2016–2017 seasons.

Table 2
Spatial characterisation of burned areas (ENN_MN: average distance between neighbours burned areas; ENN_SD: standard deviation; AI: aggregation degree between wildfires affected lands; NLSI: compacity and aggregation degree of burned areas).

Season	ENN_MN (km) (ENN_SD).	AI (%)	NLSI (0–1)
2000–2001	0.64 (±10.05)	56.53	0.43
2001–2002	11.14 (±13.99)	74.01	0.26
2002–2003	5.48 (±10.73)	74.54	0.25
2003–2004	6.91 (±11.07)	74.32	0.26
2004–2005	7.60 (±13.54)	71.86	0.28
2005–2006	7.39 (±11.35)	67.84	0.32
2006–2007	5.42 (±10.04)	70.37	0.30
2007–2008	7.31 (±12.31)	73.06	0.27
2008–2009	7.42 (±10.45)	71.37	0.29
2009–2010	6.83 (±9.58)	73.74	0.26
2010–2011	8.54 (±10.50)	70.91	0.29
2011–2012	6.68 (±10.78)	74.85	0.25
2012–2013	6.80 (±11.21)	68.08	0.32
2013–2014	6.71 (±9.97)	74.36	0.26
2014–2015	6.34 (±8.11)	75.37	0.25
2015–2016	7.35 (±16.29)	67.28	0.33
2016–2017	8.47 (±15.13)	87.98	0.12

3.2. Wildfires according to LULC

Burned areas composition are calculated for 16 summer seasons: from 2001 to 2002 to 2016–2017. The most burned LULC were savannas, representing 22.3% of all the burned areas. Forest types (evergreen needleleaf forests (ENF), evergreen broadleaf forests (EBF), deciduous needleleaf forests (DNF), deciduous broadleaf forests (DBF) and mixed Forests (MF)), reach 31.1%, where the most affected forests are EBF and DBF types, representing a major part of the forest plantations. Urban areas (UL) show very little burned areas (10,625 ha) (Table 3). Burned areas with a significant increase ($p < .05$) between 2001–2002 and 2016–2017 are EBF (+1428.75 ha/yr), ENF (237.50 ha/yr) and BR (+76.56 ha/yr). The LULC areas with significant decreases are CL (−1931.79 ha/yr), DBF (−1421.25 ha/yr) and GL (−1201.25 ha/yr). The other LULCs do not have statistically significant change trends in the period analysed (Table 4).

3.3. Wildland urban interface according to LULC 2014 and census blocks population data of 2017

Central Chile groups almost 14 million inhabitants, 89% of them living in urban areas (Table 5). The overlapping areas of fuel LULC (and their 400 m buffer) and urban areas (and their 200 m buffer) showed a total of 900 km^2 of WUI, many of them located in the Valparaiso and Biobio regions (Fig. 7).

Almost 3 million people live in WUI areas, highlighting exposed populations of the Valparaíso, Biobio and Metropolitan regions (exposed population is considered all the population that may be potentially affected by wildfired; affected population refers to all the population living in burned WUI between the 2000–2001 and the 2016–2017

