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Case Studies

A recent review of fire behavior and fire effects on native vegetation in Central Chile

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ABSTRACT

Central Chile experienced a very extended and devastating fire season during 2016–17. After 3 years, here we present the results of an analysis of behavior of the wildfires occurred in that season. We used a modeling approach to estimate the physical parameters of fire behavior: speed of linear spread, front-line intensity and flame length; as well as qualified fire severity, and the potential danger of recurrent fires. We selected eight study areas in four regions of Central Chile, under sclerophyllous forest and shrublands with variable composition. To run the model, we gathered data on vegetation structure and composition, and physical information. The values of the physical parameters were in a comparable range in the eight studied areas, with two of these areas showing maximum values. This could result from differences in vegetation. We detected rapid regrowth post-fire, despite the high levels of fire intensity and damage, ascribed to a high availability of very dry fine biomass. Given the predictions of increased drought, we should expect recurrence of wildfires. Based on our results, we anticipate fires of high severity and damage, with emphasis in areas with very high increase of dry biomass. We suggest restoration programs, with frequent monitoring of passive restoration practices, resorting to more active physical support in areas more severely affected.

1. Introduction

Wildfires and their effects are receiving increased attention, especially in fire-prone regions such as the Mediterranean regions of the world. The predominant perception is that wildfire frequency and severity have increased in recent decades (Clarke et al. 2013; North et al. 2015), and are expected to increase more in coming years (Liu et al. 2010; Jolly et al. 2015). This seems to be true for some regions but the overall view is not supported by the available statistics (Doerr and Santin, 2016). Whereas in regions such as California and western Nevada in the US, the extension of forests affected by wildfires increased (Miller et al. 2009), in some regions of Europe the frequency and extension of wildfires have decreased (Mancini et al. 2017). In contrast, the frequency and extension of wildfires close to urban settlements (WUI) have increased (Fischer et al. 2016; Modugno et al. 2016). More research is needed to clarify these complex issues, meanwhile, the matter remains controversial.

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Some statistics from Chile, for the period 1984–2016 show that the number of fires has increased but the area burnt has not (Úbeda and Sarricolea, 2016). González et al. (2018) compared fire regimes from 2010 to 2015 to those from 1990 to 2009, demonstrating that the number of fires, the length of fire season as well as the fire duration, increased. In the last 53 years (1964–2017), Chile had an average of 4346 fires per year, affecting an average of 58,053 ha year^{-1} (CONAF, 2018). Figures vary greatly in time, possibly due to a lack of information available from before 1990, but also probably to changes in fire incidence in the last 15 years. Several factors have been considered as important drivers of fire occurrence and extension in central Chile. These include physical, climatic and biotic factors such as elevation, slope, vegetation type, as well as human factors such as population density, increased human occupation of the urban-rural interface (WUI) and the expansion of exotic tree plantations (Carmona et al. 2012; McWethy et al. 2018; Gonzalez et al. 2018; Urrutia-Jalabert et al. 2018; Gómez-González et al. 2019). McWethy et al. (2018) predict that the combination of increased fuel-rich forest plantations and warmer and drier climatic conditions may further induce fire frequency and magnitude.

The greatest and most damaging wildfires in Chilean history took place in 2017 (CONAF, 2017; Bowman et al. 2018) affecting about 600,000 ha. In three months more than 115,710 ha of native sclerophyllous forests were burnt, emphasizing the need for more studies and initiatives to restore ecosystems degraded by fire (CONAF, 2017). These megafires had a great impact beyond the ecological destruction, the loss of human lives and economic losses. This includes increased air pollution and the increased risk of landslides and flooding (de la Barrera et al. 2018).

Fire is considered an important ecological factor, sustaining biodiversity and deterring the invasion of exotic species (Fernández et al. 2010). Fire regimes, which comprises fire frequency, intensity, and severity, are key determinants of ecosystem functioning of many ecosystems. However, burning of vegetation, especially fires out of season and megafires, may induce severe changes in the functioning of ecosystems, even in those adapted to frequent burning. These changes may result in the fragmentation of the landscape, changes in soil properties, facilitating soil erosion and decreasing fertility (Pausas et al. 2008; Garcia-Chevesich et al. 2010) and made many native species more vulnerable to fire occurrence (Armesto et al. 2009). These negative effects may affect ecosystem services and bring sizeable economic losses (Castillo et al. 2016).

Sclerophyllous forests and shrublands are the dominant vegetation in the Mediterranean zone of central Chile, occupying an area with the most frequent and extended wildfires. This vegetation shows a predominance of tall shrubs with sclerophyllous leaves and short shrubs with xerophytic leaves, thorny or succulent shrubs, and taller laurifolia trees. This vegetation occupies the slopes of the Coastal Cordillera and the Andes, as well as the central depression (Gajardo, 1994). In the area selected for this study, the current condition of this vegetation has been considered a regressive climax, described as degraded shrubland and open forest with some dominance of invasive species exhibiting rapid growth and regeneration, under recurrent wildfires (Castillo, 2015).

