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Live fuel moisture content and leaf ignition of forest species in Andean Patagonia, Argentina

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Abstract. Wildfires are common from summer to early fall in Patagonian forests of Argentina. Live fuel moisture content (LFMC) and leaf ignition are important factors for understanding fire behaviour. In this study, we determined seasonal LFMC and leaf ignition of some key fire-prone species of these forests, and their relationships with environmental variables. Species investigated were the native trees ñire (*Nothofagus antarctica*) and cypress (*Austrocedrus chilensis*), the understorey tree-like radal (*Lomatia hirsuta*) and laura (*Schinus patagonicus*), the bamboo caña colihue (*Chusquea culeou*), and the non-native black poplar (*Populus nigra*). LFMC differed among species, with caña colihue having lower values (LFMC $<100\%$); ñire, laura, cypress, and radal having medium values (110–220%); and black poplar, upper values ($>220\%$). Ignition characteristics differed among species (caña colihue $>$ ñire $>$ radal $>$ cypress $>$ laura $>$ black poplar) and were inversely related to LFMC. Correlations between LFMC and environmental variables were highly significant for caña colihue, significant for ñire, radal, and laura, and weakly significant or non-significant for cypress and black poplar. These results contribute to our understanding of fire behaviour, and validate the fuel typology for Patagonian forests. At the same time, they add some useful knowledge for comparison with other fire-prone Mediterranean ecosystems around the world.

Additional keywords: fire behaviour, foliar moisture, Patagonian forests, wildfires.

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Introduction

In the Andean Patagonian region of Argentina, vegetation grows under a Mediterranean climate, with precipitation concentrated during winter and early spring, followed by a drought period that goes from mid-November to early April (late spring to early fall in the southern Hemisphere, Villalba 1995). Plants in this region have developed organs and physiological adaptations to water stress, including drought resistance and drought-evading mechanisms (Larcher 1983; Castro *et al.* 2003). Among these mechanisms, cessation of growth of aboveground structures during the summer is common for some shrubs of the region (Bertiller *et al.* 1991). Patagonian trees, instead, may have contrasting physiological adaptations. For example, cypress (*Austrocedrus chilensis* (D. Don) Pic.Serm. & Bizarri) avoids desiccation by maintaining high leaf moisture levels through closure of stomata (Gyenge *et al.* 2005, 2007). In contrast, ñire (*Nothofagus antarctica* (G. Forst.) Oerst.) leaves remain with their stomata open until leaf water potential drops below a threshold value of −2.7 MPa (Peri *et al.* 2009). The high air temperatures, low relative humidity, high winds and low soil water availability in the region during summer and early fall not only affect vegetation development, but also favour wildfire occurrence (Dentoni *et al.* 2001; Defossé *et al.* 2011).

In any terrestrial ecosystem, fuel moisture content plays a key role in the probability of fire ignition, initial fire spread and subsequent fire behaviour (Rothermel and Anderson 1966; Dimitrakopoulos and Bemmerzouk 2003). When a fire front advances, the heat released first vaporises the water contained in the fuel (Byram 1959). Then, if the energy required to heat fuel to combustion temperature is less than the energy available through convection and radiation from an adjacent flame, combustion occurs. In general, fire intensity, rate of spread and difficulty of fire control increase as fuel moisture content decreases (Matthews *et al.* 2007). Moisture content in plant living tissues (i.e. leaves and small twigs) – termed live fuel moisture content (LFMC) – is then a key parameter influencing crown ignition (Van Wagner 1977; Agee *et al.* 2002). However, and for the same species, differences in moisture content between live and dead foliage in the tree canopy may greatly affect foliage ignition and consumption (Kuljian and Varner 2013).

Leaf ignition is then an important parameter influencing fire initiation and spread (Trabaud 1974, 1976; Dimitrakopoulos and

