Science of the Total Environment 579 (2017) 1410–1418

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

A system to evaluate fire impacts from simulated fire behavior in Mediterranean areas of Central Chile

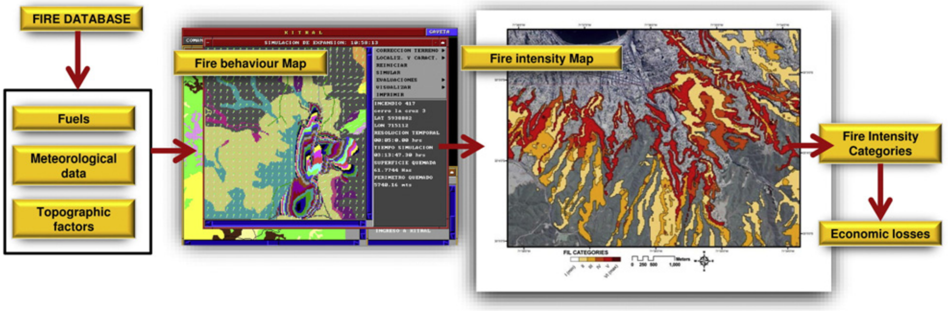
Miguel E. Castillo [a,*], Juan R. Molina [b], Francisco Rodríguez y Silva [b], Pablo García-Chevesich [c,d,e], Roberto Garfias [c]

[a] *Fire Management Laboratory, Faculty of Forest Sciences and Nature Conservation, University of Chile, P. Box 9206, Santiago, Chile*
[b] *Fire Management Laboratory, School of Agricultural and Forestry Engineering, University of Cordoba, Leonardo da Vinci Building, Rabanales Campus, 14071 Cordoba, Spain*
[c] *International Hydrology Research Group, Faculty of Forest Sciences and Nature Conservancy, University of Chile*
[d] *Department of Hydrology and Atmospheric Sciences, Department of Agricultural and Biosystems Engineering, University of Arizona, United States*
[e] *International Hydrological Programme (International Sediment Initiative and Water and Forests Program), United Nations Educational, Scientific, and Cultural Organization (UNESCO), Uruguay*

HIGHLIGHTS

- We estimated fire impacts through simulations, considering fire variables.
- We classified fire intensities.
- Fire intensity values resulted in six fire effects categories with indicators.
- We developed a preliminary assessment of wildfire impacts for Mediterranean zones.
- The study represents a useful tool to prioritize future wildfire interventions.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 16 August 2016
Received in revised form 13 November 2016
Accepted 20 November 2016
Available online 4 December 2016

Editor: Simon Pollard

Keywords:
Wildfire intensity
Wildfire simulation
Wildfire behavior

ABSTRACT

Wildfires constitute the greatest economic disruption to Mediterranean ecosystems, from a socio-economic and ecological perspective (Molina et al., 2014). This study proposes to classify fire intensity levels based on potential fire behavior in different types of Mediterranean vegetation types, using two geographical scales. The study considered >4 thousand wildfires over a period of 25 years, identifying fire behavior on each event, based on simulations using "KITRAL", a model developed in Chile in 1993 and currently used in the entire country. Fire intensity values allowed results to be classified into six fire effects categories (levels), each of them with field indicators linking energy values with damage related to burned vegetation and wildland urban interface zone. These indicators also facilitated a preliminary assessment of wildfire impact on different Mediterranean land uses and, are therefore, a useful tool to prioritize future interventions.

1. Introduction

Large forest fires constitute a worldwide problem, given the serious socio-economic and ecological impacts associated with them (Chatto and Tolhurst, 2004). There is no knowledge about the direct correlation

---

[*] Corresponding author at: University of Chile, Faculty of Forest Sciences and Nature Conservancy, Avenida Santa Rosa 11315, La Pintana, Santiago, Chile.
E-mail address: migcasti@uchile.cl (M.E. Castillo).

http://dx.doi.org/10.1016/j.scitotenv.2016.11.139
0048-9697/

between fire damages and fire intensity in Chile and, as a consequence, field inventories point out subjective evaluations. Furthermore, there is an urgent need to evaluate net changes of the value of resources, or level of depreciation, caused by wildfires (Zamora et al., 2010; Molina et al., 2011; Rodríguez y Silva et al., 2012). An economic evaluation of natural resources not only provides a tool for post-fire evaluations, but also represents an opportunity as a preventive diagnostic of potential fire damage, taking into account meteorological conditions (Chuvieco et al., 2010), and the fact that these have a direct impact on the final condition of the resources affected by wildfires.

Many studies around the world have focused on fire-related variables and modeling in Mediterranean ecosystems. Catchpole et al. (1993), for example, evaluated different vegetation-based fuel types to determine fire behavior to determine scales of intensity and effect, considering the variety of species and plant types affected by different wildfire intensities, concluding that the model used by the authors (Rothermel) needed improvements. Morvan and Dupuy (2004), on the other hand, simulated the propagation of wildfires through Mediterranean shrubs (*Quercus coccifera*) and grasses (*Brachypodium ramosum*), showing the effects of wind on heat transfer between fire front and vegetation. The authors also identified two fire-propagating models. Similarly, Vilar et al. (2016) modeled the temporal evolution of human-caused wildfires in the European Mediterranean basin (i.e. Portugal, Spain, South-France, and Italy), finding that >90% of wildfires in the region were caused by humans, with good correlations in most of the countries (except Portugal). Finally, Piñol et al. (2005) studied the relevance of fuel accumulation and meteorological variability as a control mechanism for the occurrence of large Mediterranean wildfires, by developing a simple model of vegetation dynamics and fire spread over homogeneous areas, incorporating variables such as meteorological variability, rates of fuel accumulation, number of ignitions per year, fire-fighting capacity, and prescribed burning. The authors concluded that, for a given region and considering the above variables, the most important factor to minimize the occurrence and spreading of wildfires is to decrease fuel loads (i.e. prescribe burns) rather than fighting them.

Just like in the above investigations, as well as in many other studies (e.g. Chafer et al., 2004), fire behavior-related research evaluate the effects of intensity and severity on fire development and the germination of seeding (Chappell and Agee, 1996), the survival of trees (Dickinson and Johnson, 2001), watershed processes (Doerr et al., 2006; Vega et al., 2013), and the establishment of invasive plants (Keeley, 2006b), just to name some of them. The concept of intensity and severity can be evaluated based on the effects of fire behavior in the field (Keeley, 2009). The former concept is related to the energy released during the process of combustion (normally expressed in units of temperature or radiation), considering also how long the fuel burns (Bradstock, 1995; Chafer et al., 2004). Fire severity, on the other hand, is related to the damage caused by the event in property, the hydrologic cycle, and natural resources in general, i.e. measurable effects (Chappell and Agee, 1996; Chatto and Tolhurst, 2004). Bothe intensity and severity can be measured and categorized either in the filed or through indirect methods such as satellite image analysis and remote sensing (Bobbe et al., 2004; Chuvieco et al., 2006).

