



Research article

From leaves to landscape: A multiscale approach to assess fire hazard in wildland-urban interface areas



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ABSTRACT

The overlapping zone between urbanization and wildland vegetation, known as the wildland urban interface (WUI), is often at high risk of wildfire. Human activities increase the likelihood of wildfires, which can have disastrous consequences for property and land use, and can pose a serious threat to lives. Fire hazard assessments depend strongly on the spatial scale of analysis. We assessed the fire hazard in a WUI area of a Patagonian city by working at three scales: landscape, community and species. Fire is a complex phenomenon, so we used a large number of variables that correlate *a priori* with the fire hazard. Consequently, we analyzed environmental variables together with fuel load and leaf flammability variables and integrated all the information in a fire hazard map with four fire hazard categories. The *Nothofagus dombeyi* forest had the highest fire hazard while grasslands had the lowest. Our work highlights the vulnerability of the wildland-urban interface to fire in this region and our suggested methodology could be applied in other wildland-urban interface areas. Particularly in high hazard areas, our work could help in spatial delimitation policies, urban planning and development of plans for the protection of human lives and assets.

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1. Introduction

Housing development adjacent to shrublands and forests increases the fire hazard of wildland-urban interface (WUI) areas due to an increase of ignition sources (Chas-Amil et al., 2013) and due to changes in fuel structure that make houses more vulnerable to fire (e.g. wooden roofs, plantation of trees near houses) (Gill et al., 2013).

This vulnerability is an increasingly serious social problem (Bar-Massada et al., 2013; Gill et al., 2013; Prior and Eriksen, 2013). Many fire-prone regions, principally but not only those with Mediterranean climate, have suffered significant losses of lives and property in recent years due to increasing urbanization and fire frequency (Pausas et al., 2008; Veblen et al., 2008; Gill et al., 2013; Penman et al., 2013; Keeley et al., 2012). The alteration of fire regime in

fire-prone systems can be a consequence of the climate change, but fire is a complex phenomenon and fire activity depends on interactions among many variables (Krawchuk et al., 2009). Even in developed countries where great social and financial effort is invested in fire control and prevention, WUI wildfires can be very destructive (Gill et al., 2013; Penman et al., 2013).

Fire hazard assessments can help to prevent and manage wildfires in WUI areas because increase awareness among the general public, policy makers and managers about the fire danger and create a framework for discussion about future urban planning (McAneney et al., 2009). These assessments usually include the estimation of dead and live fuel load, the spatial arrangement of vegetation, and the flammability of individual species (Hardy, 2005), but they should ideally include both social and ecological variables (Hardy, 2005). However, even in developed countries, social factors such as land use planning, homeowner actions and improvement in building regulations are rarely included in fire management plans (Prior and Eriksen, 2013; Syphard et al., 2013).

Flammability is a complex trait that can be defined in different

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ways and measured at varying spatial scales, from leaves to landscape (Pausas and Moreira, 2012). The breadth of this concept has generated linguistic uncertainty (Thompson and Calkin, 2011) based on different conceptions of flammability in fire ecology and in wildfire prevention and management. Flammability can be measured at different spatial scales, including vegetation type (e.g.: grasslands, shrublands, forests), individual plants, or components of plants (generally leaves or litter). Fuel load (live vegetation along with fallen branches and logs) and the spatial arrangement of vegetation (vertical and horizontal distribution) contribute to landscape flammability and modify the capacity of fire to spread. Little is known about flammability at leaf level because the flammability changes among species and these values are not available for all species. However, increases in foliar moisture content consistently reduce leaf flammability (Santana and Marss, 2014).

In South America, 86% of fires have anthropogenic origins (FAO, 2005). Vulnerability of WUI areas to fire is determined by climate, ecological factors and land use changes, and is influenced by the high number of human-caused ignitions (de Torres Curth et al., 2012; Curt et al., 2013). In many fire-prone areas land-use planning policies fail to consider the risk of mega-fires and people are living in dangerous locations without accurate fire protection measures (Stephens et al., 2014).

In Northwestern Patagonia, most fires reported are of unknown cause, probably because the investigation of the causes is still rare, but few fires have natural origins (de Torres Curth et al., 2012). Regardless of ignition source, fire spread and fire severity are influenced by local topography and vegetation structure. For example, fire can threaten neighbors and property if vegetation and terrain have specific characteristics. Forests with low horizontal continuity will have a low probability of fire spread; forests with high vertical continuity will have a greater chance of high intensity crown fires and fire spread more readily on steep, dry slopes (Lampin-Maillet et al., 2010).

In regions with Mediterranean climates, meteorological or climatic variables are important factors in the fire hazard assessment, because most fires occur during the warm and dry seasons (late spring, summer and early autumn) (Keeley et al., 2012). In our study area, fires normally occur from October (late spring) to March (early autumn). A previous study has shown that drought and high temperatures influence fire hazard (by drying vegetation) and fire spread (de Torres Curth et al., 2008). Further, if a wildfire develops in extreme meteorological conditions, spread is difficult to control because of high fire intensity and windblown embers that readily cross firebreaks.

Andean-Patagonian native forests are located in a region with a Mediterranean climate and frequent fires (de Torres Curth et al., 2008). The forests provide a variety of ecosystem services, including direct (wood, firewood, fruits, hunting and fishing, tourism) and indirect uses (water regulation, habitat conservation, genetic resources) (Chauchard et al., 2008).

Populations of the major cities located in or near these forests are increasing as people seek better economic opportunities or quality of life; this population growth significantly increases the anthropogenic pressure on the WUI areas. Catastrophic fires are still relatively uncommon, but the increasing probabilities of ignition (mainly due to the growing population) enhances the probability of catastrophic events (de Torres Curth et al., 2012). Several big fires have occurred in the past two decades in WUI areas of NW Patagonia cities, endangering lives and houses, and affecting extensive natural areas. For example, in January 1996 (summer in the southern hemisphere), a big wildfire that started in Cathedral mountain burned 675 ha and caused the evacuation of Villa Los Coihues, a neighborhood of Bariloche. However, little research on WUI fires in the region has been conducted (de Torres Curth et al.,

2012; Dondo et al., 2013; Mundo et al., 2013) and no previous research had developed a methodology to assess fire hazard.

Our study was inspired by the 2006 Villa Los Coihues neighborhood fire. Our goal was to evaluate the fire hazard of this peri-urban area through a protocol that could be replicated in other WUI areas of Argentina and worldwide. A careful knowledge of how local environmental and social-ecological variables influence the fire hazard in WUI areas is necessary to deal with fires and to define adequate natural resource management policies. Studies about WUI fire hazard generally do not integrate different scales of analysis, likely because this approach greatly increases study complexity. However, in this study, we included a large number of variables that we assumed *a priori* were important in fire ignition and spread. The general objective was to assess the WUI fire hazard combining three scales (landscape, community and species) in Villa Los Coihues, a WUI sector of Bariloche (Patagonia, Argentina) through the analysis of environmental variables, live and dead fuel, and leaf flammability and produce a fire hazard map that integrated all the variables.

2. Materials and methods

2.1. Study area

Bariloche is located along the southern coast of the Nahuel Huapi Lake in Patagonia, Argentina. The Nahuel Huapi National Park (700,000 ha) surrounds the 22,000-ha municipal district, creating a very long perimeter of contact (more than 40 km). In this WUI area, vegetation contacts and intermingles with housing and other infrastructure. The climate is Mediterranean with dry summers and precipitation in autumn-winter. The average annual temperature is 8 °C and annual accumulated precipitation is 1344 mm. Winds are strong and frequent with an average annual speed of 4.5 km/h with maximum average values of 64.4 km/h (DPA, 2011). Bariloche is located in a very fire-prone region (de Torres Curth et al., 2008) where fire causes have been related to social-economic problems (de Torres Curth et al., 2012; Dondo et al., 2013).