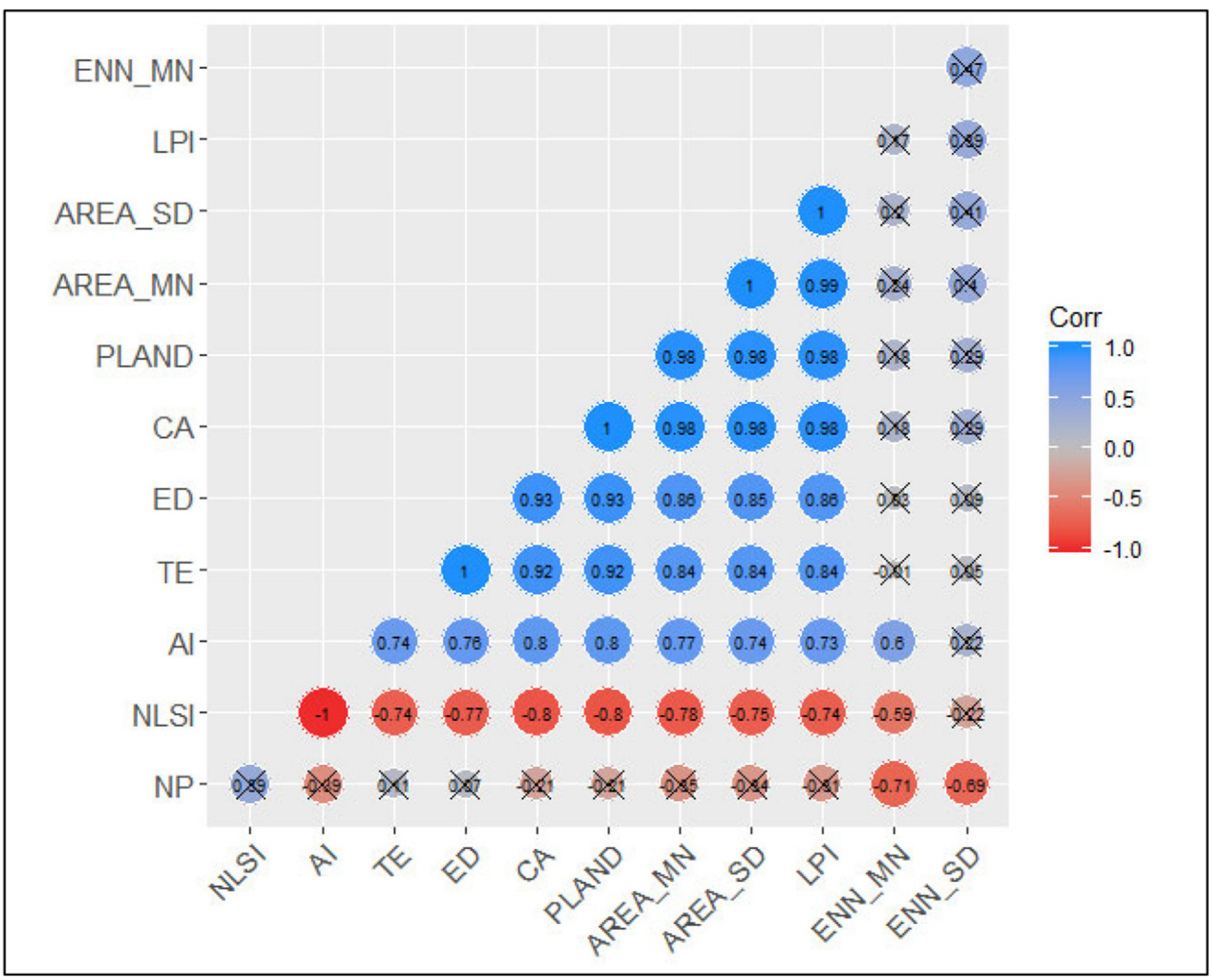

Fig. 5. Correlations among the landscape metrics variables measured in Fragstat, generated by the corrplot package in R (ENN_MN: mean Euclidean nearest-neighbour distance; ENN_SD: Euclidean nearest-neighbour distance standard deviation; LPI: largest patch index; AREA_SD: area affected by wildfires standard deviation; AREA_MN: mean area affected by wildfires; PLAND: percentage of landscape; CA: class area; ED: edge density; TE: total edge; AI: aggregation index; NLSI: normalised landscape shape index; NP: number of patches).