In this study, intensity values have been identified spatially within the study area, for each type of burned vegetation. Even though there are studies focusing on this issue within the available literature (Julio, 2007), references for forestry-related developing countries continue to be scarce. Being often necessary to adopt methods and results on different environments and scenarios. For this particular study, the authors propose an affecting scale applied to the simulation of wildfire propagation in wildland-human interface, which is a progressively common situation in countries with worldfires. Thus, this investigation intends to study the magnitude of the energy release as a result of wildfire spreading, checking whether it is possible to zone the different affecting levels, based on a case study in Central Chile. As indicated in the Methods, such checking process is based on the development of algorithms specifically adapted to different types of wildfires occurred in the country, as well as other areas around the world located under Mediterranean climates. Additionally, this study was justified by the need to have better technical references for decision makers in terms of preventing and combat wildfires. The closes references on fire behavior in Mediterranean forests are represented by Rothermel (1972) and Albini (1976), who proposed mathematical expressions to relate heat intensity with fire spreading models, under different wind and topographic scenarios. For the particular case of this manuscript, calculations were made using the previously mentioned KITRAL model, statistically validated by Castillo (1998) and widely used in Chilean wildfires (Julio et al., 2012).

Fire behavior is a key aspect in the progression of wildfires and, consequently, the ultimate level of damage according to the vulnerability of vegetation. Conceptually, this is expressed as the interrelationship between meteorological and topographical variables, fuels, and chemical, physical, and mechanical processes derived from fire progression (Byram, 1957; Finney, 1998; Julio, 2007). Fire behavior simulators such as Behave Plus (Andrews and Queen, 2001), Farsite (Finney, 1998), FlamMap (Finney, 2007), Visual Cardin (Rodríguez y Silva et al., 2010) or KITRAL (Julio et al., 1997) consider these variables when calculating fire behavior on the basis of fire rate spread, flame length, fire-line intensity, and heat per unit of surface area (Cheney, 1978). Fire behavior simulation has great importance, since it provides valuable support for decision-making processes on various fire management procedures, especially in terms of resource allocation and the definition of suppression strategies and tactics (Julio et al., 1997). Consideration of fire behavior and potential progression makes it possible to plan the necessary approaches and measures for wildfire suppression, determining an effective plan of attack (Albini, 1976; Rothermel, 1972). Wildfire spreading rate is defined as the rate in which wildfires increase or the time wildfires take to reach from one geographical point from another, generally expressed in m s^{-1} or m min^{-1}. Thus, spreading rate is the result of a complex association of variables, influenced by the heat flux absorbed by fuels, density of surface fuels, pre-ignition temperatures, and vertical gradient of intensity (Frandsen, 1971). Rothermel (1972) designed an empirical model for lineal fire spreading rate, based on the principle of energy conservation in one unit of fuel, immediately ahead of a wildfire advancing front extended across a layer of homogenous vegetation. Such model has been incorporated into numerous wildfire behavior simulators, such as Behave, Farsite, FlamMap or Visual Cardin (Finney, 1998, 2007; Andrews and Queen, 2001; Rodríguez y Silva et al., 2010). In this study, we chose this model instead of Behave, Farsite, or FlamMap, because of the strong concordance that present field parameters' mathematical models, especially on heat release, flame length, and burned area (and its perimeter), being all of them relevant variables for the calculation of wildfire intensities. Spreading rate calculation was undertaken using KITRAL model (Julio et al., 1997), based on the type of fuel, moisture content of fine and dead fuel material, wind speed, and land topography.

Consequently, this study suggests a process to classify field post-fire severity, resulting from mathematical relationships among calorific power of affected fuels, average spreading of fire, average flame length, and fuel load present on each evaluated area, considering as a reference point an area of Valparaíso Region in Central Chile. The second objective of this evaluation was to establish initial references for the appraisal of direct damages, using the references of economic losses proposed and calculated in the SEVEIF project (Rodríguez y Silva et al., 2010) for the same area of study.

2. Methods

2.1. Study area

The study took placed in Valparaíso Province (Valparaiso Region of Chile), considering an area of 176,000 ha. The selected zone comprises the greatest density of wildfires in Chile (Castillo, 2013). As an example, during red flag conditions (summer), an average of 15 wildfires per km^2 commonly occur in the region, a number that has been increasing in the past decade, especially in the urban-wildland interface (Rodríguez y Silva et al., 2010). To validate the results, a 29,378-hectare quadrant was defined within the study area, corresponding to the outskirts of the city of Quilpué (Fig. 1).

Local climate is characterized by the presence of mists, which move inland to form a temperate zone with temperatures ranging between 17 and 25 °C. Mean annual precipitation is 370 mm. As described in CONAF-CONAMA-BIRF (1999), native vegetation in the Valparaíso and Viña del Mar counties is mainly Mediterranean woodlands, shrubs, and bushes, with species adapted to repeated cycles of forest fires during warm periods. The study area included important areas of wildland-urban interface, which are of particular interest for the classification of fuel and potential fire behavior because these are vital factors for risk assessments due to their position in areas with extreme gradients, high combustibility, and potential fire propagation.

2.2. Methodological process

Historical dataset of forest fires, including meteorological, topographical, and fuel modeling variables, were used to simulate fire behavior. A 25-year period of analysis was considered, with the first 10 years used for construction of the model (1987–1997) and the subsequent 15 years (1998–2012) for validating the model (Fig. 2). However, it should be noted that the spatial resolution for both periods was different; in the first period, the information was generated on a scale of 1:50,000 because such dataset was generated only for the city of Quilpué's quadrant. On the second period (validation), the scale was 1:250,000 because the study zone corresponds to the SEVEIF project (Rodríguez y Silva et al., 2010). A total of 4116 wildfires were considered and a density of 109.07 fires per annum $*$ 100 km^2 (Table 1), for the validation period.

Modeling fire behavior for documented wildfires required geo-referenced information about meteorology, topography, and vegetation (Table 2). Using this information, slope factor, fuel moisture content factor, and fuel model factor were obtained (Julio et al., 1997) to further simulate wildfire spreading rate, flame length, and heat intensity using the KITRAL model (Castillo, 1998).

Mathematical equations from the KITRAL model were used. A mathematical equation includes the interaction between fuel model, fuel moisture, and environmental variables, such as topography (slope) and wind (velocity and direction), in the form of:

$$Vp = (Fmc) \times (Fch)(Fp + Fv) \tag{1}$$

where *Vp* is the fire's spreading rate (m s^{-1}), *Fmc* is the fuel model factor (classified into 34 categories, as described in Julio (2007)), *Fch* is the fuel humidity factor, whose values range from 0.2 (maximum humidity) to 51.46 (minimum humidity) (Castillo, 2013), *Fp* is the slope factor, whose values range from 0.001 (-90% with minimum spread) to 4.199 ($>90\%$ with maximum spread), and *Fv* is the wind factor, whose values range from 0 (for no wind) to 9.34 for wind speeds >25 m h^{-1}.