Due to the vastness of the perimeter of the municipal district, our study focused on a 378-ha portion of the WUI around Villa Los Coihues neighborhood (41° 10' - 41° 15' S, 71° 10' - 71° 23' W, Fig. 1). This neighborhood is entirely surrounded by native and exotic vegetation. The landscape of the study area is heterogeneous and the vegetation types are related to topography and soil type. *Nothofagus dombeyi* and *Austrocedrus chilensis* forests dominate southwestern sectors whereas *Nothofagus antarctica* monospecific shrublands and *N. antarctica*, *Lomatia hirsuta* and *Schinus patagonicus* mixed shrublands share northeastern sectors. Disturbed grasslands occupy a marginal area of the landscape and exotic species like *Pinus* spp., *Pseudotsuga menziesii* and *Cytisus scoparius* occupy very degraded sites (e.g. shoulders of the main road).

In the study area, there are some scattered houses but urban pressure is increasing, including illegal settlements located in *N. dombeyi* and *A. chilensis* forests. The study area is mostly used for recreation and tourism, but also shows clear evidence of disturbance, due to illegal logging and landfills.

2.2. Methods

We performed the study at three interconnected scales: landscape, vegetation community and species (Table 1). At the landscape scale, we used Google Earth images, fieldwork and a vegetation map (Naumann and Sancholuz, 2000) to identify 11 vegetation units (VUs): *N. dombeyi* forest, *A. chilensis* forest, *N. dombeyi* - *A. chilensis* forest, *A. chilensis* mixed forest, *N. antarctica*

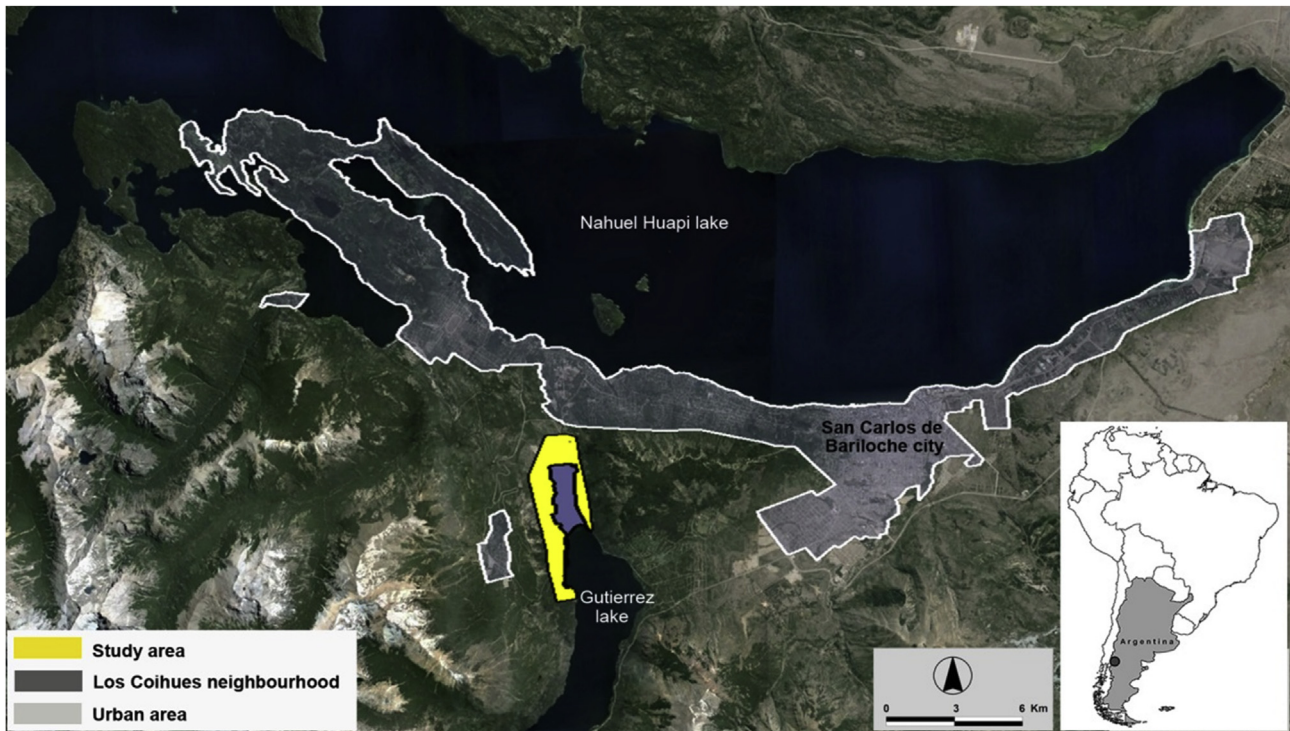


Fig. 1. Study Area map over a high-resolution image of the region (from Google Earth). Study area covers a 378-ha portion of the Wildland Urban Interface area around Villa Los Coihues neighborhood ($41^{\circ} 10' - 41^{\circ} 15' S$, $71^{\circ} 10' - 71^{\circ} 23' W$).

Table 1

Variables measured for each scale of analysis. Variables in *italics* are those used in the multivariate analysis.

Scale		
Landscape	Community	Species
<i>Slope</i>	Species richness	<i>Moisture content</i>
<i>Aspect</i>	<i>Vertical continuity</i>	<i>Flame height</i>
<i>Woody cover</i>	<i>Horizontal continuity</i>	Flame temperature
	<i>Litter amount</i>	Ember temperature
	<i>Dead fuel load</i>	<i>Ignition time</i>
		<i>Combustion time</i>
		<i>Ignition probability</i>

shrubland, *N. antarctica* mixed shrubland, riparian shrubland, exotic corridor (a continuous and narrow corridor at both sides of the main road, dominated by exotic species), mixed shrubland, disturbed grassland and shrubby grassland. We mapped the VUs using a Geographic Information System (GIS) tools with POSGAR 94 (Gauss-Kruger projection/Datum WGS84) as the reference system. VU boundaries were defined by visual digitalization from Google Earth images and GPS field data. We used GIS tools to calculate slope, aspect and the percentage of woody cover in each VU.

To get information at plant community scale, we randomly located nine 15-m long transects in each VU in spring 2010. Transects were located randomly in each VU; transects did not cross and were separated by at least 10 m. Transect starting points and bearings were randomly selected. In each transect, we measured tree and shrub species cover (line intercept method, [Mueller-Dombois and Ellenberg, 1974](#)) and identified the three most abundant herbaceous species to characterize each VU. We calculated species richness (number of species) and the percentage of exotic species. We measured horizontal fuel continuity at ground level by estimated the percentage of the transect that had herb and/

or shrub cover. Subsequently, these percentages were converted into a qualitative variable with three categories: Low, Medium and High horizontal continuity. Dead fuel load was estimated by counting the number of branches on soil (woody debris) that intercepted the transects. We classified the branches into three size categories ([Andrews, 1986](#)): fine (up to 2.5 cm diameter), medium (2.5–7.5 cm) and coarse (greater than 7.5 cm). The number of branches in each size class was averaged within each VU. We also randomly located fifteen 0.25-m² plots in each VU (independently of the transect locations) to estimate litter amount. Litter was collected from the surface until we reached decomposed organic matter. Each sample was kept in paper bags, dried at 80 °C for 48 h and weighed. In each VU, we estimated the vertical continuity considering the height of vegetation, the number of vegetation layers and the presence/absence of drooping branches and climbing plants. We considered three categories: Low (vegetation height up to 1.5 m; one or two vegetation layers), Moderate (vegetation height > 1.5 m; three vegetation layers; drooping branches and climbing plants absent) and High (vegetation height > 1.5 m; three vegetation layers; drooping branches and climbing plants present). The presence of drooping branches and climbing plants connects the ground and the tree crowns and increases the risk of high-severity crown fire ([Corti González and Castro Rios, 2009](#)).