In accordance with the rise of interest in wildfires occurrence, the number of reports on wildfire characterization and management has also risen in recent years (Roldán-Zamarrón et al. 2006; Keeley et al. 2008; Fernandes et al. 2016; Costafreda-Aumedes et al. 2017; Turco et al. 2017). These studies are important in several ways. They contribute to the development of initiatives that prevent, manage and fight wildfires. They also help to design methods to evaluate actual and potential damages caused by wildfires. More importantly, these studies contribute to developing adequate strategies to recover ecosystems after fire damage. It is in this direction that studies on potential damages and dangerous conditions during the recovery process, usually based on the evaluation of actual intensity and severity of wildfires (Keeley, 2009), are valuable. From an ecological point of view, the study of fire behavior helps to understand the dynamic of vegetation responses (Pausas et al. 2008), as well as the effects at different scales of analysis (Keeley et al. 2008).

Studies of fire behavior have been published in Chile (Julio et al. 1997; Fernández et al. 2010; Castillo, 2013; Castillo et al. 2012, 2017), as well as in other Mediterranean regions in the world (De Luis et al. 2004; Saglam et al. 2008). Results show the relationships between vegetation traits, climate, climate change and fire behavior (intensity, severity) and the implications for recovery and restoration.

In this document, we carry out a detailed characterization of the response of the native vegetation affected by the serious forest fires that occurred in 2016–2017. This response was obtained by means of successive field measurements of the plant communities with and without affectations by fires, and also by characterizing the historical behavior that the fire had in the different areas studied through the use of simulators of fire behavior. With this background, it was then possible to make a forecast of the future state of these native communities, specifically in their regeneration characteristics, recovery in coverage, and also in the condition of vulnerability (danger) against the impact of new fires in each of the areas studied. All in all, it was then possible to establish diagnostic guidelines that make it possible to better guide decisions on restoration strategies (passive or active) for native vegetation. Consequently, this research allows supporting the restoration strategies of native plant ecosystems affected by fires. Our results are also inserted in the current problems that exist in Chile and in other Mediterranean climate regions that present the effects of climate change and the increase in fire severity.

2. Materials and methods

The study consisted of choosing areas with and without fire affectations to carry out comparative analyzes. For this purpose, four regions of Chile were chosen, and in each of them eight places where the experimental samples were made. The chosen number was based on the access capacities to the areas, the necessary permits to enter the burned areas, and also on the search for representative samples of the different scales and magnitudes of damage, in order to make comparisons between localities and their post fire recovery and severity indicators. This work was performed after fires and its results were compared with test areas without affectations. The detail is explained below.

The study involved sites from four Regions in Central Chile: Región Metropolitana (RM), Valparaíso (V), O'Higgins (VI) y Maule (VII), which add to a surface of 78,455 km^2. As shown in Fig. 1, the study comprises three phases. The first phase produces the database with information on vegetation and environmental traits needed for the simulations. In the second phase, we conduct simulations to describe fire behavior. In the third phase, we discuss the behavior and the consequences of the fires. We conclude summarizing the physical characteristics of the fires occurred in the study region during the 2016–2017 season.

2.1. *Study area and sample plots*

To create a preliminary map of the native forests, we used aerial photographs combined with field surveys in the four regions. These surveys were conducted during September and December 2016 and included all the different physiognomic variations of the native vegetation. The resulting preliminary map was used as the database to incorporate the information on wildfires occurrence in the 2016–2017 season. Then we proceed to select localities and sampling plots.

We selected eight localities under native vegetation, two in each of the four Regions already mentioned (Fig. 2, Table 1). These localities were affected by wildfires in extensions of at least 50 ha. In each location, we randomly set four 100 m^2 plots in burnt areas and a similar fifth plot was set in the non-burnt vicinity. Plots were adequately signaled using poles and strings. In each plot we described the vegetation physiognomy and listed all individual plants taller than 50 cm, measuring height, basal diameter, stem length below branching, and horizontal and vertical crown projections (Castillo, 2013). In each burnt plot we registered date of the fire, burnt extension, slope and exposure, and damage degree. In the non-burnt plots, we also described the vegetation physiognomy following Gajardo (1994), and Luebert and Pliscoff (2006). This information was then used to determine the dominant fuel models (according to Julio et al. 1995), and its spatial spread (Castillo, 2013). At the end of this phase, we had collected all the information necessary to characterize the wildfires and their effects.

Wildfires studies use two basic concepts: intensity and severity. These two concepts and their relationships allow determining vegetation response and restoration possibilities after a fire (Keeley, 2009). Intensity refers to the amount of energy liberated in the combustion of plant material. It is measured per volume unity as well as by the speed of movement of that energy and it is expressed in Wm$^{-2.}$ The front-line intensity corresponds to the rate of heat transference per unit of longitude (kW^{-1}) in the front line of the fire (Byram, 1959), and it is related to the flame length. Intensity depends on the combustion rate and the type of fuel, whether it is a mixture of different species or not (Alexander, 1982; Scott and Reindhart, 2001). Severity is associated with the damages inflicted to the ecosystem (Tolhurst, 1995), and an indicator of loss of plant biomass (Dickinson and Johnson, 2001) and of organic matter from the soil (Neary et al. 1999; Ice et al., 2004). The sooner we measure the impact of fire the better for the estimation of intensity (Ryan and Noste, 1985). To evaluate severity, the soil organic matter, soil structure, forest biomass, and hidrophobicity are commonly used (Garcia-Chevesich et al. 2010).