Wildfire behavior also requires analysis of the behavior of energy (flame length and fire-line intensity). *Flame length* is defined as the distance between the base and the tip of the flame, whereas *fire-line intensity* as the rate of energy released per unit of time and unit of fire front length's advance. Fire-line intensity depends on the availability of fuel to be burnt, fuel's calorific power, and fire spreading rate (Eq. (2)). Flame length is also related directly to calorific intensity (Eq. (3)) (Albini, 1976), affecting significantly the dynamics of the convection column. Expressions for calculating fire-line

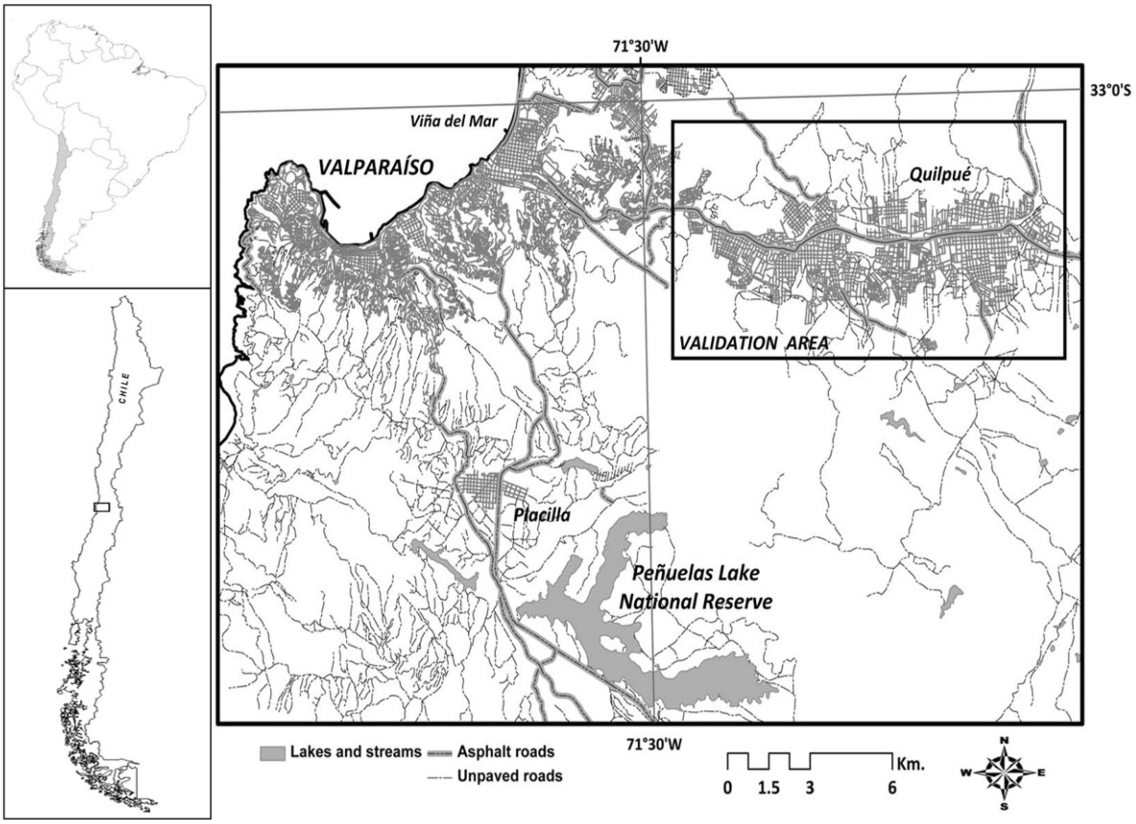


Fig. 1. Study area (Valparaiso Region of Chile), showing the area where the classification was validated (top-right corner).

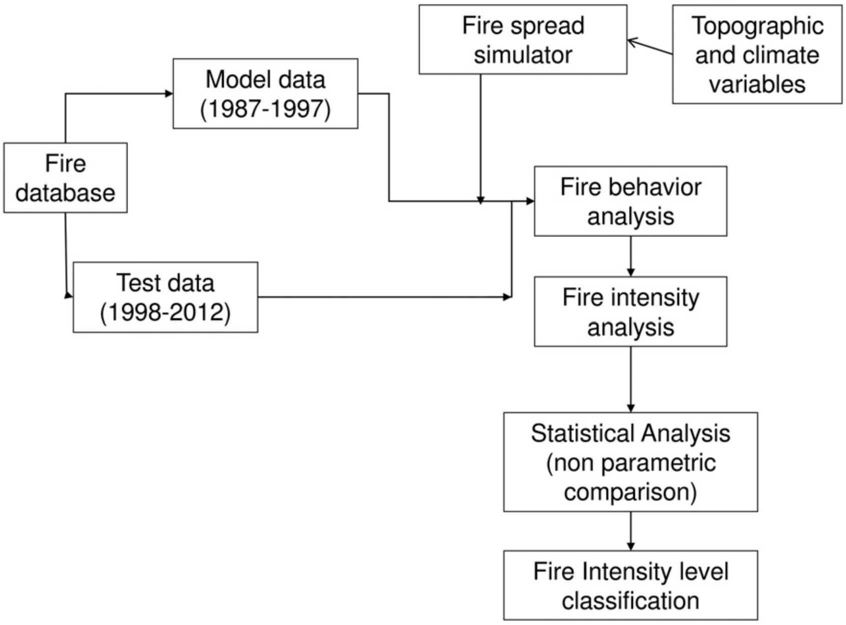


Fig. 2. Scheme used for the study.

intensity are endorsed by the statistical revision of KITRAL, expressions undertaken by Castillo (1998).

$$I = H \times W \times Vp \text{ (Julio et al., 1995)} \tag{2}$$

$$L = 0.1477 \times I^{0.46} \text{ (Julio et al., 1995; Castillo, 1998)} \tag{3}$$

where I is fire-line intensity (kcal m^{-1} s^{-1}), H is the fuel calorific power (expressed as kcal kg^{-1}), W is the quantity of fuel available in the fire path (kcal m^{-2}), which depends on the fuel type, fuel moisture, and fire spread (m s^{-1}) calculated according to Eq. 1, and L is the flame length (m).

This model's mathematical equations (Eqs. (1), (2) (Julio et al., 1995), and (3)) were applied to 4116 wildfires, indicating fire behavior variables (fire spreading, flame length, and fire intensity) for a 25 × 25 m grid size. Fuel models included in this study are related to a specific Chilean classification that has been used for 20 years (Castillo, 2013), which is based on fuel moisture, fuel load, horizontal and vertical fuel continuity, fuel depth, and canopy closure, all of the above to include different land uses: shrublands, forest plantations, native forests, and wildland urban interface.

Table 1
Wildfire occurrence within the study area over time (1998–2012 period).