Species-scale data were collected in February 2011. We collected samples of ten dominant woody species (*A. chilensis*, *Chusquea culeou*, *C. scoparius*, *Diostea juncea*, *Fabiana imbricata*, *L. hirsuta*, *M. boaria*, *N. antarctica*, *N. dombeyi*, *S. patagonicus*), in three consecutive days, between 11 a.m. and 2 p.m. and at least three days after the last rain. We randomly collected terminal twigs (20 cm long) from ten individuals (three samples per plant, 30 samples per species) that were kept in plastic bags and kept cool until analysis. To perform flammability tests, we used 1-g subsamples of healthy leaves that we placed in an epiradiator (500 W of heat capacity and 420 °C of temperature) ([Gauteaume et al., 2013](#)). We measured the

following flammability variables: ignition time (lapse until ignition, IT, in seconds), combustion duration (CD, in seconds), and flame height (FH, in centimeters) that we used as a proxy to estimate combustion intensity. We recorded negative (no burn, flame do not appears) and positive (burn, the sample ignites) trials that were used to estimate the ignition probability (IP). For all species except *F. imbricata*, *D. juncea* and *C. culeou* we measured the flame and ember temperature (FT and ET, in Celsius degrees) using two thermocouples located 2 cm and 0.5 cm above to the center of epiradiator. Except for *C. culeou*, we dried 5-g subsamples of healthy leaves (fresh weight, FW) in oven at 80 °C for 48 h (dry weight, DW) to estimate moisture content that was calculated as Moisture Content (%) = [(FW – DW)/DW] x 100.

2.3. Data analysis

We performed Kruskal-Wallis tests to compare fine, medium and coarse dead fuel load (i.e., average number of branches) and litter among and within VUs. We used one-way ANOVA to test ignition time, combustion duration, flame and ember temperatures, and Kruskal-Wallis tests to compare flame height and moisture content among species. When we obtained significant results ($p < 0.05$), we carried out post hoc multiple comparisons tests. We used Bayesian statistics to analyze the results of ignition trials. We considered the positive ignitions as an independent random variable with a binomial distribution and we estimated the ignition probability. We graphed the distribution of the ignition probability parameter. Parameters of Beta distribution were set to one to be used as an uninformative prior. For comparison among species, we estimated mean and credible region of 95% for each posterior. We performed simple linear regressions between moisture content and five flammability variables (ignition time, combustion duration, ignition probability, and flame and ember temperature). For the ignition probability, we used the mean value of distributions obtained in the Bayesian analysis as our response variable.

2.4. Classification of the vegetation units

Based on the results from the data analyses above, we conducted a Multiple Correspondence Factor Analysis (MCFA) followed by an Ascendant Hierarchical Classification Analysis (AHCA) using the most important factors obtained from the MCFA as variables (Lebart et al., 1995; for details see de Torres Curth et al., 2012). Together, the MCFA and the AHCA select the most representative categories of all variables and describe the typology in terms of those categories. MCFA was performed with seven landscape and community variables, and five flammability variables as active variables to obtain a VU typology related to fire hazard. Landscape and community variables were: slope (S), and aspect (A) woody cover percentage (WC), vertical continuity (VC), horizontal continuity (HC), litter amount (L), and dead fuel load (DF). Flammability variables were: moisture content (MC), flame height (FH), combustion duration (CD), ignition time (IT) and ignition probability (IP).

For each VU, we calculated weighted averages (by relative cover of the woody species present) for the flammability variables (MC, FH, CD, IT, and IP).

For example, the numerical value for “moisture content” assigned to a specific VU was calculated as:

$$MC = \sum_{i=1}^n MC(i) \cdot CP(i)$$

where n is the maximum number of woody species considered in that VU, $MC(i)$ represents the moisture content for the species “ i ” and, $CP(i)$ represent the relative cover percentage estimated for this species in the VU. Flame and ember temperature (FT and ET) were not used in this analysis because measurements were missing for several species.

Because fine, medium and coarse dead fuel were highly correlated (>86%), we used an average value for “dead fuel load”. Subsequently, the continuous variables were transformed into categorical variables with three categories (Table 2). Afterwards, each VU was assigned to one category of each categorical variable. Next, we performed an AHCA that allowed us to get a typology, classifying the VUs into classes based on the active variables. All procedures were carried out with the Facto Mine R (Lê et al., 2008) and Facto Class (Pardo and Del Campo, 2007) R packages.

We established four fire hazard categories: low, moderate, high and very high fire hazard. Using these categories, we constructed a WUI Fire Hazard map for the whole study area. Each category was described integrating the different scales of results. To do this, we interpreted the fire hazard of the vegetation units, taking into account the dominant species (hazard associated with flammability); fuel amount (hazard associated with fire spread) and woody cover (hazard associated with fire intensity).

3. Results

3.1. Vegetation units

We identified 11 vegetation units (Fig. 2, Table 3). Species richness varied between eight (disturbed grassland) and 20 species (*N. dombeyi* forest; Appendix A). Exotic corridor and disturbed grassland had the highest exotic species percentage (55% and 37%) whereas *N. dombeyi* forest had the lowest (5%). Species richness and exotic species percentage in grasslands were underestimated because we did not identify grasses.

Shrublands had high horizontal continuity (higher than 80%); forests were generally less continuous (lower than 35%) except for *A. chilensis* mixed forest (75%). Disturbed grassland showed higher horizontal continuity at soil level than shrubby grassland (Appendix A). Almost all VUs had high vertical continuity, with the exception of *N. dombeyi* forest (medium) and grasslands (low).

The VUs differed in fine ($H_{10,99} = 51.87$, $p < 0.001$), medium ($H_{10,99} = 64.54$, $p < 0.001$), and coarse ($H_{10,99} = 70.91$, $p < 0.001$) dead fuel, and in litter amount ($H_{10,99} = 94.15$, $p < 0.001$).

Table 2

Description of variables used in the Multiple Correspondence Factorial Analysis (MCFA) and the Ascendant Hierarchical Classification Analysis (AHCA). Flammability variables are a weighted average of the mean values for the dominant woody species, weighted by the relative cover percentage. Multivariate analyses also used aspect, which is not included in this table.

Variable	Label	Categories		
		1	2	3
		Low	Moderate	High
Dead fuel load (average number)	DF	14.5	>14.5–25.8	>24.8
Woody cover (%)	WC	47.3	>47.3–73.6	>73.6
Litter amount (g)	L	110	>110–195	>195
Horizontal continuity (%)	HC	53	>53–76	>76
Vertical continuity	VC	Low	Moderate	High
Slope (degrees)	S	8	>8–16	>16
Moisture content (%)	MC	<109.5	>109.5–198.4	>198.4
Flame height (cm)	FH	<1.1	>1.1–2.2	>2.2
Combustion duration (s)	CD	<4.9	>4.9–10.5	>10.5
Ignition time (s)	IT	<15.7	>15.7–29.9	>29.9
Ignition probability	IP	<0.6	>0.6–0.9	>0.9