In the present study, we characterize the wildfires using two approaches: one analyzes the behavior of the fires using a simulation model; the other is a qualitative appraisal that allows a global estimation of the fire effects, involving vegetation assessment. This complementary approach is based on the classification of the relative effects.

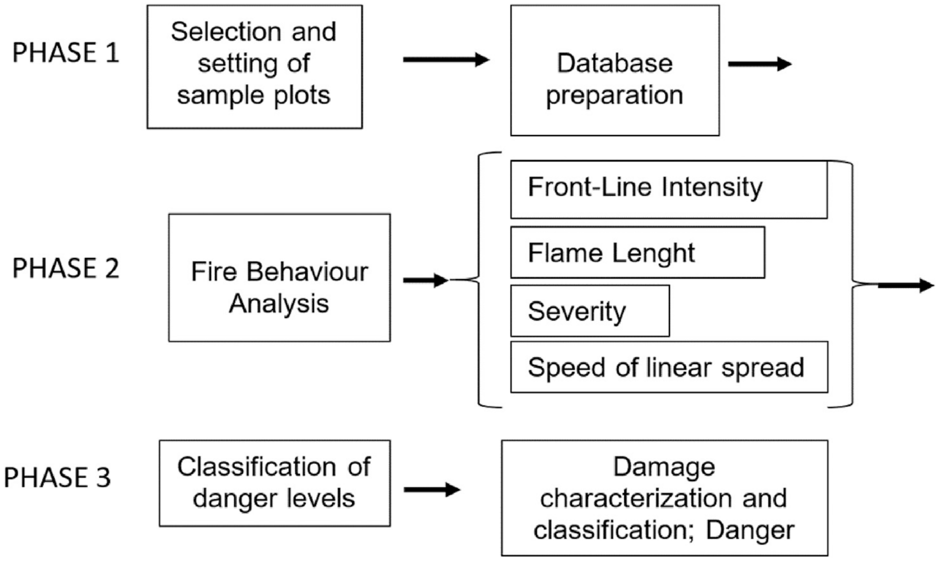

Fig. 1. Diagram showing the three phases of the study, as explained in the text.