Year	Number of fires	Burnt area (ha)	Fire density (no./year ∗ 100 km^2)
1998	293	127	131.90
1999	282	340	126.95
2000	303	94	136.41
2001	312	137	140.46
2002	372	162	167.47
2003	315	922	141.81
2004	202	1955	90.94
2005	189	212	85.09
2006	251	251	113.00
2007	227	247	102.19
2008	212	406	95.44
2009	277	315	77.02
2010	301	381	67.81
2011	331	274	83.17
2012	249	394	76.45
Average	274.40 ± 50.18	284.26 ± 207.22	109.07 ± 30.39

The process for organizing plots of land and acquiring data was the following: 40 rectangular land plots of 200 m^2 in area, based on the methodology used by Julio et al. (2012) to evaluate field damage for Mediterranean ecosystems between the summers of 2011 and 2012 in the Valparaíso Region. Wildfires with a surface area greater than (or equal to) 1 ha were considered in order to give a detailed description of the different degrees of fire effects. The percent effect was established by counting live branches and fire-killed branches, in all layers of vegetation and for all plant types (shrubs, and trees). Regeneration was measured via the proportion of green and burnt areas to establish cover values for each plot. Soil conditions were evaluated with 15-cm-deep profile analyses (Castillo, 2013) to check for leaf litter, roots, and parent material damage.

The results of the fire behavior variables were classified into categories or fire intensity levels (FIL) according to Jenks' classification method (Jenks, 1963). This method seeks to reduce the variance within classes, maximizing the variance between levels. The results of Molina et al. (2014) were used as a reference for associating simulation results for each fire event. These results classify the level of fire damage in terms of flame length, defining six categories of deterioration rates. The definition of each category (upper and lower limits) was undertaken using the Jenks' algorithm application (Jenks, 1963), also tested by Castillo (2013) to characterize post-fire intensity on different Mediterranean ecosystems. The classification took into account the sample's standard deviation and tested the area for all parameters of fire behavior considered in this experiment. The non-parametric Wilcoxon test for paired data was used for fire propagation simulation, with statistical software's support and considering two samples: records generated by the SEVEIF project (1987–1997) (Rodríguez y Silva et al., 2010) and records generated for the validating period (1998–2012). The Wilcoxon test made possible to establish whether there were significant differences between the population of data ($p < 0.05$) in variables such as flame length, fire spreading rate, intensity, and FIL, between fires on the previously mentioned scales. If there were no significant differences between both samples, an evaluation of levels of effect and socio-economic impacts resulting from the fire could be carried out in combination.

The result of the above process was the creation of a GIS data matrix to run an analysis of variance (ANOVA), with the purpose of identifying significant differences ($p < 0.05$) in fire behavior parameters between the different vegetation types affected by wildfires and the two geographical scales proposed in this study.

Table 2
Geographic layers and criteria used for fire behavior analysis.

Variable (see mathematical expressions[a])	Database	Units
Fire occurrence	Forest fire database (1987–2012)	Number of fires per year
Slope factor	Digital elevation model (25 × 25 m)	Percent (−90% to +90%).
Humidity content factor	Calculation of average meteorological variables for the study area from temperature and relative humidity data	Values between 0.52 and 51.46
Wind factor	Calculation of average meteorological variables for the study area, considering information for wind speed and direction	Values between 0 and 25 m h^{-1}
Fuel model factor	Fuel map from the SEVEIF project (Rodríguez y Silva et al., 2010)	34 categories, with fire spreading data (m h^{-1})
Classification of fire intensity level (FIL), based on flame length (L)	Scale of intensity for different flame lengths in Mediterranean ecosystems (Molina et al., 2014)	The following categories were used: L 0–2 m: FIL = I L 2–3 m: FIL = II L 3–6 m: FIL = III L 6–9 m: FIL = IV L 9–12 m: FIL = V $L > 12$ m: FIL = VI

[a] Mathematical expressions in this table are expressed in Eqs. (1)–(3).

3. Results

The different simulations indicated average fire spreading rate, with values that ranged between 0.21 m s^{-1} in native woodlands, to 0.93 m s^{-1} in grasslands. Flame lengths ranged between 1.88 m in grasslands to 34.04 m in interface areas (Table 3). The maximum and minimum values of fire-line intensity were found in Rodríguez y Silva et al. (2010) and Castillo (2013) for this type vegetation and study zone. A geographic record of these results (Fig. 3) shows the scale of effect of six levels of intensity. When comparing both geographical scales, the classification of fire behavior parameters (fire spreading rate, flame length, and fire-line intensity) presented no obvious differences. In general, indicators showed slightly higher values for the 1:50,000 scale. The Wilcoxon test did not indicate any significant differences between flame length ($p = 0.249$), fire rate spread ($p = 0.833$), and fire intensity value ($p = 0.338$), for both work scales (Table 4).

The above means that the level of data entry detail (in this case, the information collated from all wildfires) allows reliable results to be generated for fire behavior, independently of the used geographical scale, also bearing in mind that the algorithm has been validated by successive software updates (Castillo, 1998, 2013). These records were previously detailed according to the type of vegetation affected, with their respective fire behavior parameters, drawn from simulations that now consider average values and their respective standard deviations in an ANOVA. The analysis of 4116 fires by an ANOVA indicates that, for a critical p value of 0.087 ($\alpha = 0.05$), there were no significant differences between the parameters of fire propagation, with these differences (Tukey with a critical p value of 0.021; $\alpha = 0.05$) being demonstrated for parameters of intensity and flame length, as was expected for the specific characteristics of the fuels involved in the simulation process.

Table 5 shows the relationship between the different heat intensity levels developed in the presence of six groups of fuel models, to whom heat intensity, fire spreading rate, and flame length were calculated. Heat intensity values calculated for plantations had an average available fuel load of 35–55 t ha^{-1}, approximately, a data corroborated by Pérez (2006), who analyzed fuel loads below the canopy in pine and eucalyptus plantations subject to forestry treatments in Mediterranean environments of southern Chile (Castillo, 2013). These values differ from the values found in native woodland, where fuel load exceeds 150 t ha^{-1} (Julio et al., 2012; Castillo, 2013), thus giving a greater energy potential due to the combustion of species with greater calorific power, as well as horizontal and vertical structures that are denser than in plantations, where thinning and pruning occurs. These differences are evident in the statistical separation of groups. A similar situation occurs in the shrub-type, where available fuel values fluctuate between 112.5 and 180 t ha^{-1} (Castillo, 2013). The characteristics of highly flammable materials in homes located within the wildland-urban interface and their respective calorific power values (studied in Rodríguez y Silva et al., 2010), allowed another combustion risk group to be identified, giving much greater field intensity results than for the other fuel model groups.

Given that there may be no direct links between fire intensity and fire severity (since the latter depends on residence time based on fire spread and fuel availability), severity level is based on field indicators. Fire behavior performs a stakeholder analysis to identify fire damages based on fire severity. Morgan et al. (2014)'s approach carried out severity evaluations using remote sensing at landscape level (Heward et al., 2013). In this sense, differences between fire intensity and fire severity should be considered to field inventories (Keeley, 2009). Field indicators enable the direct impact of wildfires on each type of vegetation to be easily evaluated. Field indicators (Table 6) include parameters for both, the condition of different vegetation layers (aerial, surface, vertical, and underground) and the soil, as well as the proportion of available fuel and post-fire regeneration after 6 weeks.