Papaioannou 2001). These two parameters have often been related to LFMC (White and Zipperer 2010), and together with leaf chemical characteristics (Ormeño *et al.* 2009), physical leaf traits (Scarff and Westoby 2006; Engber and Varner 2012) and vegetation traits retained in dead fuels (Schwilk 2003), are components of what has been broadly termed 'vegetation flammability' (Pellizzaro *et al.* 2007; Alexander and Cruz 2013). Vegetation flammability has been defined as the ability of fuels to ignite and sustain a fire (Dimitrakopoulos and Papaioannou 2001), and includes three variables that describe (1) how well the fuel ignites (*ignitability*), (2) how well it burns (*combustibility*) and (3) for how long it burns (*sustainability*; Anderson 1970; White and Zipperer 2010; Curt *et al.* 2011; Ganteaume *et al.* 2011). Flammability of the litterbeds also includes the term *consumability*, which represents the percentage of the material that is consumed in this layer (Martin *et al.* 1994; Fonda 2001). Although in general these terms have been developed for laboratory studies, there are conceptual equivalents in the field when a wildfire occurs. These equivalents respectively are rate of spread, intensity and residence time (Gill and Zylstra 2005). In particular, leaf ignition and flammability are commonly measured or estimated using different methods and under different laboratory conditions (Xanthopoulos and Wakimoto 1993; Ganteaume *et al.* 2011; Madrigal *et al.* 2012). One method to determine either leaf ignition or flammability uses a standard epiradiator (Trabaud 1976; De Lillis *et al.* 2009). Leaf ignition could be simply determined by placing a known weight of leaf samples over the epiradiator and measuring time to ignition, ignition frequency and combustion duration. To determine flammability, however, additional information about leaf chemical characteristics, physical leaf traits and retained dead fuels is necessary. Besides the importance of flammability, and in addition to LFMC, information about leaf ignition of a particular plant or group of plants can improve understanding of fire development and the associated fire danger if an ignition occurs (Gill and Zylstra 2005).

In Patagonia, vegetation of the temperate forest–steppe region comprises several plant species that accumulate substantial living biomass during the growing season. Among them there are key species identified as important because of their wide extent or burning characteristics when wildfires occur. These species are the overstorey trees cypress and ñire and the understorey tree-like species laura (*Schinus patagonicus* (Phil.) I. M. Johnst. ex Cabrera) and radal (*Lomatia hirsuta* (Lam.) Diels ssp. *obliqua* (Ruiz & Pav.) R. T. Penn.). These trees grow in different arrays accompanied by a bamboo cane locally named caña colihue (*Chusquea culeou* E. Desv.) (Dimitri 1972; Schlichter and Laclau 1998). In this region, the non-native black poplar (*Populus nigra* var. *italica* (Munchh.) Koehne) has been widely planted to build windbreak barriers in agricultural fields. Apart from protecting these fields against dominant winds, black poplar has been shown through empirical observation to act as a fire barrier during wildfires (Dentoni *et al.* 1999).

A better understanding of the seasonal variation of LFMC and leaf ignition, and their relationships with some environmental variables is essential to improve our knowledge about burning characteristics and fire behaviour of these key species of Andean Patagonia in southern Argentina and Chile. This information is also important for fire managers working in prevention and control operations, and for characterising and evaluating the fuel typology being developed for the region. The objectives of this study were, therefore to (1) determine, during several growing seasons, the LFMC dynamics of the most representative native tree species of this forest–steppe ecotone (ñire and cypress), and also of the accompanying understorey species (laura, radal, and caña colihue); (2) determine LFMC of the non-native black poplar and compare its values with those of the native species; (3) determine possible relationships between LFMC and some of the most common environmental variables measured in the area (air temperature, relative humidity, precipitation and soil moisture); and (4) determine leaf ignition and its associated parameters (ignition frequency, ignition time and combustion duration) of all the species considered, and their relationship with LFMC. These results add new information about LFMC and leaf ignition, and their relationships with environmental factors of key species in Patagonia. The study will also contribute to add and expand this knowledge for comparison with other fire-prone Mediterranean ecosystems around the world.

Materials and methods

Species and study area

The study area is located in the forest–steppe ecotone of the central region of Sub-Andean Patagonia in Chubut Province, Argentina, in which ñire and cypress forests represent the dominant vegetation types. In Argentina, ñire forests occupy 750 000 ha, distributed in a long and narrow longitudinal belt at medium altitude on the eastern side of the Andes, spanning 19° of latitude from the 37 to the 56° SL parallels (Dimitri 1972). Ñire is a deciduous tree that may reach up to 10 m in height. This species is the only member of the Patagonian *Nothofagus* genus that vigorously re-sprouts after fire, changing its structure from a single-stemmed, tree-like form in pristine areas, to a multi-stemmed, shrub-like tree in areas exposed to recurrent fires (Dimitri 1972). Cypress forests occupy ~140 000 ha also distributed in a narrow belt at lower altitudes than ñire. Cypress forests span ~7° in latitude, from the 37 to the 44° SL parallels (Bran *et al.* 2002). Cypress is a perennial tree that generally grows in an erect form, reaching up to 22 m tall (La Manna *et al.* 2006). However, as a consequence of disturbances and changing environmental conditions, some structural differences can be observed among cypress stands (Kitzberger 2005). Laura is a broadleaf perennial shrub that grows up to 4 m tall, and radal (also a broadleaf perennial) is a small to medium-size tree that can reach up to 8 m tall. Caña colihue is a perennial, rhizomatous and shallow-rooted (up to 60-cm soil depth) bamboo cane that has shoots up to 5 cm in diameter and can reach 7 m tall (Dimitri 1972; Veblen 1982). In Patagonia, black poplar has been widely planted to provide windbreak barriers near ranch dwellings and agricultural fields.