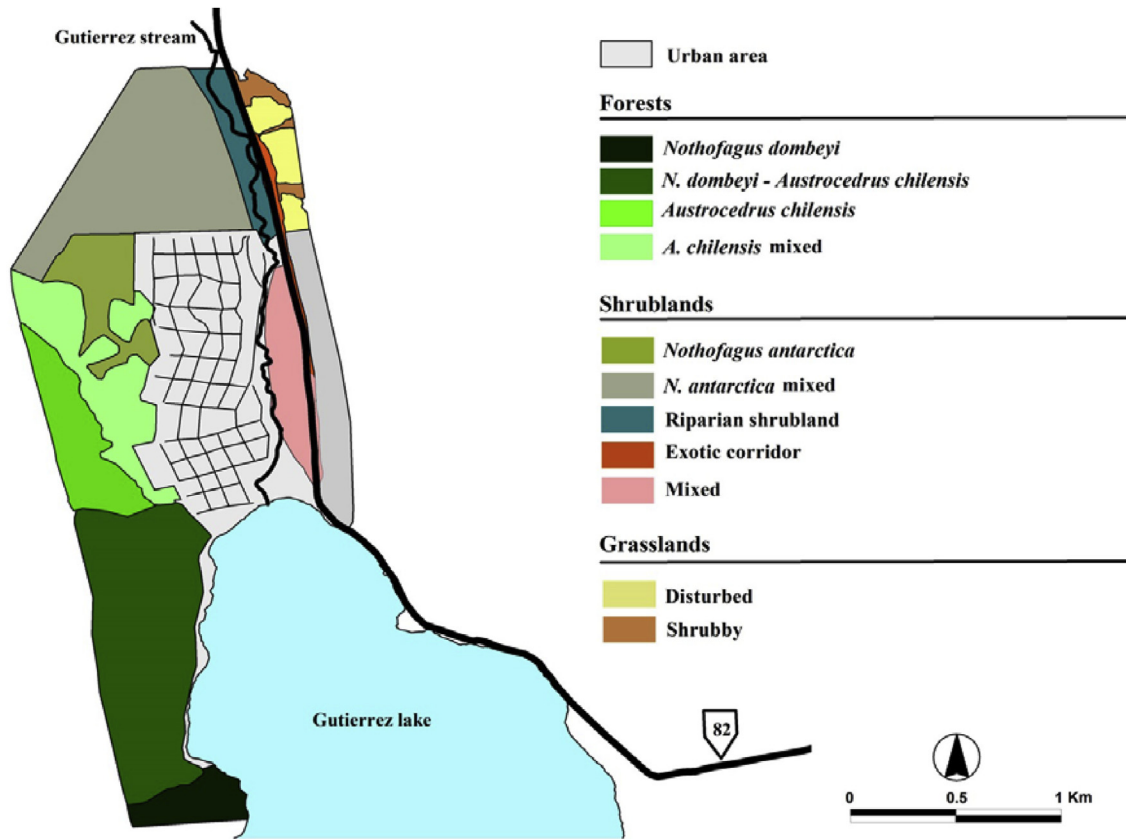


Fig. 2. Vegetation units (VUs) map.

Table 3
Topographic characteristics (altitude, slope and aspect), and area and woody cover area of the 11 vegetation units.

Vegetation units	Altitude (masl)	Slope (degrees)	Aspect	Area (ha)	Woody cover (ha)
Forests					
<i>N. dombeyi</i>	869	8	Northeast	22	22
<i>N. dombeyi</i> - <i>A. chilensis</i>	855	10	East	102	102
<i>A. chilensis</i>	942	24	East	33	29
<i>A. chilensis</i> mixed	855	10	East	47	47
Shrublands					
<i>N. antarctica</i>	869	2	Northeast	27	21
<i>N. antarctica</i> mixed	848	3	Northeast	92	61
Riparian	808	0	–	17	14
Exotic corridor	808	1	West	2	2
Mixed	815	2	Northwest	18	13
Grasslands					
Shrubby	809	3	West	5	4
Disturbed	811	2	West	13	3

Nothofagus dombeyi forest had the most dead fuel. *Nothofagus dombeyi* and *N. dombeyi* - *A. chilensis* forests had the highest values of fine woody fuel and disturbed grassland had the lowest (Fig. 3a). We observed a similar pattern for medium fuel (Fig. 3b). Forests had higher values of coarse fuel that were underrepresented in the rest of VUs (Fig. 3c). Litter biomass was highest in the *N. dombeyi* forest and lowest in the disturbed grassland (Fig. 3d). In most VUs, fine woody fuel was significantly higher than medium and coarse fuel, except in *N. antarctica* forest, exotic corridor and shrubby grassland (Fig. 4). In *N. antarctica* mixed shrubland and in exotic corridor, coarse fuel was significantly lower than the other two categories of dead fuel (Fig. 4).

3.2. Species flammability and moisture content

We observed differences among species for all recorded flammability variables (ignition time: $F_{9,87} = 24.14$, $p < 0.0001$; combustion duration; $F_{9,87} = 24.15$, $p < 0.0001$; flame temperature: $F_{6,63} = 5.58$, $p = 0.0001$; ember temperature: $F_{6,63} = 4.19$, $p = 0.001$; flame height: $H_{9,97} = 75.96$, $p < 0.0001$; moisture content: $H_{8,87} = 71.16$, $p < 0.0001$). The shrubs *C. scoparius* and *D. juncea* had the longest ignition time values whereas the trees *A. chilensis*, *N. dombeyi*, *N. antarctica*, and *L. hirsuta*, and the bamboo *C. culeou* had the shortest (Fig. 5a). *Lomatia hirsuta*, *N. dombeyi* and *C. culeou* produced taller flames (proxy for combustion intensity) (Fig. 5b). *Lomatia hirsuta* had the longest combustion duration whereas

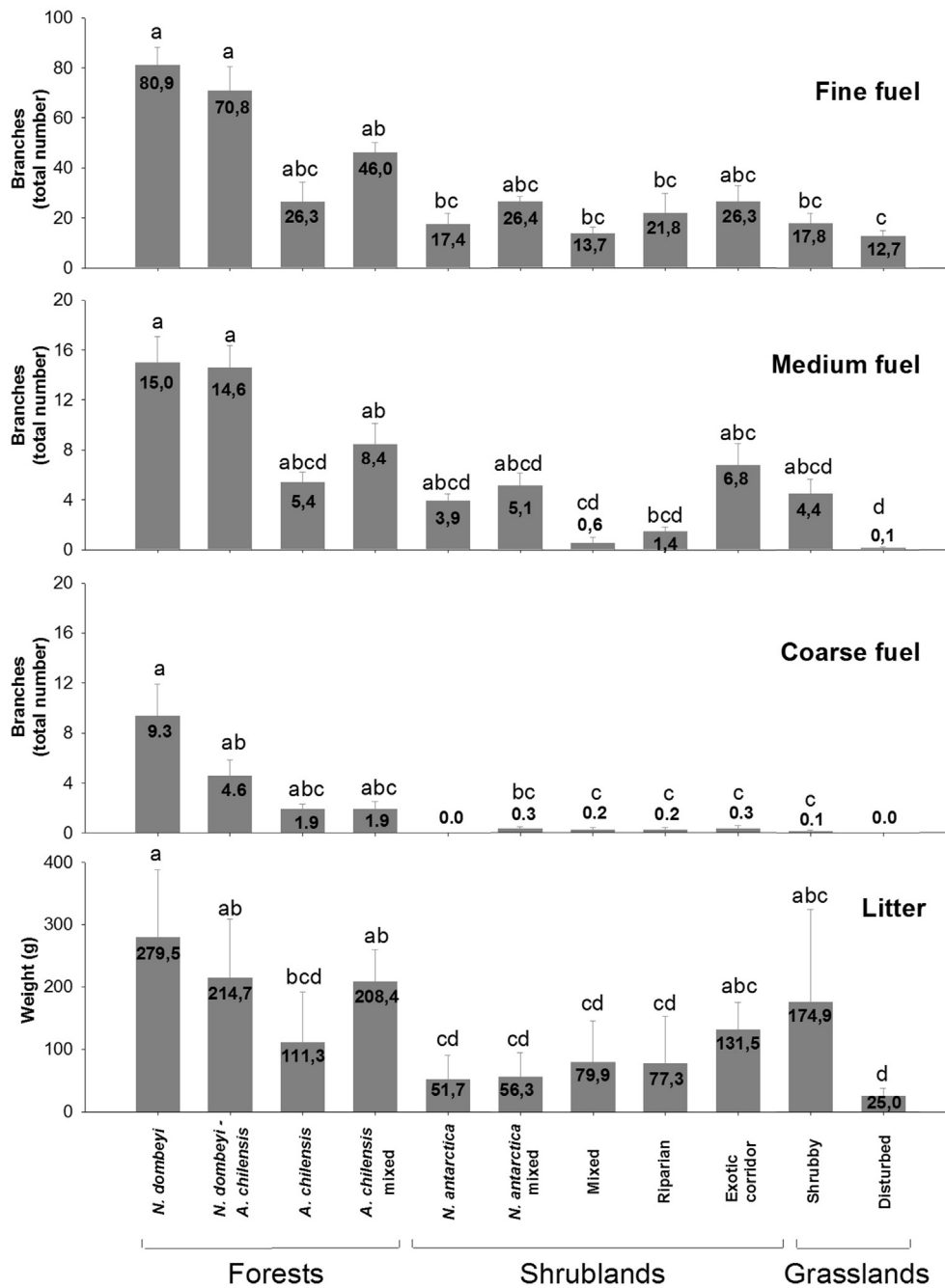


Fig. 3. Dead fuel comparisons among vegetation units. Mean (\pm sd) of a) fine dead fuel load, b) medium dead fuel load c) coarse dead fuel load (average number), and d) litter (weight). Different letters indicate significant differences ($p < 0.05$).