4. Discussion

By incorporating interface areas and the use of historic records over 25 years into the land analysis, a great variability of meteorological and fire spreading rate scenarios can be included in the fire behavior

Table 3
Fire intensity levels (FIL), based on two spatial resolutions, considering data registry between 1987 and 1997 (1:50,000) and between 1998 and 2012 (1:250,000).

FIL	Scale 1:50,000 (22,000 ha)						Scale 1:250,000 (176,000 ha)					
	L (m)		Vp (m s^{-1})		I (kcal m^{-1} s^{-1})		L (m)		Vp (m s^{-1})		I (kcal m^{-1} s^{-1})	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
I	0.30	1.88	0.01	0.17	0.00	171.07	0.05	1.77	0.06	0.22	0.01	158.41
II	1.88	3.07	0. 17	0.21	171.07	444.52	1.77	3.59	0.22	0.29	158.41	506.31
III	3.07	5.49	0.21	0.41	444,52	1077.04	3.59	5.72	0.29	0.44	506.31	1022.98
IV	5.49	7.12	0.41	0.60	1077.04	1812.37	5.72	7.85	0.44	0.58	1022.98	2070.87
V	7.12	12.01	0.60	2.67	1812.37	14,331.01	7.85	12.45	0.58	3.45	2070.87	16,770.00
VI	12.01	34.04	2.67	6.61	14,331.01	70,000.00	12.45	30.03	3.45	5.70	16,770.00	62,428.00

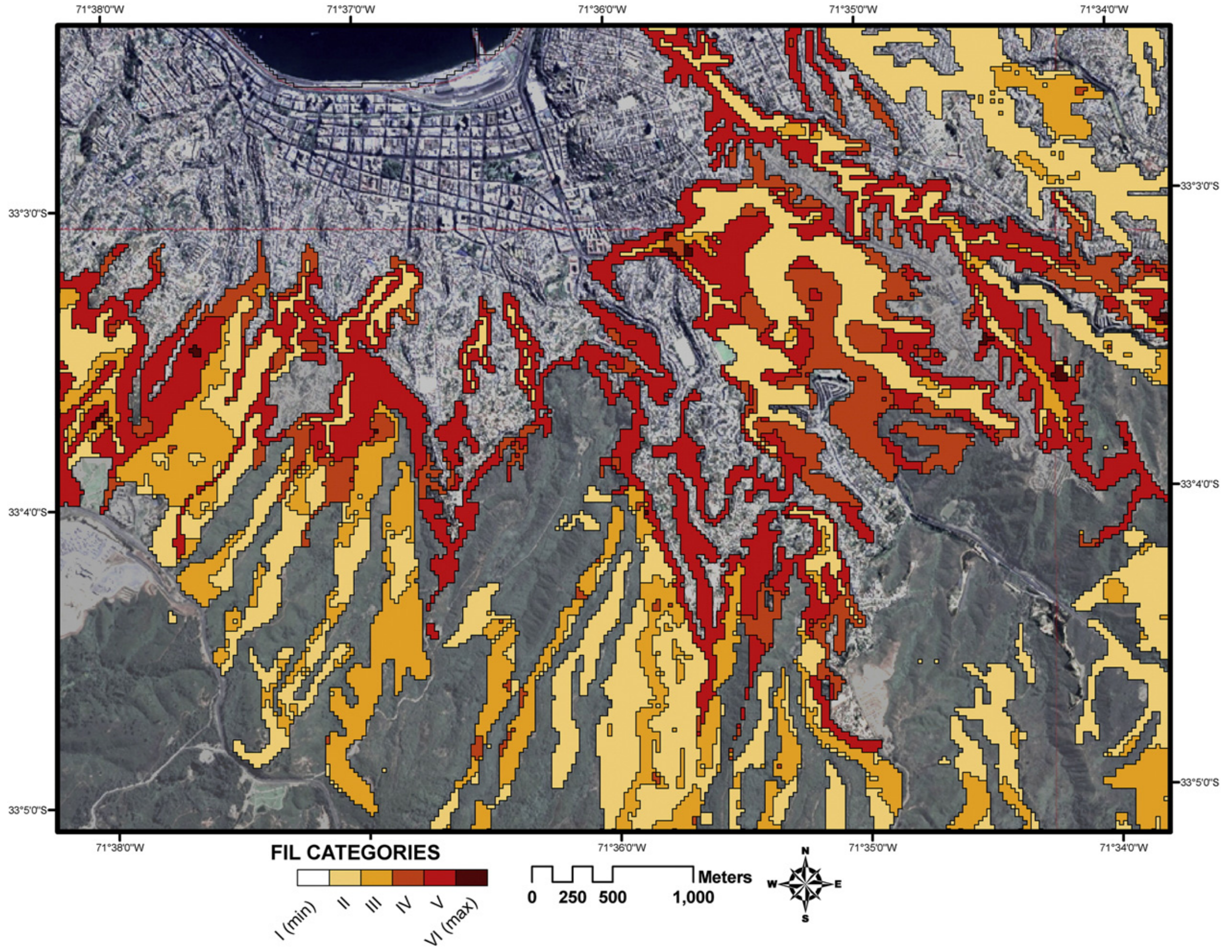


Fig. 3. Fire intensity levels (FIL) based on forest fire simulation using KITRAL, for the validating area (Valparaíso). The greatest fire intensity values were found in the Wildland-urban interface zones, where values reached around 62,000 kcal m^{-1} s^{-1}. Classification was based on flame length values from fire behavior analysis.

Table 4

Wilcoxon statistical test for significant differences in flame length, fire spreading rate, and fire-line advance, between the two spatial resolutions used (1:50,000 and 1:250,000).

Differences between scales			
Wilcoxon	L^{a}	Vp^{a}	I^{a}
Z_o	1.153	0.211	−1.153
Z_c	1.282	1.282	1.282
p	0.249	0.833	0.241

Z_o = observed value; Z_c = critical value; p = bilateral p value.

[a] $\alpha = 0.02$. Bilateral test.

analysis. From the ecological perspective of vegetation affected by fire and the field indicators described in Table 6, fire intensity is usually evaluated from two viewpoints: via calculation of temperatures generated by the passage of fire over the soil (Alexander, 1982) or by evaluating fire impacts on the ecosystem's structure and dynamics (Bradstock, 1995). This former approach compares different situations of burnt soils in southeast Australia, in relation to the response of leguminous plants, assigning response and survival percent for the area affected and recovered, as expressed in the scales of effect (Table 6). In general, there was a direct link between FIL and the interface areas (Fig. 3), agreeing with similar studies (Castillo, 2013), due to the presence of steep and very deep areas with scrubland and buildings made out of highly flammable material (Rodríguez y Silva et al., 2010). The interface zones in the study area were directly associated with greater amounts of released energy, compared to plant matter (Table 5), due to the combustion of materials with higher flammability than the surrounding plant species, agreeing with other studies (Hammer et al.,

Table 5

Fire intensity values, flame length, and fire spreading rate for different types of plant fuels in the area of Valparaíso, Central Chile.