An area in Los Cipreses, Chubut (43°14′SL, 71°34′WL, 550 m above sea level, ASL) was chosen to determine LFMC in ñire, cypress, laura, radal and caña colihue. Thirty km away from this area and 10 km from Esquel (42°54′ S, 71°10′W, 560 m ASL), another area was chosen to determine LFMC in black poplar plantations. Both study sites were representative of the dominant native vegetation and of the black poplar plantations present in this forest–steppe ecotone. Cypress stands were 10–12 m tall, while ñire stands were 3–5 m tall. Black poplar plantations were ~45–60 years old and 12–15 m tall.

LFMC dynamics

The dynamics of LFMC were determined during five consecutive growing seasons for ñire and cypress (2007–08 to 2011–12), two seasons for the understorey species laura, radal and caña colihue (2010–11 and 2011–12) and one season for black poplar (2009–10). Vegetation sampling was done every 10–15 days during the fire season (from around mid-November to early April). At every sampling date we collected, from randomly selected individuals of each species, 10 samples of living leaves (100 g from each individual tree) at ~2-m height. This height represents the portion of the crown at which a surface fire may become a crown fire (Fuglem 1979). Samples were taken from the north side of each individual tree (which is more exposed to solar radiation in the southern Hemisphere), on the assumption that leaves from this side of the tree will have the lowest moisture content (Fuglem 1979; Alessio *et al.* 2008). For cypress, we only sampled green leaves at the extreme end of the branches. Leaf samples were packed in individual hermetic bags and weighed on terrain to obtain their fresh weight. Samples were then taken to the laboratory in a closed box, oven dried at 105°C for 24 h and reweighed to obtain their dry weight. The LFMC of each species was then calculated using the gravimetric method.

Environmental and soil moisture data

Daily air temperature (°C), relative humidity (%) and 24 h of accumulated rainfall (mm), were recorded using a Vantage Pro2 Weather Station (Davis Instruments, Illinois, USA). We installed the station near the Los Cipreses study site, recording these meteorological data for each growing season from September to April. Long-term meteorological data (Fig. 1) were gathered from the Berwyn Ranch meteorological station, located 3 km away from the study site. During the sampling dates of 2010–11 and 2011–12, and at the same time as when LFMC data were determined, we also collected soil moisture samples at 10–30 and 30–60-cm soil depth ($n = 10$ samples per soil depth at each sampling date). These samples were taken at 10 randomly selected points at the Los Cipreses study site near the sampled cypress and ñire trees. Moisture content was calculated using the gravimetric method.

Ignition tests

Ignition tests were performed once per month on the same dates as LFMC sampling. Leaf ignition was determined by following the procedure described in Elvira and Hernando (1989) and in Valette (1990). Leaf samples (~600 g fresh weight) were collected at ~2-m height from 10 trees of each species. Samples were placed in plastic bags, taken to the laboratory in a portable cooler and put in a refrigerator until the next day, when we performed these tests. Each test consisted of 70 sub-tests. For each one, we randomly took some leaves from the collected samples and cut them into small pieces using scissors. These pieces were put inside a Petri box and weighed in a precision balance (0.1-g resolution), to within 1 g (fresh weight). Cut leaves were then put over a standard epiradiator of 500 W. A pilot flame was located 4 cm above the centre of the epiradiator. This flame allowed the ignition of the air–gas mixture resulting from the thermal decomposition of the sample, but it did not play any part in this decomposition. For each sub-test we measured three parameters: (a) ignition time, which is the time between the moment when the sample is put over the epiradiator and the appearance of the first flame; (b) combustion duration, which is the duration of the flame after ignition; and (c) ignition frequency, which represents the proportion of positive sub-tests over the 70 sub-tests performed (a sub-test was considered positive if the ignition time was less than 60 s). The final values of ignition time, combustion duration and ignition frequency resulted from averaging the data over the 70 sub-tests. Moisture content of the leaf material used during the tests was estimated using the standard gravimetric method taking four sub-samples from the leaves, two at the beginning and two at the end of the tests.