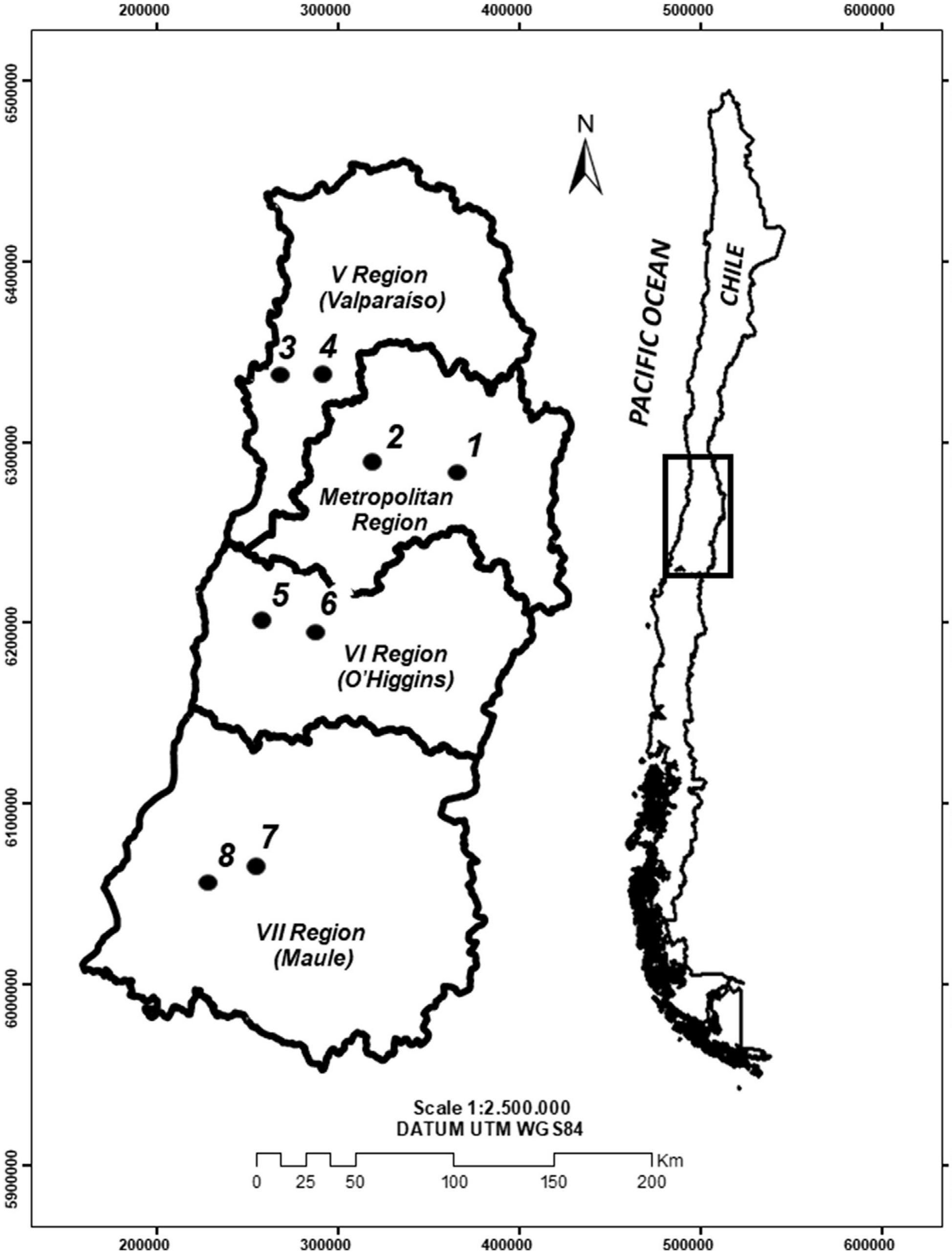

Fig. 2. Map showing the relative position of the eight localities in the four Regions of the study area.

2.2. *Analysis of fire behavior: the simulation model KITRAL*

To analyze the behavior of the wildfires in the different localities we used the simulation model KITRAL. This model was built by a group of scientists from the School of Forestry at Universidad de Chile in 1995, attending to the peculiarities of the Mediterranean ecosystems of Central Chile. The model has been described in technical reports (Julio et al. 1995; Castillo, 1998) and has been used in several previous studies (Castillo et al. 2011, 2013, 2017). Following we present a brief description of the model. Model inputs are humidity contents of the fine vegetation, wind speed and direction, air temperature, air relative humidity, available fuel load, and terrain slope. This last parameter is obtained from a topographic analysis in a Geographical Information System specially designed for this fire simulator. Furthermore, we count with a database with fuel models for the

Table 1
The eight localities with the date of last fire and a summary of geographical and climatic information.

Region	Locality	Fire date	Evaluation date	Mean slope (%)	Dominant exposure	Mean T (°C)	Mean HR (%)	Dominant wind direction
Región Metropolitana	Cuesta Barriga	Mar-2017	Apr-2017	70	East	28	40	South
	San José de Maipo	Jan-2017	Mar-2017	65	Northwest	28	40	South
V Región (Valparaíso)	Rodelillo	Apr-2016	Feb-2017	50	West	30	35	South
	Limache	Feb-2017	Feb-2017	55	Variable	25	45	South
VI Región (O'Higgins)	Pichidegua	Dec-2016	Dec-2016	25	Southwest	28	40	South
	La Estrella	Jan-2017	Feb-2017	15	Northeast	30	35	South
VII Región (Maule)	Ovejería	Feb-2017	Feb-2017	25	Northeast	28	40	South
	Nirivilo	Jan-2017	Feb-2017	13	West	25	45	South

Mediterranean region in Chile, which resume two variables: the vegetation calorific power (*H*) and the fire spread potential (*Fmc*). To prepare this database we used 34 different land cover types. Input data is obtained in the field and arranged in fire-cards for each fire event. Local meteorological parameters, such as air temperature, wind speed and direction, and relative air humidity, were obtained from meteorological stations near each sampling plot, to more closely represent the initial conditions of each fire. The date and time of each fire was obtained from the logbooks and historical records from the National Forest Corporation of Chile (CONAF) for the four research regions. These meteorological parameters were necessary to apply the KITRAL expansion simulator, for the modeling of fire behavior in each of the sampling areas.

The outputs of the simulation with KITRAL are parameters such as the speed of linear spread (*VP*), the front-line intensity (*I*), and the flame length (*L*). To estimate the speed of linear propagation of the fire (*VP*), we used the following equation

$$\mathrm{VP} = (\mathrm{Fmc})(\mathrm{Fch})(\mathrm{Fp} + \mathrm{Fv})\ [\mathrm{ms}^{-1}]$$

Fmc is a factor representing the predominant fuel model in the plot; *Fch* is the corresponding factor for humidity contents of the fine plant material, based in the water contents of the plant tissues and the mean air temperature. *Fp* is the factor describing the predominant slope of the terrain, and *Fv* is the factor for the predominant wind (speed and direction). These two factors are relevant for the way the fire advances in the surface of the terrain. As the fire ascends to the tree branches and crowns, it becomes more complex. These factors were previously generated from field trials, and as a result, KITRAL counts with tables combining the variations of meteorological, topographic, and vegetation traits which are relevant for the estimations of the fire speed and direction. In this study, we used the wind speed and direction factors, as well as temperature and relative air humidity, were taken from stations near each sampling point. *VP* is expressed in meters of linear propagation in the surface per second (ms^{-1}) up to 3 m high, depending on the average height of the plant cover. It changes as fire propagates in different directions and local conditions change. For the calculations made here, 3 repetitions (simulations) were considered for each sampling plot, varying in each case the starting point of the fire inside each plot. This criterion was established to capture differences attributable to variation in terrain slope and changes in vegetation composition. This same process was carried out in the test plots, in order to obtain a standard deviation of each sample, and for each of the fire behavior parameters. For zones of wildland-urban interface (WUI), KITRAL is provided with the parameters of calorific power and response to fire of structural materials.