Vegetation	Heat intensity (kcal m^{-1} s^{-1})	Fire spreading rate (ms^{-1})	Flame length (m)	Intensity level[3]
Pine plantations[1]	626.21 ± 112.22^{a}	0.31 ± 0.04^{a}	4.23 ± 1.32^{a}	III
Eucalyptus plantations[2]	1821.52 ± 51.05	0.50 ± 0.11^{a}	5.51 ± 2.22^{a}	V
Native woodland	1084.15 ± 72.11^{b}	0.27 ± 0.0^{a}	3.77 ± 0.16^{a}	IV
Shrubs	388.94 ± 43.33^{b}	0.31 ± 0.21^{a}	2.41 ± 0.15^{a}	II
Mixed grasslands	135.14 ± 74.05^{c}	0.93 ± 0.02^{a}	1.88 ± 0.21^{b}	I
Interface areas	$12{,}155.01 \pm 1634.04^{d}$	0.67 ± 0.16^{a}	27.72 ± 5.36^{c}	VI

Superscript letters indicate significance at $p > 0.05$.

[1] *Pinus radiata* (D. Don), with forestry management, aged 4–11 years.

[2] *Eucalyptus globulus* (Labill), without forestry management, aged 8–18 years.

[3] Description of ranges proposed by Molina et al. (2014) and explained in Table 2.

Table 6
Severity field indicators for Mediterranean vegetation affected by wildfires, considering fire behavior variables (Keeley, 2006a; Julio et al., 2012). Intensity levels (I to VI) were classified in line with heat fire intensity (kcal m^{-1} s^{-1}). Values are based on a test area of 200 m^2 (Julio et al., 2012).

Type of fire	I (0–171.07) Surface one-dimensional	II (171.07–506.31) Surface bidimensional	III (506.31–1077.04) Tridimensional	IV (1077.04–2070.87) Tridimensional	V (2070.87–16,770.00) Tridimensional	VI (16,770.00–62,428.00) Tridimensional
Fire propagation						
Aerial layer	Not apparent	Bursts of fire. Minimal damage to crowns, <10%	Damage concentrated in sectors, 11–20%	Irregular damage, 20%–50%	Extensive damage. >50%. Enclaves of live vegetation.	Total damage (100%)
Surface layer	Partial combustion, <10%	Partial combustion, 11–25%	Extensive combustion, 25% - 75%.	Extensive combustion, 75%–90%	Total combustion. >90%	Total combustion. 100%
Vertical layer	Without apparent damage	Superficial combustion of branches and stems	Superficial combustion of stems and total combustion of branches	Combustion with cracks in stems and branches	Combustion, cracks and ruptures in stems and branches	Ruptures and total combustion
Underground layer	0.5–1.0 cm of soil with thin roots partially burnt	0.5–2.0 cm of soil with thin and thick roots partially burnt	0.5–3.0 cm of soil with burnt roots. Soil with lots of ash and fragmentation	0.5–3.0 cm of soil with total root destruction. Traces of charred soil	0.5–3.0 cm of soil with total root destruction. Partially Charred soil	0.5–3.0 cm of soil with total root destruction. Totally charred soil
Proportion of affected vegetation according to layer						
Aerial	<10%	10–25%	25–40%	40–75%	75–90%	>90%
Surface	5–15%	15–35%	35–50%	50–75%	75–90%	>90%
Underground	Not apparent	1–10%	10–35%	35–50%	50–75%	50–75%
Proportion of total fuel burnt	< 5%	6–15%	15–50%	50–70%	70–90%	90–100%
Initial post-fire regeneration[a]	Not apparent	25% presence in relation to burnt plot area (200 m^2), herbaceous and shrub layers	25–70% presence in relation to burnt plot area (200 m^2), herbaceous and shrub layers	Moderate regeneration (30–50%) in herbaceous layer; >70% in shrub layer	Scant regeneration (<15%) in all vegetal layers	Null
Effects on soil	Without apparent damage.	Apparent damage 0.5–1.0 cm.	Damage deeper than 1.0 cm into the soil. Superficial cracks.	Charring up to 2.0 cm of soil. Deep cracks. Exposed roots and stones.	Charring deeper than 2.0 cm into the soil. Moderate cracks. Exposed roots and stones.	Charring deeper than 2.0 cm into the soil. Deep cracks. Exposed roots and stones.

[a] Regeneration evaluation period: up to 6 weeks, using the records from Julio et al. (2014) for tracking the recovery of plant landscapes affected by fire in the same study zone.

2007; Mell et al., 2010; Weise and Wotton, 2010; Suzuki et al., 2012; Chas-Amil et al., 2013) where the effect of fire on different types of building materials for homes, home densities, and the location of them within areas with high risk for forest fires is assessed. Evaluating fire impacts is a complicated process, generally based on satellite imagery and supported by indirect field inventory methods to extrapolate results into the whole area under study (Brewer et al., 2005; Cocke et al., 2005; Molina et al., 2014). Studies showing direct damage from fire propagation are normally concentrated in the final quantification of losses, according to the degree of fire effects measured directly in the field (Chatto and Tolhurst, 2004). Thus, such an evaluation must be supported directly by experts who must characterize damage intensity for each type of fuel (Vega et al., 2013). If average economic value for each land use in the study zone (average information obtained from the SEVEIF project, Rodríguez y Silva et al., 2010) was known, economic appraisal algorithms developed for plantations and native woodlands of Chile by Castillo (2013) could be complemented. The value obtained from the SEVEIF project includes the appraisal of tangible and intangible (e.g. scenic beauty, biodiversity, or protection against soil erosion) resources.

The great diversity of intensities present in a forest fire is normal in Mediterranean landscapes (González-Pelayo et al., 2006), corroborated by Keeley et al. (2005 and also Keeley, 2006a) in studies on the multitemporal effects of fire in Mediterranean chaparral landscapes, which show scales of effect based on fire intensity levels. In terms of the usefulness of intensity scales in economic evaluations, field indicators can directly support the evaluation of the net-value change of the resource (NVC). The difficulty imposed in determining NVC in the field leads to the use of *indirect techniques*. Accordingly, economic evaluations supported by the identification of FIL has been used for other appraisal-related studies (Rodríguez y Silva and González-Cabán, 2010; Rodríguez y Silva et al., 2012). The use of depreciation intervals for each FIL responds to the prerequisite of clarity and dynamism required by forest managers to carry out and test appraisals in the field (Zamora et al., 2010; Molina et al., 2011). Depreciation intervals were established based on records from the SEVEIF project and from Castillo (2013). Whilst values above 4000 kcal m^{-1} s^{-1} (with flame lengths >7 m and associated with three-dimensional fires) cause total damage to bush vegetation comprising scrub and native woodland, the total combustion of pasture reaches around 200 kcal m^{-1} s^{-1}. The highest values are concentrated in mixed materials with high flammability, associated with wooden constructions and the high combustion present in eucalyptus plantations, usually exceeding 700 kcal m^{-1} s^{-1}. These records aloud for the establishment of a direct relationship between each type of flammable plant cover and also the interface zones (homes made of different types of materials) and FIL category. In doing so, it is possible to obtain the actual losses caused by wildfires. The intensity level matrix (Table 6), with the help of GIS packages, allows for a quick and easy evaluation of the potential or actual economic impact of a fire, hence constitutes an excellent support tool in the decision-making process for restoration, as well as land management.