A. chilensis and *C. scoparius* had the shortest (Fig. 5c). We observed that *N. antarctica* produced the highest flame temperature and *A. chilensis* the lowest (Fig. 6a), whereas *N. dombeyi* produced higher ember temperature and *C. scoparius* the lowest ones (Fig. 6b).

We observed a species gradient with respect to ignition probability (Fig. 7). *Nothofagus dombeyi* and *C. culeou* had the highest ignition probabilities showing similar credibility intervals (74% of overlap). *Lomatia hirsuta* also had a high ignition probability (60% of overlap with *C. culeou*). At the other extreme of the gradient, *A. chilensis* and *C. scoparius* (71% of overlap) had the lowest ignition probability. *Fabiana imbricata*, *D. juncea* and *N. antarctica* had

similar ignition probability (83% of overlap among them). *Schinus patagonicus* and *M. boaria* had intermediate values of ignition probability.

The moisture content ranged from 98.3% (*N. dombeyi*) and 238.7% (*C. scoparius*) (Fig. 8). Regressions between moisture content and flammability variables were negative, except for the relationship between ignition time and moisture content. In the case of combustion duration, *L. hirsute* had high influence on the model fit (Cook' distance > 0.5) resulting in an important shift of slope when it is not excluded from the analysis (-0.058 with *L. hirsute* vs. -0.029 without it). However, both slope values were negative.

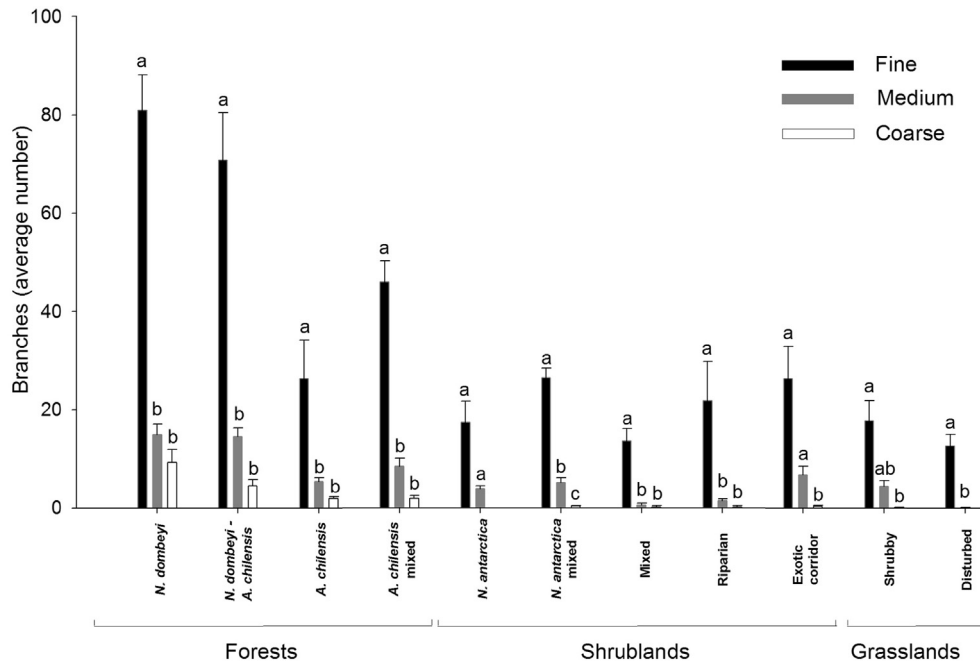


Fig. 4. Dead fuel comparisons within vegetation units for three size categories: fine (up to 2.5 cm diameter), medium (2.5–7.5 cm) and coarse (greater than 7.5 cm). Different letters indicate significant differences ($p < 0.05$).

We found significant regression relationships between moisture content and ignition time, flame height and ember temperature ($p < 0.05$, Fig. 9). The correlation between ignition probability and ignition time was not significant ($r = -0.5$, $p = 0.17$).

3.3. Multivariate analysis

In the MCFA analysis performed with landscape variables (DF, L, WC, HC, VC, S, A) and flammability variables (MC, FH, CD, IT and IP) (Table 2), the first axis explained 30.4% of the total variation; the second axis explained 22.6% of total variation. Both axes were correlated with all variables. The AHCA analysis performed after MCFA allowed the identification of a VU typology in four classes (Fig. 10, Appendix B). To describe the classes' characteristics, we used only well-represented categories (test value upper than 1.98, see Appendix B) of the active variables. Classes are characterized as follows:

Class 1: This class includes the exotic corridor, disturbed grassland, and shrubby grassland VUs. These VUs have intermediate horizontal continuity (HC.2), low vertical continuity (VC.1), low slope (S.1), intermediate litter amount (L.2) and low woody cover (WC.1). They are typically oriented to the northeast. Flammability characteristics of this class include high moisture content (MC.3), low flame height (FH.1), low combustion duration (CD.1), high ignition time (IT.3) and low ignition probability (IP.1)

Class 2: The VUs that constitute this class are *N. antarctica* mixed forest, *N. antarctica* forest, riparian shrubland and mixed shrubland. This class has high horizontal and vertical continuity (HC.3–VC.3), low amount of dead fuel (DF.1), low litter amount (L.1), intermediate woody cover (WC.2); sites are typically oriented to the northeast. Flammability characteristics of this class include intermediate moisture content (MC.2) and flame height (FH.2), low to intermediate ignition probability (IP.1–IP.2) and low combustion duration (CD.1)

Class 3: The VUs that constitute this class are *N. dombeyi* - *A. chilensis* forest, *A. chilensis* forest and *A. chilensis* mixed forest. These VUs are characterized by low horizontal continuity (HC.1), high slope (S.3), intermediate dead fuel amount (DF.2), high litter amount (L.3), high woody cover (WC.3), and are mainly oriented to the east (A.2). Flammability characteristics include intermediate moisture content (MC.2) and low to intermediate ignition time (IT.1–IT.2).

Class 4: The only VU included in this class is *N. dombeyi* forest. This forest is characterized by low horizontal continuity (HC.1), intermediate vertical continuity (VC.2) and slope (S.2), high amount of dead fuel (DF.3) and litter (L.3), and high woody cover (WC.3); sites typically face northeast. Flammability characteristics include low moisture content (MC.1), high flame height (FH.3) and ignition probability (IP.3), and intermediate combustion and ignition time (CD.2 – IT.2).

4. Discussion

4.1. Fire hazard categories

We assigned four fire hazard categories (very high, high, moderate and low) to the VUs, based on the dead fuel load, woody cover, horizontal and vertical continuity combined with flammability of the dominant species. We used these categories to create a Fire Hazard Map (Fig. 11). When necessary, we also considered other characteristics (for example, recreational use).

4.2. Very high fire hazard

The only VU with very high fire hazard was *Nothofagus dombeyi* forest, which had very high dead fuel load. This forest is dominated by *N. dombeyi* trees whose leaves have low moisture content, high flame height, flame temperature and long combustion duration, and very short ignition time, i.e. very high flammability. The low horizontal continuity is due to the recreational use of *N. dombeyi* forest that occupies a low slope sector near to the coast of the