The value obtained for *VP* is used by KITRAL to obtain other indicators of fire behavior: the front-line intensity (*I*) and the flame length (*L*). To calculate the front-line intensity the following equation was used,

$$\mathrm{I}= (\mathrm{H})(\mathrm{w})(\mathrm{VP})\ [\mathrm{Wm}^{-1}\mathrm{s}^{-1}]$$

I, the linear intensity of the fire advance, is the energy liberated in time and linear space (Wm^{-1}s^{-1}) in the combustion process. *H* is the calorific power of the combustible material (Kcal kg^{-1}) and *w* is the available load of this material (kgm-^{2}). Finally, KITRAL uses this value (*I*) for the calculation of the flame length using the following equation from Albini (1976),

$$L= (0.1477)\ (I)0.46\ [\mathrm{m}]$$

where *L* is the length of the flame in m, measured from the base to the highest point, and considers the simultaneous effects of convective heat and wind speed.

2.3. Wildfire characterization

Besides the quantitative analysis already presented, we produced a qualitative assessment of the wildfires and their effects for each plot, using categories of intensity, severity, and recovery. This approach is useful to classify the wildfires for purposes of selecting the strategies and allocating the resources for recovery and restoration.

2.4. Levels of fire intensity (FIL)

FIL is a complementary indicator based on the product of “*H*" (calorific content) and “*w*" (available fuel load) of the vegetation present in every plot. This represents the amount of energy liberated by each type of vegetation in each plot, allowing to estimate the total amount of energy liberated by the fire in each plot. This intensity is different from the front-line intensity already calculated since it considers all strata of the vegetation; we then used this intensity to calculate the flame length (L’) using the Albini equation mentioned above. Based on the range of L’ obtained we designed a classification of values within six categories which reflect the relative magnitudes of the fire intensities. The classification is inspired by Hostikka et al. (2008) and Molina et al. (2014) but is based on the vegetation characteristics of our study sites.

2.5. Fire effects: danger parameters

We used data from the non-burnt plots to determine fuel model and estimate the average fuel load for each plot. The fuel model allows estimating the spread potential, as well as the vertical and horizontal continuity (Julio et al. 1995). These parameters qualify the danger conditions of the plots for potential future fires. The qualification is subjective and is based on the presumption that the burnt plots will grow back to a plant cover similar to that present in the non-burnt plots.

2.6. Fire severity and recovery indicators

In each burnt plot we estimated the severity of the fire and the plant cover and registered the time elapsed after the last fire. To estimate severity, we used the categories from Castillo et al. (2017), who identify six degrees of increased severity based on the condition of the vegetation after the fire. This condition is evaluated in the field following Keeley (2009) and implies examining soil marks, roots, bark, branches, and leaves.

Vegetation recovery in these Mediterranean ecosystems can be detected three weeks after the fire and is based on the sprouting mechanisms of the species, favored by the changes in light regime and availability of nutrients brought about by the fire. These growth mechanisms in the species present in our study have been studied by several authors (Armesto and Picket, 1985; Muñoz and Fuentes, 1989; Arroyo et al. 1995; Quintanilla and Castro, 1998; Quintanilla, 1999; Holmgren et al., 2000; Armesto et al. 2009; Fernandez et al. 2010). Additionally, the response of the vegetation depends on the severity of the fire and should be considered to determine the alternative restoration strategies. These responses are also important for the future occurrence of new fires. Vegetation cover, an indicator of vegetation recovery, was visually assessed in each burnt plot and expressed as a percent of plant cover.

3. Results

3.1. The vegetation

The dominant vegetation in the study area is sclerophyllous forests and shrublands. More specific physiognomies are detailed in Table 2. A list of species detected in the non-burnt plots in each locality is presented in Table 3, classified by habit.

3.2. Fire behavior

Table 4 shows the results for the speed of linear spread (VP) from KITRAL. The localities of La Estrella y Rodelillo showed the maximum values, 0.3972 ± 0.080 and 0.3842 ± 0.113 m s^{-1} respectively. This was more than four times higher than the value of 0.0848 m s^{-1} estimated for the locality of Nirivilo.

Table 5 shows the results of front-line intensity (*I*) calculated for each locality. The maximum value again corresponded to Rodelillo (2905.75 ± 221.18 W $m^{-1}s^{-1}$), and it was four times higher than the minimum value of 720.14 ± 48.54 W $m^{-1}s^{-1}$ calculated for Nirivilo.

The results for flame length are presented in Table 6. The maximum flame length was for Rodelillo, and it is almost two times the value estimated for Nirivilo.

Table 2
Dominant types of vegetation in each of the eight localities.