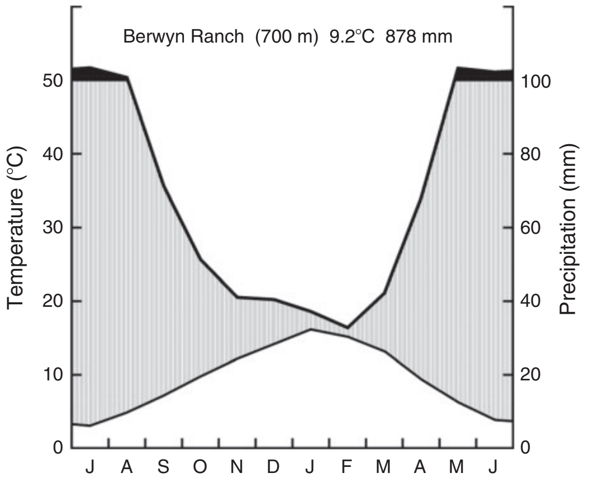

Fig. 1. Climatic diagram in the format of Walter and Lieth (1967). Data gathered from the Berwyn Ranch weather station, located 3 km away from the Los Cipreses study site. The lower line represents mean monthly temperatures, and the upper line mean monthly precipitation, both from the last 15 yr. The upper levels denote name of the station, altitude above sea level, mean annual temperature and mean annual precipitation. In the abscissa are shown the months starting from July to June (summer months are shown in the middle). The vertical shading area represents a humid period, and black area (scale reduced to 1/10) represents a per-humid period (mean monthly precipitation above 100 mm).

Statistical analyses

For each species, correlations were computed between LFMC and environmental variables during different periods (accumulated precipitation, air temperature, relative humidity and soil moisture content) using the Pearson's product moment correlation coefficient. We compared the soil moisture values in the 10–30 and 30–60-cm soil depth using a repeated-measures ANOVA. We combined the three ignition parameters for each species using principal components analysis (PCA, Blackhall *et al.* 2012). With PCA, a large number of independent variables can be systematically reduced to a smaller, conceptually more coherent set of variables. These 'principal components' are a linear combination of the original variables (Dunteman 1989). PCA scores were generated using standardised (mean = 0 and s.d. = 1) values for each parameter. We performed a regression analysis to study the relationships between ignition parameters and LFMC for each species. We used a hierarchical cluster analysis to group the species studied according to the ignition parameters measured during the tests. All statistical analyses were conducted with the software R, version 2.15.1 (R Core Team 2012).

Results

LFMC dynamics

In Andean Patagonia and for the six species analysed, LFMC dynamics had three different levels (Fig. 2*a*). In the lower level, represented by caña colihue, LFMC never surpassed 110% during the two seasons analysed. In the medium level, represented by ñire, cypress, laura and radal, LFMC ranged from 110 to 220%. The upper level, represented by black poplar, LFMC varied from 220 to 300% in the 2009–10 growing season.

Individually, LFMC of cypress varied subtly across the five seasons, with above-average peaks during January and February of the second growing season. The deciduous ñire followed similar trends in LFMC as cypress during the first, third, fourth and fifth seasons. Differences in LFMC were found between these two species during the second growing season analysed. For black poplar, maximum LFMC values were recorded in early to mid-summer during the 'green up' period (*sensu* Alexander 2010), when leaves fully expanded and before starting their aging process. The understorey species laura and radal had LFMC values that closely followed those of cypress and ñire. In contrast, caña colihue LFMC values peaked at the beginning of the growing season and steadily declined thereafter to the end of both recorded seasons (Fig. 2*a*).