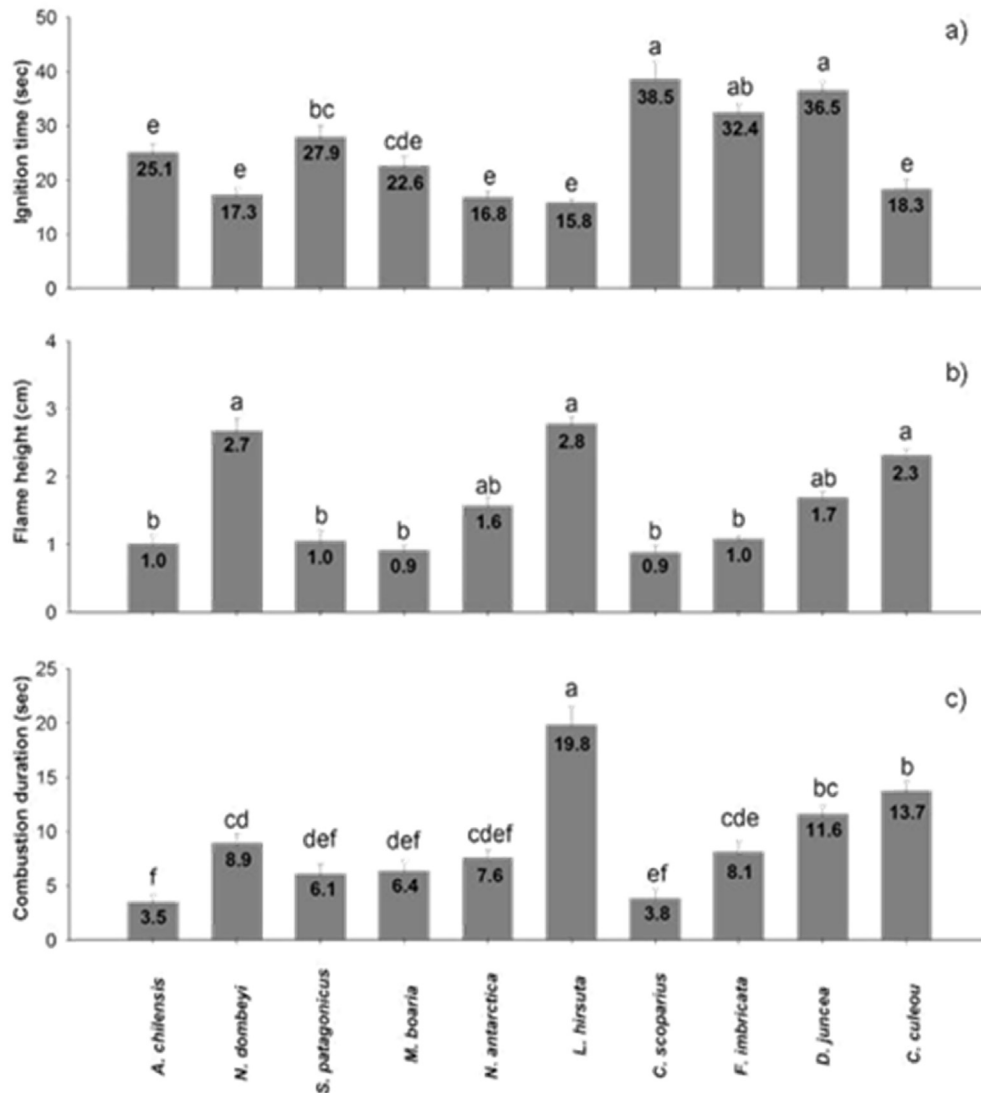


Fig. 5. Species flammability analysis: a) ignition time (sec), b) flame height (cm) and c) combustion duration (sec). Different letters indicate significant differences ($p < 0.05$).

Gutierrez Lake, very accessible by urban buses. The low horizontal continuity could decrease the fire hazard but, conversely, the intense recreational use could presumably increase the probability of accidental fires. Moreover, we recorded in the shrubby layer 22% cover of *C. culeou*. This species is a very flammable native bamboo that can reach three meters of height and produces a massive synchronic flowering (followed by mass mortality) every 50–70 years. In the study area, this infrequent phenomenon occurred recently (2011 summer), causing the accumulation of abundant dead fuel. Green *C. culeou* leaves (Fig. 5) had a short ignition time (18 s), as well as a long combustion duration (14 s) and ignition probability (Fig. 7), that signifies high flammability. Bianchi and Defossé (2015) independently noted the low moisture content of live *C. culeou* leaves, confirming the high flammability of this species.

4.3. High fire hazard

Three of the four forest VUs and the mixed shrubland were assigned to the high fire hazard category. *Austrocedrus chilensis* (Cupressaceae) dominated these forests, which occupy steep slopes and have high vertical continuity and high dead fuel loads. In spite

of the content of resin, that is a characteristic of Cupressaceae family, the flammability of *A. chilensis* leaves was much lower than *N. dombeyi*. Similar results were reported by Della Rocca et al. (2015) in relation to another Cupressaceae.

Some of the local populations use these forests as illegal dumping sites for pruned biomass; these cuttings accumulate and dry in summer and increase the fire risk. Due to the high dead fuel loads, *N. dombeyi* - *A. chilensis* forests are the most dangerous within this category. Mixed shrubland also has high fire hazard because of the high horizontal continuity and high cover of *Pinus* spp. and *Mulinum spinosum*. We did not evaluate the flammability of these species but both are considered very flammable (Dimitrakopoulos et al., 2013; Ghermandi et al., 2004).

4.4. Moderate fire hazard

Four of five shrublands were assigned to the moderate fire hazard category. *Nothofagus antarctica*, which dominates these shrublands, had intermediate values of most flammability variables. Vertical and horizontal continuity were high but the dead fuel load was low or intermediate. Riparian shrubland had high woody cover but this VU is a narrow strip located bordering the

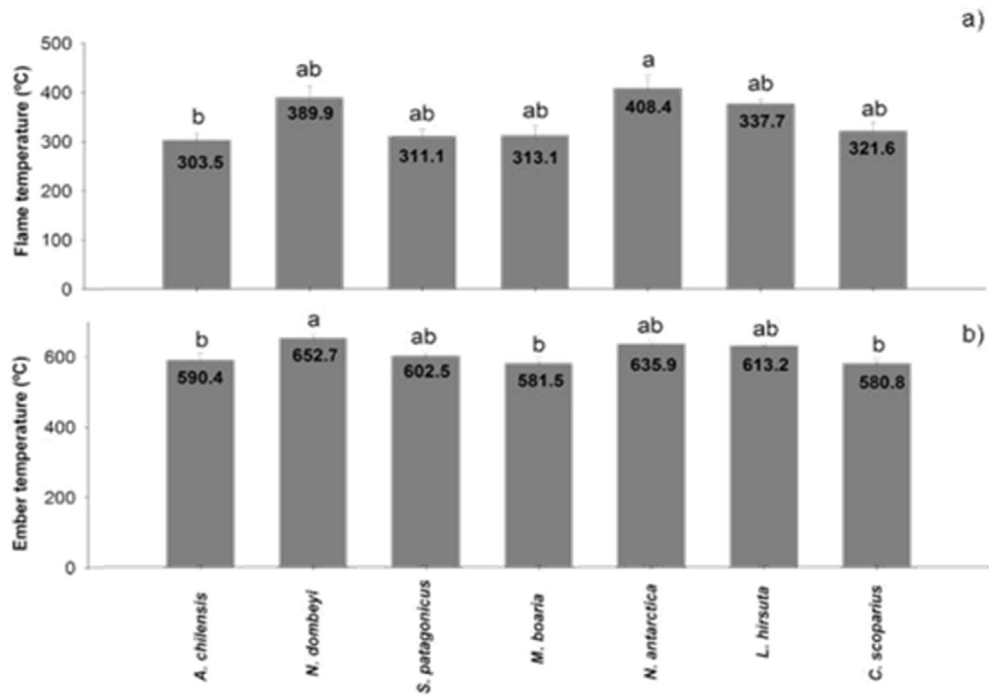


Fig. 6. Species flammability analysis: a) flame temperature (°C) and b) ember temperature (°C). Different letters indicate significant differences ($p < 0.05$).

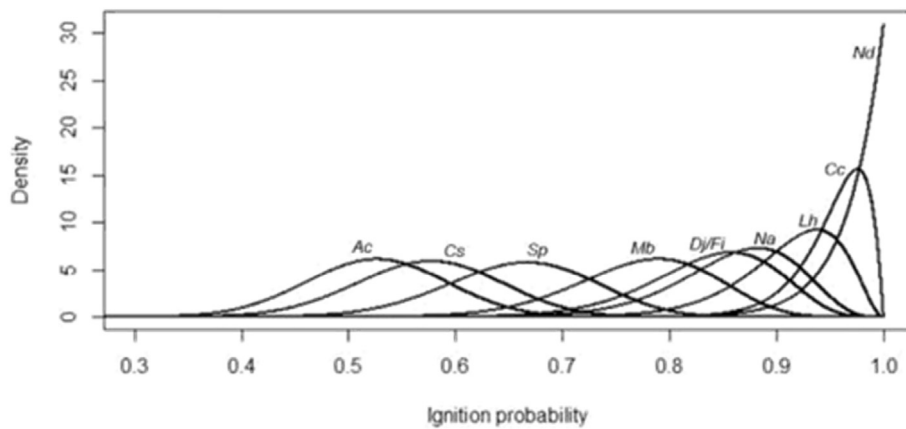


Fig. 7. Posterior distribution for the ignition probability for the ten species considered. Ac: *Austrocedrus chilensis*; Cs: *Cytisus scoparius*; Sp: *Schinus patagonicus*; Mb: *Maytenus boaria*; Dj: *Diostea juncea*; Fi: *Fabiana imbricata*; Na: *Nothofagus antarctica*; Lh: *Lomatia hirsuta*; Cc: *Chusquea culeou*, and Nd: *Nothofagus dombeiyi*.