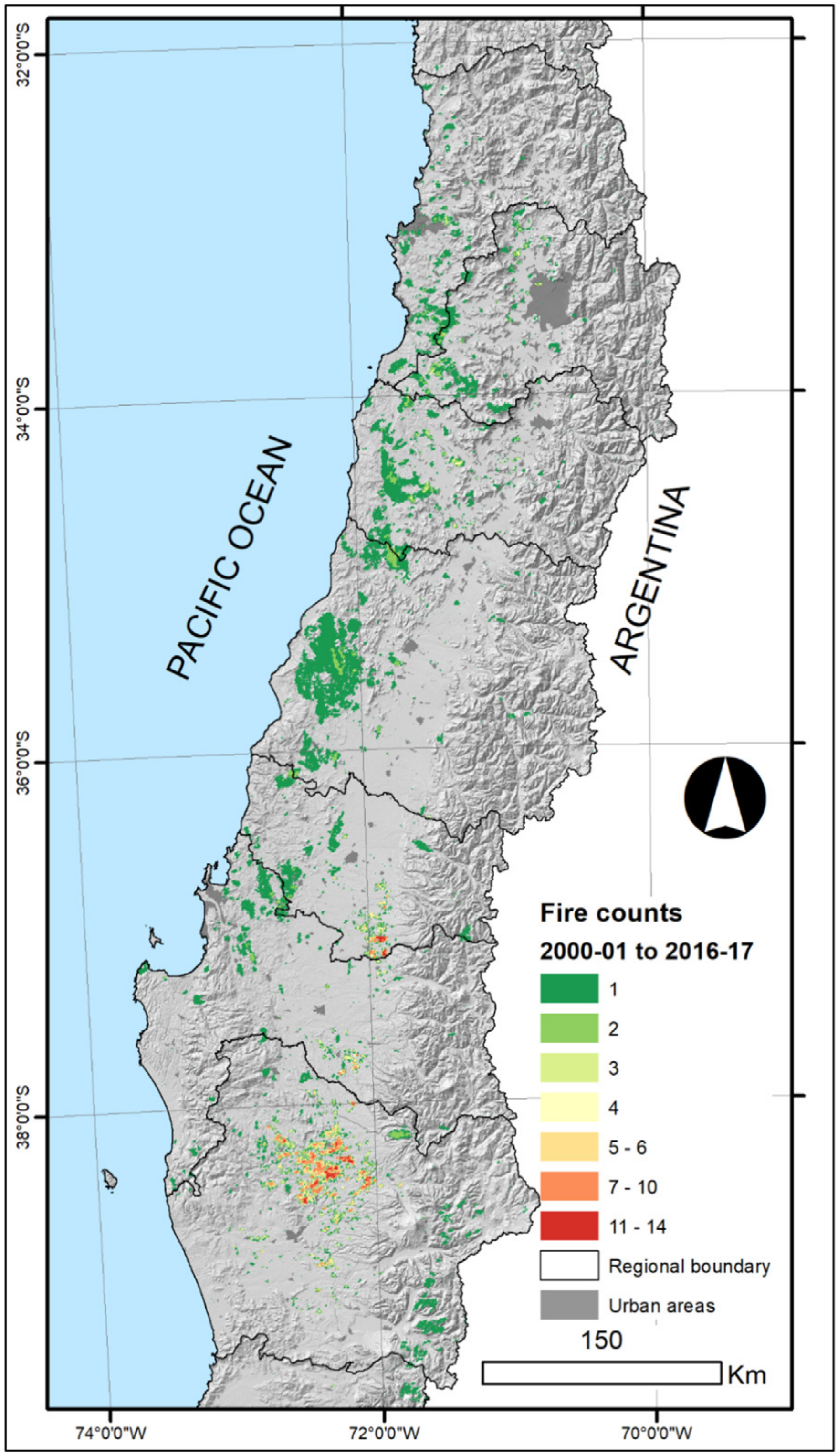

Fig. 6. Summer season wildfires between 2000–2001 and 2016–2017, obtained from the MODIS MCD45A1 product.

seasons, both considering the 2017 census). The 3 metropolitan areas of Chile are located there (Valparaiso, Concepcion and Santiago). Almost 3 million people (2,979,132 inhabitants) live in the WUI areas located between the Valparaíso and Araucanía regions (Table 5). The regions with the highest urban population in the WUI area are Valparaiso, Metropolitan Santiago and Biobio, coinciding with the three metropolitan cities of Chile (Valparaiso, Santiago and Concepción). However, while looking to the percentages of affected populations, the most affected regions are Biobio (60%), Araucania (49%), Valparaíso and Maule (both with 40%). When considering the WUI areas affected by wildfires in the study period (2000–2001 to 2016–2017), the population affected by wildfires is obtained (55,680 inhabitants), and >84% of them live regions of Valparaiso (27,535 inhabitants), Araucanía (12,001 inhabitants) and Biobio (7507 inhabitants).

Table 3
Burned LULC from the 2001–2002 to the 2016–2017 summer season.