5. Conclusions

The inclusion of the amount of energy released in the combustion process, brought into an evaluation scale, allows for the identification of different fire intensity levels. In this sense, our results point out the impact of different environmental variables, fuel model characteristics, and fire spread conditions for resources affectation. Results are fully representative for the wooded and scrubland region in Mediterranean

Chile, since they consider a wide variety of vegetation type, climate, and topography conditions, which have a direct bearing on the characteristics of fire propagation. Using computer-based simulations and studying records of more than four thousand wildfires, it was possible to define evaluation scales that support field severity characterization.

This fire intensity proposal and its relationship to potential impacts may also be employed as a decision-making tool in a preventive context, by incorporating it into the analyses of risk and loss potentials from forestry agencies and authorities. The methodological process is not localized and thus may be replicated in other countries, if entry data is updated and validated in the field. All of the above requires information for meteorological and topographical variables, as well as tree, shrub, and herbaceous vegetation types, which may also be replicated by other forest fire simulations, since they are able to characterize the fire spread variables expressed here. References derived from fire behavior modeling in wildland-urban interface areas are of particular relevance, due to the constant increase of these types of fires in other parts of the world, especially in countries with Mediterranean climates.

Acknowledgements

The authors of this study would like to express their gratitude to the "application and adaptation of the SEVEIF model for the socio-economic evaluation of the impacts of forest fires in Valparaíso, Chile" (A/017536/08), funded by the Spanish Agency for International Cooperation and Development (AECID) – Program of Inter-University Cooperation and Scientific Research between Spain and Latin America, undertaken by the University of Cordoba's Department of Forest Engineering and the University of Chile's Faculty of Forestry Science and Nature Conservancy. Moreover, special recognition is given to the National Forestry Corporation's Unit of Forestry Management, V Region of Chile.

References

Albini, F.A., 1976. Spot Distances from Burning Trees. A Prediction Model. USDA For. Serv. (Gen. Techn.Rep.INT-56, 73 p).

Alexander, M.E., 1982. Calculating and interpreting forest fire intensities. Can. J. Bot. 60, 349–357.

Andrews, P.L., Queen, L.P., 2001. Fire modelling and information system technology. Int. J. Wildland Fire 10, 343–352.

Bobbe, T., Finco, M.V., Quayle, B., Lannom, K., Sohlberg, R., Parsons, A., 2004. Field Measurements for the Training and Validation of Burn Severity Maps from Spaceborne, remotely Sensed Imagery. Joint Fire Science Program, Boise, ID.

Bradstock, R.A., 1995. Soil temperatures during experimental bushfires in relation to fire intensity: consequences for legume germination and fire management in south-eastern Australia. J. Appl. Ecol. 32:76–84. http://dx.doi.org/10.2307/2404417.

Brewer, K.C., Winne, J.C., Redmond, R.L., Opitz, D.W., Mangrich, M.V., 2005. Classifying and mapping wildfire severity: a comparison of methods. Photogramm. Eng. Remote. Sens. 7, 1311–1320.

Byram, G.M., 1957. Some principles of combustion and their significance in forest fire behavior. For. Fire Control Notes 18 (2), 47–57.

Castillo, M.E., 1998. Método de Validación para el Simulador de Incendios Forestales del Sistema Kitral. Memoria de Título. Ingeniería ForestalUniversidad de Chile (123p).

Castillo, M.E., 2013. Integración de Variables y Criterios Territoriales Como Apoyo a la Protección Contra Incendios Forestales. Área Piloto: Valparaíso – Chile Central. Tesis Doctoral. ETSIAM. Escuela Técnica Superior de Ingenieros Agrónomos y de Montes, Córdoba – España (247p).

Catchpole, E.A., Catchpole, W.R., Rothermel, R.C., 1993. Fire behavior experiments in mixed fuel complexes. Int. J. Wildland Fire 3:45–57. http://dx.doi.org/10.1071/WF9930045.

Chafer, C.J., Noonan, M., Mcnaught, E., 2004. The post-fire measurement of fi re severity and intensity in the Christmas 2001 Sydney wildfires. Int. J. Wildland Fire 13: 227–240. http://dx.doi.org/10.1071/WF03041.

Chappell, C.B., Agee, J.K., 1996. Fire severity and tree seedling establishment in *Abies magnifica* forests, Southern Cascades, Oregon. Ecol. Appl. 6:628–640. http://dx.doi.org/10.2307/2269397.

Chas-Amil, M.L., Touza, J., García-Martínez, E., 2013. Forest fires in the wildland-urban interface: a spatial analysis of forest fragmentation and human impacts. Appl. Geogr. 43 (2013), 127–137.

Chatto, K., Tolhurst, K.G., 2004. A Review of the Relationship Between Fireline Intensity and the Ecological and Economic Effects of Fire, and Methods Currently Used to Collect Fire Data. Department of Sustainability and Environment, Fire Management Branch, Melbourne Research Report No. 67.

Cheney, N.P., 1978. Predicting fire behavior with danger tables. Aust. For. 32 (2), 71–79.

Chuvieco, E., Riano, D., Danson, F.M., Martin, P., 2006. Use of a radiative transfer model to simulate the post-fire spectral response to burn severity. J. Geophys. Res. 111: G04S09. http://dx.doi.org/10.1029/2005JG000143.

Chuvieco, E., Aguado, I., Yebra, M., Nieto, H., Salas, J., Martín, M.P., Vilar, L., Martínez, J., Martín, S., Ibarra, P., de la Riva, J., Baeza, J., Rodríguez, F., Molina, J.R., Herrera, M.A., Zamora, R., 2010. Development of a framework for fire risk assessment using remote sensing and geographic information system technologies. Ecol. Model. 221:46–58. http://dx.doi.org/10.1016/j.ecolmodel.2008.11.017.

Cocke, A.E., Fule, P.Z., Crouse, J.E., 2005. Comparison of burn severity assessments using differenced normalized burn ratio and ground data. Int. J. Wildland Fire 14: 189–198. http://dx.doi.org/10.1071/WF04010.

CONAF-CONAMA-BIRF, 1999. Catastro y Evaluación de Recursos Vegetacionales Nativos de Chile – Informe Regional V Región. Contempo Gráfica, Santiago (102 p).

Dickinson, M.B., Johnson, E.A., Miyanishi, K., 2001. Fire effects on trees. In: Johnson, E.A. (Ed.), Forest Fires: Behavior and Ecological Effects. Academic Press, San Francisco, CA, pp. 477–525.

Doerr, S.H., Shakesby, R.A., Blake, W.H., Chafer, C.J., Humphreys, G.S., Wallbrink, P.J., 2006. Effects of differing wildfire severities on soil wettability and implications for hydrological response. J. Hydrol. 319:295–311. http://dx.doi.org/10.1016/J.JHYDROL.2005.06.038.

Finney, M.A., 1998. FARSITE: fire Area Simulator-model development and evaluation. USDA For Serv Res (Pap RMRS-RP-4).