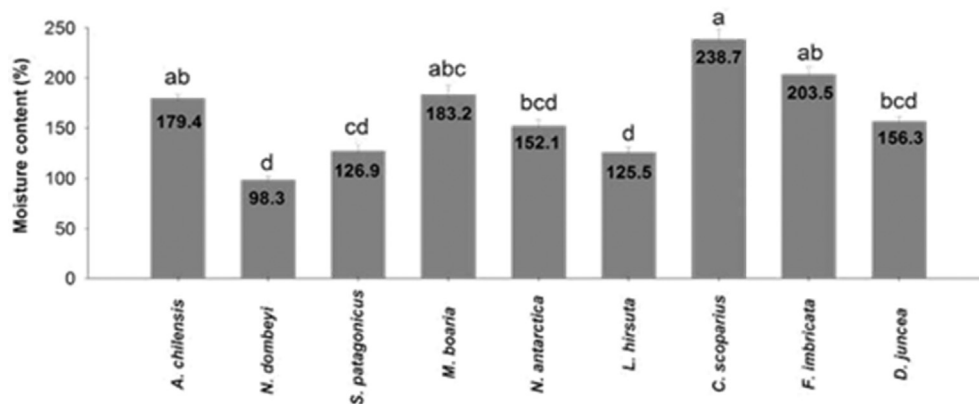


Fig. 8. Moisture content (%). Different letters indicate significant differences ($p < 0.05$).

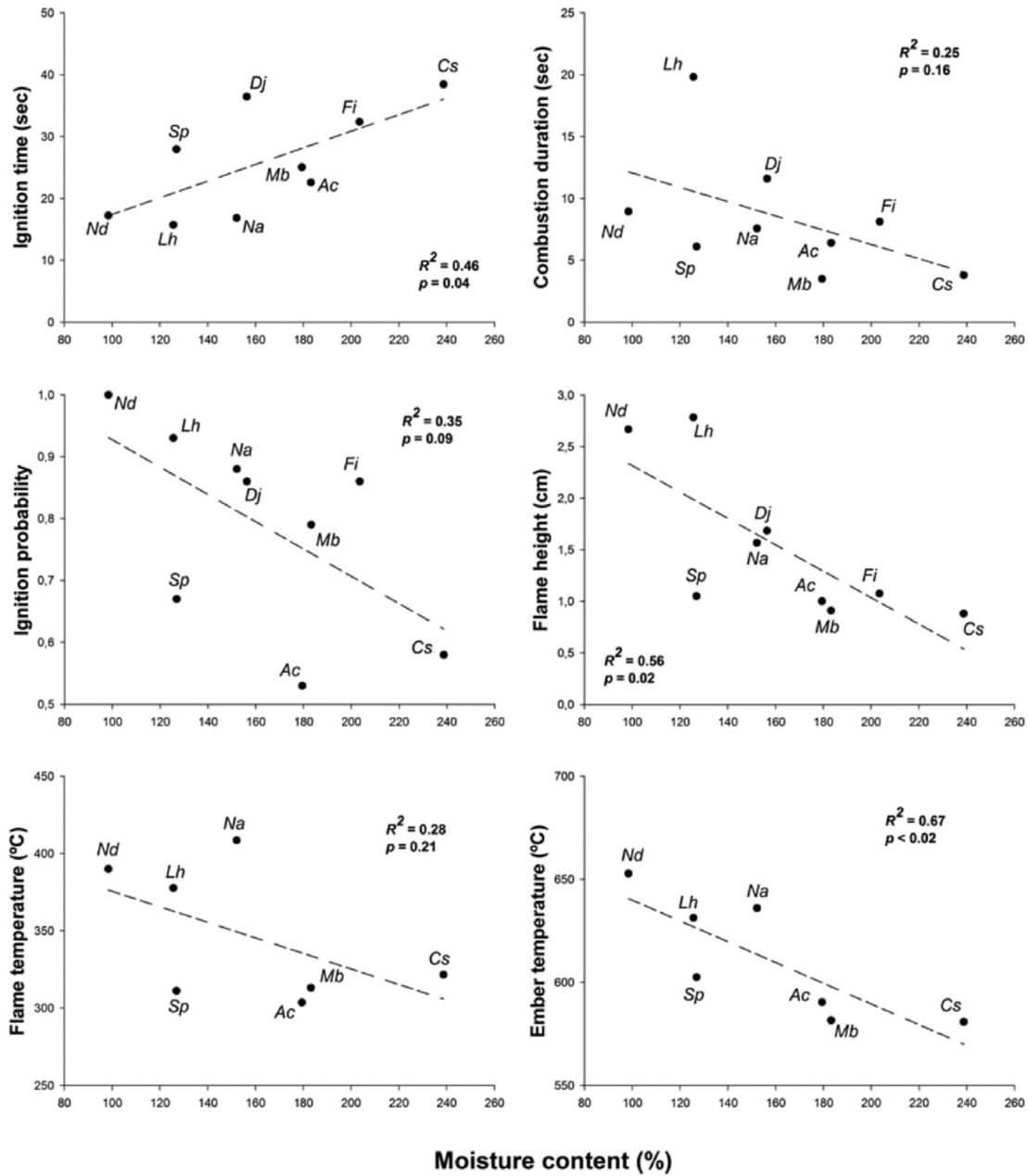


Fig. 9. Linear regressions between flammability variables and moisture content. Ac: *Austrocedrus chilensis*; Cs: *Cytisus scoparius*; Sp: *Schinus patagonicus*; Mb: *Maytenus boaria*; Dj: *Diostea juncea*; Fi: *Fabiana imbricata*; Na: *Nothofagus antarctica*; Lh: *Lomatia hirsuta*; and Nd: *Nothofagus dombeyi*.

Gutierrez stream that can be considered a fire barrier. Slope was low in all the cases. The high horizontal continuity was due to the herbaceous layer, composed principally of the herbs *Rumex acetosella*, *Fragaria chiloensis*, *Acaena splendens* (Table 3). These herbs have low biomass and do not dry during the summer, slowing fire spread.

4.5. Low fire hazard

The three most disturbed VUs had low fire hazard. Two of these were grasslands with very high degree of disturbance caused by the intensive use for camping, motocross, rides and horse grazing. The high horizontal continuity is due to perennial grass cover but the dead fuel load is very low and vertical continuity is meaningless because there is only one vegetation layer. In the exotic corridor VU,

C. scoparius, an exotic shrub, forms a continuous corridor at the sides of the main road. The moisture content and the ignition time of *C. scoparius* leaves showed the longest values, and the combustion duration the shortest value: this species could slow fire spread.

From a strictly ecological point of view, fires started by natural causes should determine the fire regime of an ecosystem. However, deep and long-lasting human influence on environment have modified the natural fire regimes via the elimination or substitution of vegetation types and, consequently, through the change in the amount and arrangement of the potentially combustible biomass (Prior and Eriksen, 2013).