Locality	Dominant types of vegetation
1. Cuesta Barriga	Shrubs and Scrubs, mesomorphic, open to dense; Open Grasslands with herbaceous mesomorphic layer.
2. San José de Maipo	Shrubs and Scrubs, mesomorphic, open to dense; Dense Grasslands with herbaceous mesomorphic layer.
3. Rodelillo	Shrubs and Scrubs, mesomorphic, open to dense; *Quila* (Chusquea spp.) communities.
4. Limache	Shrubs and Scrubs, mesomorphic, open to dense; *Quila* (Chusquea spp.) communities.
5. Pichidegua	Shrubs and Scrubs, mesomorphic, open to dense.
6. La Estrella	Shrubs and Scrubs, mesomorphic, open to dense; Open Grasslands with herbaceous mesomorphic layer.
7. Ovejería	Shrubs and Scrubs, mesomorphic, open to dense; Open Grasslands with herbaceous mesomorphic layer.
8. Nirivilo	Shrubs and Scrubs, mesomorphic, open to dense; Open Grasslands with herbaceous mesomorphic layer.

Table 3
Presence of species in each locality, classified by habit. Results from surveys in non-burnt plots. (*) denotes exotic species.

Main Habit	Species	Cuesta Barriga	San José de Maipo	Villa Alemana	Rodelillo	Pichidegua	La Estrella	Ovejería	Nirivilo
Trees	*Acacia caven* (Espino)	X		X		X	X	X	X
	Aristotelia chilensis (Maqui)			X					
	Colliguaja odorífera (Colliguay)	X	X						
	Cryptocarya alba (Peumo)				X			X	
	Lithrea caustica (Litre)	X	X	X	X	X		X	X
	Maytenus boaria (Maitén)	X				X	X		X
	Peumus boldus (Boldo)			X	X	X	X	X	X
	Pyrrhocactus curvispinus (Cactus)		X						
	Quillaja saponaria (Quillay)	X	X	X		X			X
	Schinus latifolius (Molle)			X	X				X
Shrubs	*Aira Caryophyllea* (Aira común)			X		X			
	Aristotelia chilensis (Maqui)			X					
	Azara dentata. (Corcolén)				X				X
	Baccharis linearis (Romerillo)			X		X	X		
	Baccharis sp.				X				
	Berberis sp. (Michay)							X	
	Buddleja globosa (Matico)				X				
	Cestrum parqui (Palqui)		X	X		X			
	Clinopodium chilense (Menta del cerro)			X					
	Echinopsis chiloensis (Quisco)			X					
	Escallonia sp.				X				
	Juncus imbricatus (Junco) (*)								X
	Muhelembekia hastulata (Quilo)			X		X	X		
	Puya chilensis (Chagual)				X				
	Retanilla trinervia (Tevo)	X	X	X	X	X			
	Rosa moschata (Rosa mosqueta)								X
	Rubus ulmifolius (Zarzamora) (*)					X			
	Trevoa quinquenervia (Tralhuén)							X	
Herbs	*Aira caryophyllea* (Heno de Castilla) (*)			X		X			X
	Avena barbata (Avena) (*)			X		X			X
	Brassica campestris (Nabo silvestre)			X					
	Briza maxima (Tembladerilla)								X
	Briza minor (Tembladera)			X		X			X
	Capsella bursa-pastoris (Bolsa de pastor)					X			
	Cirsium vulgare (Cardo negro)					X			
	Conanthera campanulata (Papita del campo)					X			
	Cuscuta sp (Cabellos de ángel)					X			
	Dioscorea sp. (Papa cimarrona, camisilla)			X		X			
	Gamochaeta sp. (Peludilla, Vira)			X		X			
	Hordeum hordeaceus (Cebadilla)								X
	Hordeum marinum (Espiguilla)								X
	Lactuca serriola (Lechuguilla) (*)			X		X			
	Leontodon taraxacoides (Diente de león)								X
	Loasa sp (Ortiga)					X			
	Petrorhagia prolifera (*)								X
	Pseudognaphalium sp. (Vira-vira)			X					
	Rumex acetosella (Vinagrillo)								X
	Tolpis barbata (Chicoria andaluza) (*)								X
	Verbascum sp. (Hierba del paño) (*)								X
	Vulpia bromoides (Vulpia) (*)								X

In the three parameters presented above, Nirivilo (VII Region) showed the minimum values. The maximum values were found in Rodelillo (V Region) and La Estrella (VI Region).

3.3. *Fire characterization: intensity levels (FIL), Mean Severity and vegetation recovery*

Table 7 shows the Fire Intensity Level, the Mean Severity and Vegetation Cover as results of Fire characterization.

Six of the eight localities have FIL qualifications of High and Very High. FIL values do not appear related to the categories of Mean Severity, which are predominantly medium. The recovery of vegetation is remarkable, with values of plant cover medium to high in five of the eight localities, but with no relationship to the values of FIL or Severity. Vegetation recovery is mostly from sprouts without visible contribution from seedlings.

Table 4
Speed of Linear Spread (*VP*) calculated with KITRAL for the eight localities. Parameters used are as follows, *FMF*: Fuel Model Factor; *HF*: Humidity Factor; *SF*: Slope Factor (factors are one-dimensional). Wind speed and direction factors, as well as temperature and relative air humidity, were taken from stations near each sampling point.