Land use and land cover (LULC)	Total area (ha)	Percentage from the total area (%)	Area mean (ha)	Standard deviation	Coefficient of variation
Evergreen Needleleaf Forests (ENF)	77,050	4.1%	4815.6	10,414.8	2.2
Evergreen Broadleaf Forests (EBF)	301,675	16.1%	18,854.7	33,577.2	1.8
Deciduous Needleleaf Forests (DNF)	100	0.0%	6.3	24.2	3.8
Deciduous Broadleaf Forests (DBF)	144,625	7.7%	9039.1	7521.7	0.8
Mixed Forests (MF)	59,700	3.2%	3731.3	7084.2	1.9
Closed Shrublands (CSL)	7325	0.4%	457.8	541.5	1.2
Open Shrublands (OSL)	12,975	0.7%	810.9	1033.7	1.3
Woody Savannas (WSA)	239,400	12.8%	14,962.5	21,508.6	1.4
Savannas (SA)	416,375	22.3%	26,023.4	15,837.2	0.6
Grasslands (GL)	229,900	12.3%	14,368.8	7281.2	0.5
Permanent Wetlands (PWL)	2075	0.1%	129.7	326.8	2.5
Croplands (CL)	306,875	16.4%	19,179.69	10,053.7	0.5
Urban and Built-up Lands (UL)	10,625	0.6%	664.1	1108.7	1.7
Cropland/Natural Vegetation Mosaics (CNV)	13,400	0.7%	837.5	683.7	0.8
Permanent Snow and Ice (PSI)	725	0.0%	45.3	113.6	2.5
Barren (BR)	12,375	0.7%	773.4	1334.7	1.7
Water Bodies (WB)	33,450	1.8%	2090.6	5945.9	2.8
Total	1,868,650	100%	116,790.7		

4. Discussion

Here we performed an independent calculation of wildfires using the Google Earth Engine platform to analyse multitemporal satellite images and derived products. This serves to audit and compare official wildfire data series, such as those generated by CONAF (McWethy et al. 2018). The results shown here compared to those obtained in other investigations at a global scale (Andela et al. 2019; Chuvieco et al. 2019) are coherent, giving consistency to the quantification of the burned area obtained with the Google Earth Engine algorithm used in this study. Despite this, it is of high interest to add better spatial resolution beyond location, distribution and repetition of wildfires at a moderate resolution (500 m), giving more details about the severity of these events (De la Barrera et al. 2018), both with MODIS and Landsat images. It could be interesting to consider also Sentinel-2 imagery.

The Megadrought in Mediterranean Chile coincides with the warmest period (Garreaud et al. 2017) and led to the most devastating wildfires season in 2016–2017. In this context, the increase of burned areas makes relevant the use of landscape metrics to estimate and quantify the damage. The 51% of the LULC affected by wildfires correspond to savanna, pastureland and crops, and 31.1% correspond to native forest and forest plantation. These results coincide with those presented in Andela et al. (2019), mainly due to the cover category of savanna. IGBP data does not incorporate a to discrimination between native forests and forest plantation it. Obtaining this information for each wildfire season with high-resolution satellite images (30 m) could help to improve the characterisation of the burned LULC because a higher resolution in the images allows the detection of native species forest. Advances in this direction are those presented in Nahuelhual et al. (2012), de la Barrera et al. (2018) and McWethy et al. (2018), whom has used or applied ad hoc classifications for a specific period or season. Moreover, LULC changes allow to inform the growth in forest and built/urban areas for the whole period, agreeing with other studies (Nahuelhual et al. 2012; Ruiz et al. 2017; Aliste et al. 2018).

Mapping the burned areas throughout Central Chile according to satellite imagery is novel, and allows contrasting with other results that are not necessarily spatially explicit at the level of wildfires, but rather aggregated to the communal level (Ubeda and Sarricolea 2016; Bowman et al. 2019). These findings show relevant inputs for different actions, not only to recognise burned areas, but also previous situations that help prevention, and also post-fire restoration actions. Preventive actions cannot be only limited to informative campaigns or to improving fuel management at WUI; they should also include planning of LULC in terms of extension, aggregation, density and continuity, in order to prevent megafires, especially in regions where WUI are large and highly populated, as the three metropolitan areas shown in this study. In this regard, it is key to advance towards legal and geographical definitions of WUI and other areas that need of urgent preventive actions in order to reduce these type of disasters (Haight et al. 2004). For the Chilean case, WUI are areas that are not explicitely delimited (Castillo 2016), and need to be discussed and solved under the wildfires evolution scenarios pointed in the present study.