Finney, M.A., 2007. A computacional method for optimizing fuel treatment locations. Int. J. Wildland Fire 16, 702–711.

Frandsen, W.H., 1971. Fire spread through porous fuels from the conservation of energy. Combust. Flame 16, 9–16.

González-Pelayo, O., Andreu, V., Campo, J., Gimeno-García, E., Rubio, J.L., 2006. Hydrological properties of a Mediterranean soil burned with different fire intensities. Catena 68:186–193. http://dx.doi.org/10.1016/J.CATENA. 2006.04.006.

Hammer, R.B., Radeloff, V.C., Fried, J.S., Stewart, S.I., 2007. Wildland–urban interface housing growth during the 1990s in California, Oregon, and Washington. Int. J. Wildland Fire 16, 255–265.

Heward, H., Smith, A.M., Roy, D.P., Tinkham, W.T., Hoffman, C.M., Morgan, P., Lannom, K.O., 2013. Is burn severity related to fire intensity? Observations from landscape scale remote sensing. Int. J. Wildland Fire 22, 910–918.

Jenks, G.F., 1963. Generalization in statistical mapping. Ann. Assoc. Am. Geogr. 53, 15–26.

Julio, G.H., 2007. Formulación de Lineamientos Políticos y Estratégicos para la Protección Contra Incendios Forestales en Chile. Tesis Doctoral. Universidad de Córdoba, España (341 p).

Julio, G., Castillo, E., Pedernera, P., 1995. Modelación de combustible. Actas de Taller Internacional sobre Prognosis y Gestión en Control de Incendios Forestales, Santiago, Chile, pp. 111–127.

Julio, G.H., Aguilera, R., Pedernera, P.G., 1997. The KITRAL System. Proc. International Workshop on Strategic Fire Planning Systems. USDA Forest Service, Fire Research Lab., Riverside, California (100 p).

Julio, G.H., Castillo, M.E., Fuentes, J.P., Garfias, R.A., 2012. Estudio de Impactos de Incendios Forestales en la Zona Central de Chile – Propuestas de Acciones de Restauración y Mitigación. Proyecto Fondecyt 1095048, Santiago (177 p).

Keeley, J.E., 2006a. Fire severity and plant age in post-fire resprouting of woody plants in sage scrub and chaparral. Madrono 53:373–379. http://dx.doi.org/10.3120/0024-9637-53[373:FSAPAI]2.0.CO;2.

Keeley, J.E., 2006b. Fire management impacts on invasive plant species in the western United States. Conserv. Biol. 20:375–384. http://dx.doi.org/10.1111/J.1523-1739.2006.00339.

Keeley, J.E., 2009. Fire intensity, fire severity and burn severity: a brief review and suggested usage. Int. J. Wildland Fire 18, 116–126.

Keeley, J.E., Fotheringham, C.J., Baer-Keeley, M., 2005. Determinants of post-fire recovery and succession in Mediterranean-climate shrublands of California. Ecol. Appl. 15: 1515–1534. http://dx.doi.org/10.1890/04-1005.

Mell, W.E., Manzello, S.L., Maranghides, A., Butry, D., Rehm, R.G., 2010. The wildland–urban interface fire problem – current approaches and research needs. Int. J. Wildland Fire 19, 238–251.

Molina, J.R., Herrera, M.A., Zamora, R., Rodríguez y Silva, F., González-Cabán, A., 2011. Economic losses to Iberian swine production from forest fires. Forest Policy Econ. 13, 614–621.

Molina, J.R., Castillo, M.E., Rodríguez y Silva, F., 2014. Determining the economic damage and losses of wildfires using MODIS remote sensing images. Adv. For. Fire Res. 1821–1831.

Morgan, P., Keane, R.E., Dillon, G.K., Jain, T.B., Hudak, A.T., Karau, E.C., Sikkink, P.G., Holden, Z.A., Strand, E.K., 2014. Challenges of assessing fire and burn severity using field measures, remote sensing and modelling. Int. J. Wildland Fire 23, 1045–1060.

Morvan, D., Dupuy, J.L., 2004. Modeling the propagation of a wildfire through a Mediterranean shrub using a multiphase formulation. Combust. Flame 138 (3), 199–210.

Pérez, P.C., 2006. Caracterización del combustible en plantaciones de pino radiata sometida a diferentes esquemas de manejo. Estudio de Caso: Empresa Forestal Monteaguila S.A. Memoria de Título. Ing. Forestal. Universidad de Chile (72p).

Piñol, J., Beven, K., Viegas, D.X., 2005. Modelling the effect of fire-exclusion and prescribed fire on wildfire size in Mediterranean ecosystems. Ecol. Model. 183 (4), 397–409.

Rodríguez y Silva, F., González-Cabán, A., 2010. "SINAMI": a tool for the economic evaluation of forest fire management programs in Mediterranean ecosystems. Int. J. Wildland Fire 19, 927–936.

Rodríguez y Silva, F., Julio, G.H., Castillo, M.E., Molina, J.R., Herrera, M.A., Toral, M.A., Cerda, C.L., González, L.A., 2010. Aplicación y Adaptación del Modelo SEVEIF para la Evaluación Socioeconómica del Impacto de Incendios Forestales en la Provincia de

Valparaíso. Agencia Española de Cooperación Internacional para el Desarrollo (AECID), Chile (51p).

Rodríguez y Silva, F., Martínez, J.R.M., Soto, M.C., 2013. Methodological approach for assessing the economic impact of forest fires using MODIS remote sensing images. In: González-Cabán, A. (Ed.), Proceedings of the fourth international symposium on fire economics, planning, and policy: climate change and wildfires. Gen. Tech. Rep. PSW-GTR-245 (English). U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA, pp. 281–295.

Rothermel, R.C., 1972. A Mathematical Model for Predicting Fire Spread in Wildland Fuels. USDA Forest Service (Res. Paper INT-115. 40p).

Suzuki, S., Manzello, S., Lage, M., Laing, G., 2012. Firebrand generation data obtained from a full-scale structure burn. Int. J. Wildland Fire 21, 961–968.

Vega, J.A., Fontúrbel, T., Fernández, C., Arellano, A., Díaz-Raviña, M., Carballas, T., Marín, A., González-Prieto, S., Merino, A., Benito, E., 2013. Acciones Urgentes Contra la Erosión en Áreass Forestales Quemadas. Guía para su planificación en Galicía. Xunta de Galicía-INIA-FuegoRed, Santiago de Compostela (139 pp).

Vilar, L., Camia, A., San-Miguel-Ayanz, J., Martín, M.P., 2016. Modeling temporal changes in human-caused wildfires in Mediterranean Europe based on land use-land cover interfaces. For. Ecol. Manag. 378 (October), 68–78.

Weise, D.R., Wotton, B.M., 2010. Wildland–urban interface fire behaviour and fire modelling in live fuels. Int. J. Wildland Fire 19, 149–152.

Zamora, R., Molina, J.R., Herrera, M.A., Rodríguez y Silva, F., 2010. A model for wildfire prevention planning in game resources. Ecol. Model. 221, 19–26.