Factors	*FMF*	*HF*	*SF*	*VP* (m s^{-1})([a])
Localities				
1. Cuesta Barriga	0.00838	2.5	3.3	0.2452 ± 0.017
2. San José de Maipo	0.00812	2.5	3.09	0.2331 ± 0.004
3. Rodelillo	0.01067	3.3	2.51	0.3842 ± 0.113 ([b])
4. Limache	0.00953	1.94	2.7	0.2053 ± 0.042
5. Pichidegua	0.00994	2.5	1.67	0.2502 ± 0.027
6. La Estrella	0.01231	3.3	1.38	0.3972 ± 0.080
7. Ovejería	0.00939	2.5	1.67	0.2363 ± 0.077
8. Nirivilo	0.00449	1.94	1.33	0.0848 ± 0.003

[a] 3 repetitions inside the sample plot, moving the starting point based on the differences in slope and vegetation cover.
[b] Sampling unit with high slope variation (±50%).

Table 5
Front-Line Intensity (I) calculated for each locality. *w* is the load or weight of available fuel; *H* is fuel's calorific power per unit of weight; VP is Speed of Linear Spread from the previous Table.

Localities	*w* (kg m^{-2})	*H* (Kcal kg^{-1})	*VP* [ms^{-1}]	*I* (Wm^{-1} s^{-1})
1. Cuesta Barriga	1.765	4566	0.2452 ± 0.017	1975.41 ± 113.02
2. San José de Maipo	2.438	4637	0.2331 ± 0.004	2634.98 ± 99.15
3. Rodelillo	1.687	4484	0.3842 ± 0.113 (**)	2905.75 ± 221.18
4. Limache	2.203	4653	0.2053 ± 0.042	2104.52 ± 124.25
5. Pichidegua	1.682	4438	0.2502 ± 0.027	1867.72 ± 109.22
6. La Estrella	1.484	4747	0.3972 ± 0.080	2797.08 ± 206.67
7. Ovejería	1.959	4532	0.2363 ± 0.077	2097.95 ± 188.31
8. Nirivilo	1.928	4403	0.0848 ± 0.003	720.14 ± 48.54

Table 6
Values calculated for Flame Length (m) with local parameters for the eight localities.

Localities	*I* (Wm^{-} s^{-1})	*L* (m)
1. Cuesta Barriga	1975.41 ± 113.02	4.85 ± 0.32
2. San José de Maipo	2634.98 ± 99.15	5.53 ± 1.01
3. Rodelillo	2905.75 ± 221.18	5.79 ± 0.88
4. Limache	2104.52 ± 124.25	4.99 ± 0.61
5. Pichidegua	1867.72 ± 109.22	4.72 ± 0.09
6. La Estrella	2797.08 ± 206.67	5.69 ± 0.74
7. Ovejería	2097.95 ± 188.31	4.98 ± 0.46
8. Nirivilo	720.14 ± 48.54	3.05 ± 0.23

Table 7
Levels of fire intensity (FIL), Mean Severity and Vegetation Cover (%) for each of the eight localities. See text for details on the methodology.

Localities	Fire Intensity Level (FIL)	Mean Severity	Vegetation Cover (%)
1. Cuesta Barriga	III Medium	III	25–50
2. San José de Maipo	IV High	III	50–75
3. Rodelillo	III Medium	V	50–75
4. Limache	IV Medium	IV–V	>75
5. Pichidegua	V High	III	25–50
6. La Estrella	V High	IV-V	50–75
7. Ovejería	VI Very High	III-IV	50–75
8. Nirivilo	IV High	II-III	25–50

3.4. Danger condition

Based on the surveys of the non-burnt plots we characterized the danger condition for each locality as shown in Table 8. Six of the eight localities show conditions of High and Very High Danger.

4. Discussion

Our results show a way to determine fire behavior parameters based on historical evidence of fuel vegetation before the ignition process. The values found for linear propagation velocity and intensity in the eight sampling areas are extremely sensitive to local meteorological conditions and also to the precision or location of fire onset within the sampling area. For this reason, these evidences can only be considered as reference values to better understand the potential behavior of fire and the effects at different scales of affectation in this type of vegetation. However, we registered higher values of these parameters in two localities: Rodelillo (V Región) y La Estrella (VI Región). These differences may be related to variations in available fine biomass at the ground level. Castillo (2013) found similar values in experimental fires on the coastal zone in this region, with analogous vegetation. The front-line intensities found in our study are characteristic of fires with high-energy output and low residence time. These can be a consequence of low humidity contents in the fine and very fine plant material, after an extended drought in the study area. Rodríguez y Silva et al. (2010) reported similar values for the same vegetation in a rural-urban interface; in their case, severity levels were higher due to the presence of structural materials with high flammability. Ignition time depends not only on the humidity contents of the fuel material but also in their flammability. Flammability is the capacity of a material to continue burning after ignition until it is totally consumed, without further addition of caloric energy from the outside. In our case, the presence of leaves from exotic species (such as *Pinus radiata*) in the litter favors ignition, as demonstrated by Murray et al. (2013). Fire Intensity Levels estimated in our study were high in all localities (from IV to VI). This is probably the consequence of a very large load of dry and fine plant biomass combined with the high calorific contents of the shrub species present. These intensities usually result in a high level of damage, but in our case, we also observed a rapid post-fire recovery. Roldán-Zamarrón et al. (2006) found similar severity levels in Southern Spain. However, these severity levels are higher than the ones reported by Muñoz-Navarro et al. (2018) in their study of fuel models for Mediterranean vegetation.