Burned areas with a significant increase ($p < .05$) between 2001 and 2017 are EBF, ENF and BR. Based on the geographical distribution of native forests and forest plantations it is possible to feed some interpretations between variations in LULC affected by wildfires and their tree type composition: EBF shows an increase of 1428 ha/yr burned, corresponding mostly to *Eucalyptus globulus* (Zhao et al. 2016) plantations in the coastal mountain range and also to sclerophyllous native forest highly fragmentated in the area (Heilmayr et al. 2016). The ENF burned area increases 237.5 ha/yr, affecting mostly *Pinus radiata* plantations in the coastal mountain range and *Araucaria araucana* in the Andes (Zhao et al. 2016). The differences identified from these results and those shown by Zhao et al. (2016) may be explained because in this previous study only 2014 data are used. These data were only used in the present work only to define the WUI and not to delimit year-to-year LULCs. BR areas, with increasing rates of 77 ha/yr, may be areas where seasonal grasslands grow, very similar to burned water bodies areas. This can be explained by the former dynamics of the water bodies during the Megadrought (Garreaud et al. 2017), while the wildfires may affect riparian vegetation.

Table 4
Burned LULC trends between 2001–2002 and 2016–2017.

Land use and land cover (LULC)	Sen slope (ha/year)	
Evergreen Needleleaf Forests (ENF)	237.50	*
Evergreen Broadleaf Forests (EBF)	1428.75	*
Deciduous Needleleaf Forests (DNF)	0.00	
Deciduous Broadleaf Forests (DBF)	−1421.25	*
Mixed Forests (MF)	62.24	
Closed Shrublands (CSL)	17.71	
Open Shrublands (OSL)	−38.27	
Woody Savannas (WSA)	277.50	
Savannas (SA)	190.97	
Grasslands (GL)	−1201.25	*
Permanent Wetlands (PWL)	0.00	
Croplands (CL)	−1931.79	*
Urban and Built-up Lands (UL)	21.35	
Cropland/Natural Vegetation Mosaics (CNV)	63.49	
Permanent Snow and Ice (PSI)	0.00	
Barren (BR)	76.56	*
Water Bodies (WB)	27.27	

* The significant trend ($p < .05$).

Table 5
Study area population (total and urban) and of WUI areas in 2017.

Region	Total population	Urban population	Urban population (%)	Exposed Urban population in WUI	Exposed Urban population in WUI (%)	Affected urban population in WUI
Valparaiso	1,815,902	1,652,575	91%	654,483	40%	27,535
Metropolitan Santiago	7,112,808	6,849,310	96%	481,690	7%	1204
O'Higgins	914,555	680,363	74%	255,292	38%	1106
Maule	1,044,950	765,131	73%	309,842	40%	3350
Ñuble	480,609	333,680	69%	122,207	37%	2977
Biobio	1,556,805	1,379,015	89%	824,726	60%	7507
Araucanía	957,224	678,544	71%	330,892	49%	12,001
Total	13,882,853	12,338,618	89%	2,979,132	24%	55,680