In this study, we measured burn variables to compare burning behavior, as proxy of flammability, among the dominant woody species. Little is known about the flammability of most plant species (Santana and Marss, 2014) and, in Patagonia, these studies are

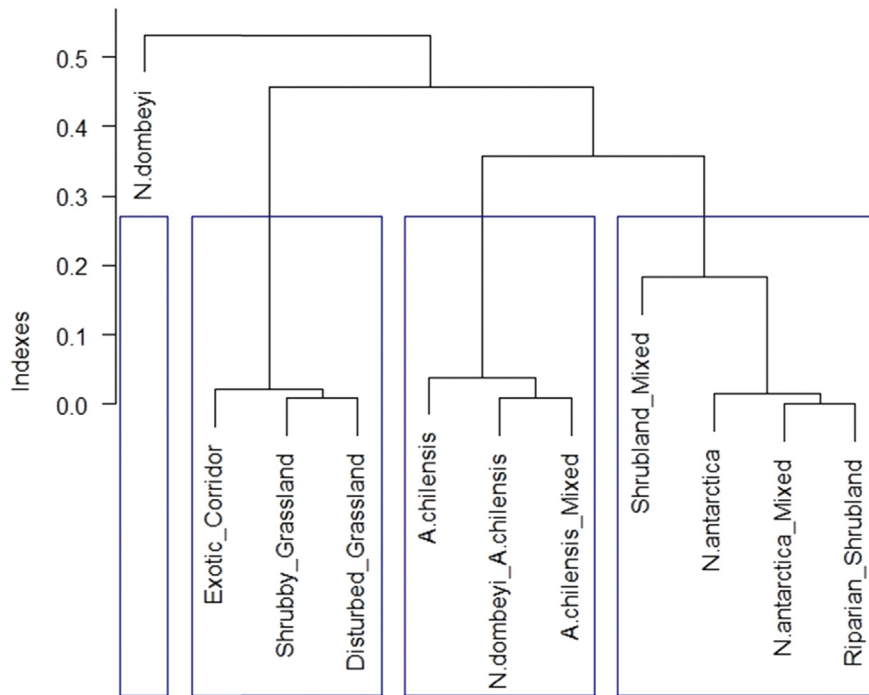


Fig. 10. VUs typology resulting from the Ascendant Hierarchical Classification Analysis performed after the Multiple Correspondence Factor Analysis. Grouped VUs constituted a class in the typology.

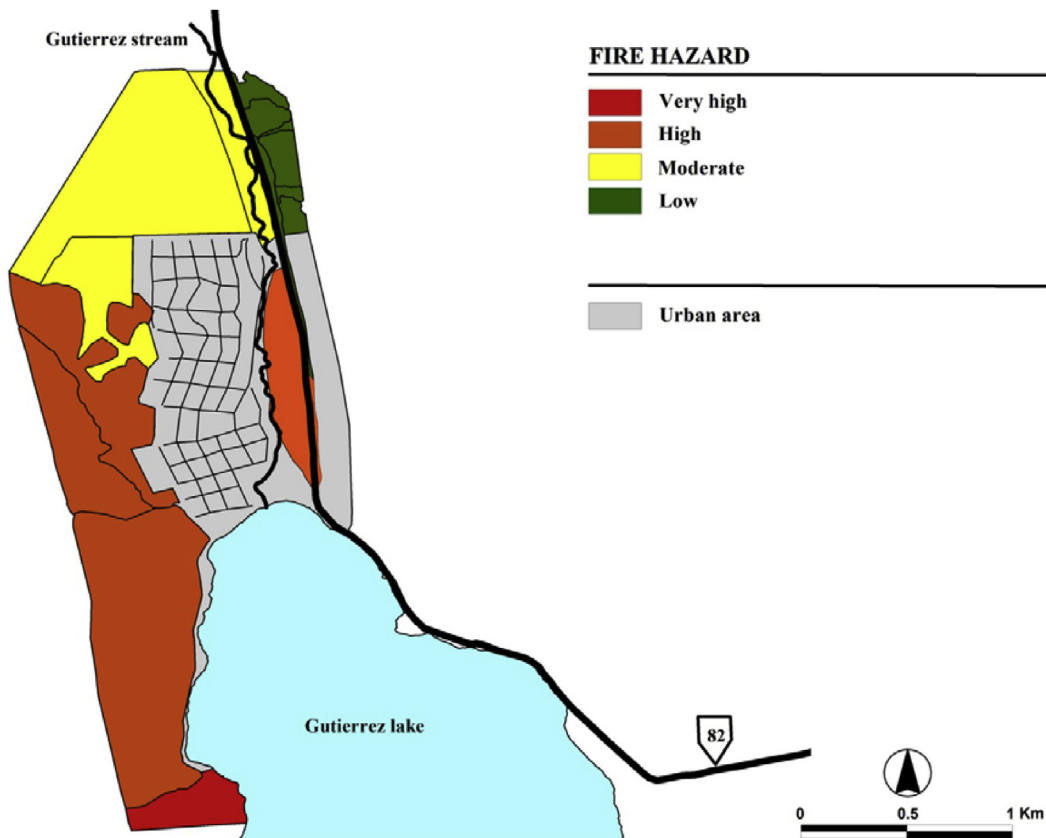


Fig. 11. Fire hazard map.

particularly scarce (Weindler, 1996; Beletzky, 2012; Bianchi and Defossé, 2015) or focus on the relationship between flammability

and cattle herbivory (Blackall et al., 2012). Hence, our study is the first in Northwestern Patagonia WUI areas that evaluated seven

flammability variables (see Figs. 5–8) of ten dominant woody species in eleven fire-prone Patagonian vegetation communities.

We found large differences in fire hazard among the 11 vegetation units in our study area. Dead fuel loads, vertical and horizontal fuel continuity varied greatly among plant communities. Furthermore, leaves of the dominant species varied in ignition probability, combustion duration, and temperature. This information is important in understanding species-level flammability and was previously lacking for these species.

Moisture content is considered an important component of flammability (Fig. 9; Santana and Marss, 2014) and varies with the weather because of the continuous interchange of moisture between the foliar tissues and the atmosphere. For this reason, we sampled leaves during a short period without precipitation that could increase the moisture content. Surprisingly *A. chilensis* (tree, Cupressaceae) and *F. imbricata* (shrub, Solanaceae) leaves had high moisture content. Both species have persistent, squamous and compact leaves typical of species adapted to stressful environments like sunny and rocky slopes. Despite the high content of secondary compounds (terpenes; Olate et al., 2011; Dudinszky and Ghermandi, 2013) the leaves of both species did not have high flammability; the high water content likely increased the thermal capacity of the tissue and inhibited combustion (White and Zipperer, 2010). Similarly, Gauteaume et al. (2013) showed that *Cupressus sempervirens* (tree, Cupressaceae) had very low flammability (ignition time: 35 s and combustion duration: 6 s). In contrast, the evergreen and coriaceous leaves of *N. dombeyi* (tree, Nothofagaceae) have the lowest moisture content and their flammability was the highest.

While our methods are commonly used to analyze foliar flammability (Liodakis et al., 2011; Pausas and Moreira, 2012), we did not measure species structural characteristics (e.g., bulk density) that could contribute to fire spread (Marino et al., 2011). Our community-level measures of dead fuel load and structure could be improved by the addition of such structural data. In addition to the variables we measured, future studies should also analyze in detail the network of paths and roads present in the study area, because the fundamental role of the accessibility in fire suppression. For example, isolated houses have high fire risk (Lampin-Maillet et al., 2010; Romero Calcerrada et al., 2008).

Vulnerability of population and property is an issue particularly important to urban planning. In Patagonia and in other Mediterranean ecosystems worldwide, cities could grow in a woody matrix (towards the west, approaching to the Andes, in western Patagonia) or in areas with less vegetation (towards the east, in semiarid steppe, in western Patagonia). The decision makers could use the results of this work as a tool to stimulate urban development in environments with lower fire risk, or to concentrate city growth in areas that are already urbanized. Such decisions may reduce wildfire losses in WUI areas (McAneney et al., 2009; Gill et al., 2013; Syphard et al., 2013).

Finally, we believe that the methodology proposed in this work can be adapted and replicated in other cities. The creation of fire hazard maps using a standard methodology could help identify where there are areas with high fire risk. Nevertheless, we are conscious that the elaboration of fire hazard maps is only a part of the new fire-management strategies that policy makers need to prevent tragedies like those that occurred in 2007 and 2009 in California and Australia (Gill et al., 2013; Penman et al., 2013; Stephens et al., 2014).

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.jenvman.2016.09.051>.

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