Contrary to the predominant high FIL, severity was qualified mostly with medium values, and we estimated vegetation cover mainly at a medium level (50%) (see Table 7).

The reports on fire behavior in Mediterranean ecosystems giving detailed information on wildfire parameters are scarce, despite the abundant literature on wildfires of vegetation. Furthermore, results would depend on one hand on climate conditions and location peculiarities and in the other on the methods of analysis. All these difficult comparisons of results. Nonetheless, in comparing our results to some studies from other Mediterranean regions, we find an interesting pattern. The values of linear propagation speed (VP) are similar or even lower than ours, but our values of front-line intensity are much higher. Such is the case in De Luis et al. (2004) who report results from experimental fires in Alicante (Spain). Their VP values (from 0.66 to 1.74 m s^{-1}) are commensurate to ours, but their values of front-line intensities are much lower (from 231 to 343 kW m^{-1}s^{1}). Saglam et al. (2008) report result from experimental Mediterranean vegetation fires in the maquis from Turkey. Their VP values (from 0.38 to 7.35 m s^{-1}) are higher than ours; however, their front-line intensity values (from 45 to 1410 kW m^{-1}s^{-1}) were much lower than ours. Climatic conditions of these experiments were similar to those in our study. It is likely that these differences in the intensity of the front line are not attributable to the specific calorific value of each type of fuel, but rather in the load of fine vegetation that promotes initial ignition and later a longer residence time of the flames as the fire rises and spreads to thicker and larger plant materials. These differences have been seen in experiments carried out by Castillo (1998) when studying the caloric intensity in 250 fires under different environmental conditions in Central Chile, and at different ignition times and permanence of the flames.

They are most likely attributable to a larger medium and fine fuel load in our case, that means higher potential energy liberated in the combustion process. This warns danger respect to the potential response of new growing plant biomass, with accelerated ignition and flammability.

Table 8
Danger Parameters and Danger conditions for fire situations estimated in each of the eight localities.

Localities	Hazard Parameters				
	Fuel Load [ton ha^{-1}] [A]	Spread Potential [m hr^{-1}] [B]	Horizontal Continuity [C]	Vertical Continuity [D]	Danger Condition [E]
1. Cuesta Barriga	38	0.008147: Medium/High	Medium	Low	High
2. San José de Maipo	125	0.007603: Medium	High	High	Very High
3. Rodelillo	75	0.01266: High/Very High	Medium	High	Very High
4. Limache	45	0.008337: Medium/High	Medium	Low	High
5. Pichidegua	60	0.00771: Medium	High	Medium	High
6. La Estrella	18	0.00452: Low	Low	Low	Medium
7. Ovejería	55	0.00779: High	Medium	Medium	High
8. Nirivilo	40	0.01334: High/Very High	Medium	Low	Medium

[A] Load estimated from non-burn plots and fuel model classification according to Julio et al. (1995).
[B] Technical coefficients from Julio et al. (1995).
[C], [D] Following parameters of fuel loads from KITRAL (Julio et al. 1995).
[E] Determined using surveys from non-burnt plots.

The results presented here about the characteristics of surface linear propagation of fire suggest that these wildfires developed in a surface horizontal propagation plane, becoming three-dimensional under denser vegetation cover, as indicated by the high values of caloric intensity. It seems that the recurrence of these wildfires in the region is promoting succession towards degraded and fragmented conditions of the vegetation, which shows low tolerance to these frequent perturbations (Armesto et al. 2009).

Our study represents a meaning contribution to the knowledge of fire behavior in Mediterranean ecosystems; however, it is a reduced vision of the wildfires in Central Chile in 2016–2017. It does not include the environmental and social impacts nor the economic damages produced. This is an analysis of the physical parameters based on a limited sample of study plots in eight localities; consequently, it cannot represent all the diverse attributes of wildfires that affected an area of more than six thousand square kilometers. Technical reports post-fire qualified these events as 'megafires' and 'fire-storms' and considered 'category six' (CONAF, 2017). Furthermore, we have not addressed yet the role of the diversity of native vegetation types and exotic species in the physical properties of wildfires. After these fire events, it is urgent to implement short-term measures to recover the affected ecosystems, given the loss of vegetation cover, native species and ecosystem services. Furthermore, due to the expected droughts in the coming years as predicted by climate change studies (FAO, 2010), we should expect more frequent severe wildfires in this region (Arca et al. 2010).

Based on our results, we suggest that restoration programs concentrate on helping to maintain cohesion in these ecosystems. This requires frequent monitoring of passive restoration practices, resorting to more active physical support in areas more severely affected. Recovery efforts should aim to rapid regrowth of native plant populations.

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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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gecco.2020.e01210.

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