Environmental and soil moisture data

During the growing seasons of 2007–08, 2008–09 and 2010–11, precipitation had similar distribution patterns (Fig. 2*b*). Accumulated precipitation at the end of each season was 276 mm, 270 mm and 294 mm, which represented rainfall 5, 3 and 12.5% higher than the long-term mean for that area (262 mm). Precipitation during the 2009–10 and 2011–12 growing seasons were the highest (380 mm) and the lowest (202 mm) of the five seasons considered, representing 44% higher and 24% lower than the long-term mean. During these two seasons, precipitation was concentrated during the summer months of January and February (106 mm for 2010 and 138 mm for 2012), being 51 and 97% higher than the long-term mean for these two months (70 mm). For the same months of 2008, 2009 and 2011, precipitation was 29, 2 and 31 mm, representing only 40, 3 and 43% of the long-term mean for these months. Temperature weekly means varied from 10 to 12°C in November of all five seasons considered, and peaked to above-average values (22–24°C) in January and December 2009, and January 2012. These high summer temperatures coincided with mid-summer drought periods. In contrast, mid-summer temperatures remained below long-term averages during the wet mid-summers of 2009–10

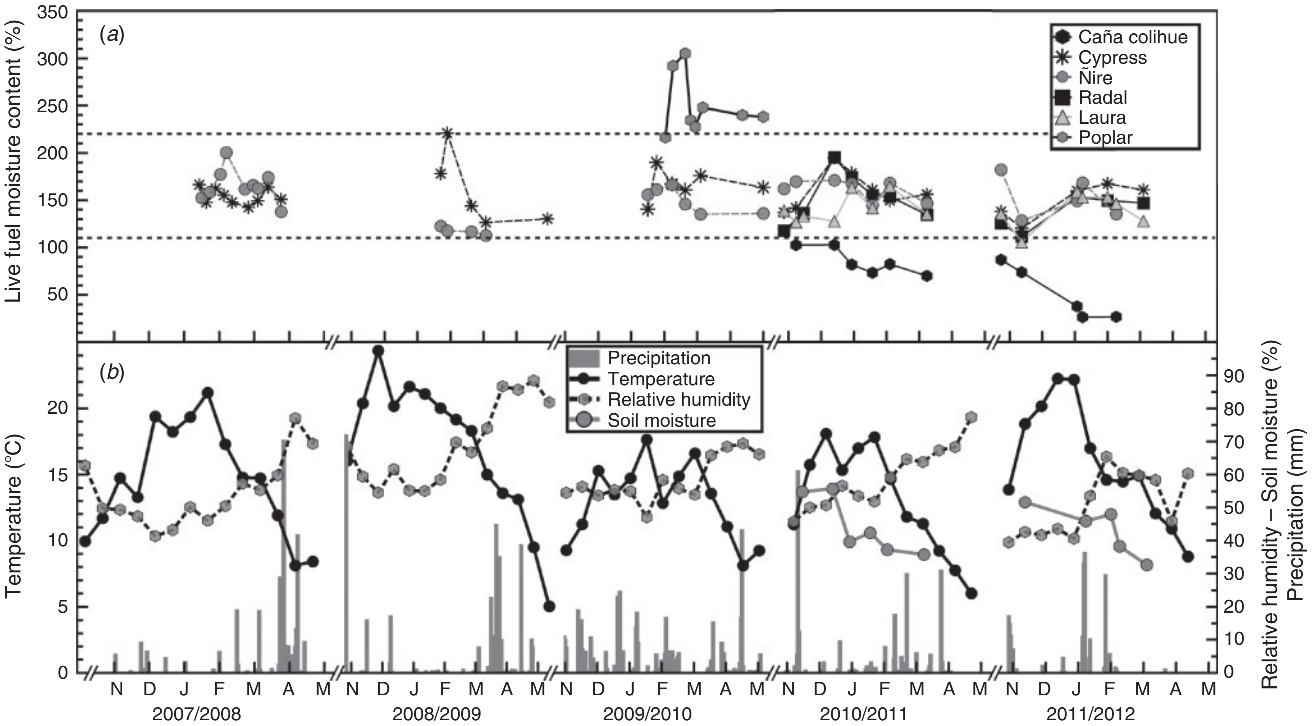

Fig. 2. (*a*) Seasonal dynamics of LFMC of the Patagonian species studied (mean values), and (*b*) environmental factors measured in the study area. Soil water content data represent average values for $n = 20$ samples taken at 10–60-cm soil depth, and were gathered simultaneously with LFMC; temperatures and relative humidity curves represent weekly averages, and bars represent the last 24 h of accumulated precipitation. For LFMC and soil moisture data, the standard errors were always lower than 10% of their respective mean values.

and 2010–11. Relative humidity values had the reverse trend compared with weekly temperatures. Differences between soil moisture values in the 10–30 and 30–60-cm soil depth were non-significant ($F(1,10) = 1.12$, $P = 0.31$), and their dynamics followed the same pattern in the two seasons considered. For this reason, all soil moisture data were pooled and averaged to represent the whole profile from 10 to 60-cm soil depth (Fig. 2*b*). These values were high (around 55%) at the beginning of both growing seasons and steadily declined as the summer season progressed (32% at the end of both growing seasons).