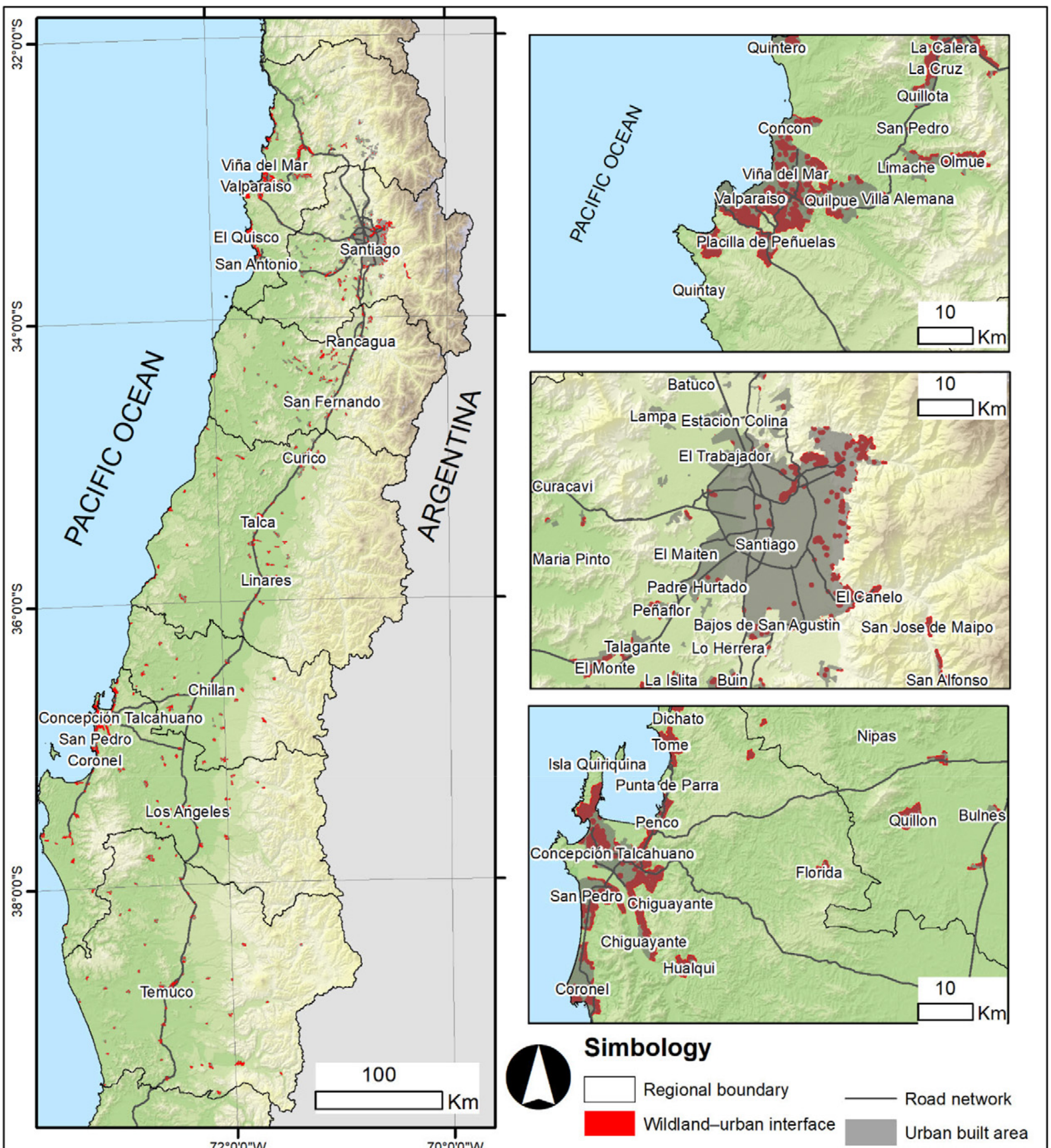

Fig. 7. WUI zones in Mediterranean Chile and in the three metropolitan areas.

The obtained results of burned areas and LULC agree with the findings of Andela et al. (2019). Both grasslands and crops are the most burned areas, but they are burning less in present that in past times. This decrease could be explained by most effective actions to prevent or combat wildfires in these areas, characterised by easier accesses. On the other hand, DBF, forests are mainly dominated by native *Nothofagus* species in the Andes range, could also be the subject of greater concern and more efficient actions, due to its ecological and socio-cultural valuation.

Landcape metrics showed significant correlations between most of them with very few exceptions as number of patches with all other metrics. This indicates that number of fires should not be used as proxy of other spatial characteristics of wildfires, i.e. institutions in charge of evaluating and/or communicating the magnitude of fires should include other spatial descriptors, beyond number of fires and total land burned, especially when the spatial distribution and size of wildfires is highly variable on time. Some explanations for this high variability are given by landscape configuration and natural/antropogenic causes (Ortega et al. 2012).

Regarding the population located in WUI, the results coincide with those presented by Ruiz et al. (2017) using the methodology proposed by Modugno et al. (2016). It is an advance to recognise the WUI areas to have a first diagnosis of the danger and risk that the increase in wildfires may mean in the future. Knowing the areas of repetition of wildfires between different seasons can provide valuable information of areas of greater exposure to such events (McWethy et al. 2018).

The north of Temuco is one of the areas with the highest wildfire recurrence, beeing this explained by the prescribed fires in pasture lands and annual crops (McWethy et al. 2018). In this sense, it is important to determine which are the effects of these practices in soil properties (Alcañiz et al. 2019; Francos et al. 2019).

In the most populated WUI areas, there is a latent danger for the population in case of a future increase of events, this would also increase the human loss.

4.1. Limitations

The present study shows limitations because the MODIS satellital information does not allow to differentiate between wildfires affecting plantations forest and wildfires affecting native forests. When considering a deeper analysis according to LULC products from MODIS imagery, it is shown that they do not discriminate plantations from native forest.

Another limitation shown is to consider fire seasons, because almost all studies agree that wildfires occur between September and May (CONAF 2018; Castillo 2016), a part of each year (from June to August) show no information, and may have presented any wildfire in the study area meanwhile.

Although it was possible to determine the WUI areas and the potentially affected population with the 2017 population census, it would be important to work with the variable "housing" since they are located in burned areas, it is very likely that they have been burned, that is, the inhabitants can escape forest fires, but not homes. Having information from other population and housing censuses would allow to see the temporal evolution of these areas.

5. Conclusions

The access to environmental information, such as vegetation dynamics and natural hazards, such as burned areas, floods and landslides has been improved thanks to satellite imagery. The MODIS satellite allows detecting burned areas in a 500 m spatial resolution and at a daily scale.

Central Chile concentrates the largest wildfires, and this is verified in the 17 studied seasons (from 2000 to 2001 to 2016–2017) and contrasted with this study by McWethy et al. (2018). Accordingly, valuable information was generated on the location and repetition of wildfires, in addition to the most affected LULCs. Consequently, MODIS images and their derived products (MCD45A1 and MCD12Q1.006) are a fundamental resource for delimiting seasonal burned areas and LULC. Thanks to that and to more recent information generation, it is possible to count on inputs for forest management decision making. For example, it helps to define mixtures of uses that allow lowering the fuel load against large fires, which could be more frequent, but, on the contrary, they are against carbon neutrality objectives.

Burned landscape metrics can be a good wildfire analysis tool. It is possible to conclude that the higher the number of patches is, the average distance between them decreases. This would mean that the spatial continuities generated by exotic forest plantations in Chile are not suitable for fire prevention. It is advisable to plan not only the fragmentation of a plantation but also the timing of its felling and the distance between to limit the effects of wildfires.

The most burned LULC in Chile are savannas, croplands, evergreen broadleaf forests and woody savannas. However, the croplands present negative trends of burned area per year. It is highly recommended to propose land uses alternatives that allow: (1) reduce the risk of wildfires; and (2) reduce the potentially affected population. The first can be achieved by regulating the size of forest patches, and the second by restricting the distance between population and combustible areas.

The conceptual and spatial definition of the WUI is fundamental to highlight the problem of catastrophic forest fires but also to taking evidence-based decisions to reduce the risks by planning WUI and surroundings. It is urgent that Chile develops a planned and spatially explicit normative definition of WUI, because under climate change, wildfires can increase its intensity and speed of propagation, so that material losses and the exposed population will increase.

The presence of WUI areas is a common phenomenon in the Mediterranean regions of the world covered by LULC that currently dominates the Chilean landscape. Growing and sustained urbanisation can increase and aggravate the risk and exposure of the population while forestry plantations also grow and approach the cities. This is how in Mediterranean Chile it is estimated that currently about 3 million people live in WUI areas and how wildfires are becoming more frequent in the densely populated areas of the WUI, resulting in greater social problems, including the loss of human lives.

These results show the imperative need for public policies as a regulating force for establishing WUI areas. Thanks to that it will be possible to identify wildfire risk in urban areas, such as to establish prevention methods such as firewalls and prescribed fires.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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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.2019.135894.

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