Relationships between LFMC and environmental and soil variables

For the last two seasons (2010–11 and 2011–12), positive ($r \geq 0.51$) and significant ($P < 0.05$) correlations were found between LFMC and soil moisture content at 10–60-cm soil depth for caña colihue, ñire and laura, while cypress and radal had non-significant ($P \geq 0.14$) correlations (Table 1). Related to accumulated precipitation, all native species had positive ($r \geq 0.55$) and significant ($P \leq 0.07$) correlations with LFMC, while for the non-native black poplar, it was not significant ($P = 0.13$). For ñire, laura, radal and caña colihue, these correlations were significant when LFMC was compared with the previous 30 days of accumulated precipitation. For cypress, instead, this correlation was significant only when the previous 90-days rain period was considered. LFMC of caña colihue was significantly correlated with both average relative humidity and temperatures of the previous 60 days. These correlations were positive ($r = 0.73$) when relative humidity was correlated with LFMC and negative ($r = -0.82$) when LFMC was correlated with temperatures. LFMC of ñire, laura and radal were positively ($r \geq 0.37$) correlated with mean temperatures. Correlations between LFMC of cypress and black poplar with average relative humidity and temperature were non-significant ($P \geq 0.19$, Table 1).

Leaf ignition

Leaf ignition parameters varied widely for the six species. The PCA for leaf ignition of the six species explained 95.5% of the variation with the first two principal components (Fig. 3). All parameters were closely related to Axis 1 (PCF1), explaining 88.5% of the variance. Axis 2 (PCF2), in turn, only added 6.9% of the variation of leaf ignition, and correlations between the variables analysed and this axis are very poor (<0.40). Ignition frequency and combustion duration were positively correlated with PCF1 (0.92 and 0.99), and ignition time and moisture content were negatively correlated with PCF1 (−0.94 and −0.87). The results of the hierarchical cluster analysis allowed grouping the six species in four clusters according to their ignition parameters (dotted circles in Fig. 3). Caña colihue was categorised as highly ignitable, ñire and radal as moderately ignitable, cypress as ignitable and laura and black poplar as poorly ignitable. The more ignitable species had large positive values for PCF1, whereas less ignitable species had large negative values for this axis (Fig. 3). Ignition time was very rapid for caña colihue (11.2 s), and increased in the following order: ñire, radal, laura, black poplar and cypress (23.3 s, Table 2). Combustion duration presented instead a reverse trend, with the shortest duration being for black poplar (3.1 s) followed by laura, cypress, ñire, radal and caña colihue (18.6 s, Table 2). Ignition frequency was the highest in caña colihue (97%), decreasing thereafter for ñire, radal, cypress, laura and black poplar (Table 2).

Ignition parameters and their relationships with LFMC

The PCA showed that LFMC was negatively correlated with leaf ignition and that the species analysed could be ordered from less to highly ignitable according to their LFMC. The only exception was laura (Fig. 3 and Table 2), which had low ignitability even though it had low levels of LFMC. Linear regression analyses were performed to determine the relationships between LFMC and ignition parameters for each species (Table 3). The analyses showed highly significant linear relationship when all the species were considered together. However, relationships between LFMC and ignition parameters differed among individual species. For caña colihue, radal and laura, all regressions were non-significant. For cypress, regressions were highly significant when LFMC was correlated with each of the three ignition parameters. For black poplar, the linear regression between ignition time and LFMC was non-significant. For ñire, linear regressions were significant when LFMC was related to ignition time and combustion duration.

Discussion

In any forest ecosystem, LFMC of vegetation plays an important role because it may retard ignition or mitigate fire propagation. In this study, we presented the results of the seasonal LFMC and

Table 1. Correlations between LFMC and environmental variables

Pearson's correlation coefficients (*r*) between LFMC, soil moisture and weather variables (precipitation, air temperature and relative humidity) for each species and period analysed

Species	Soil moisture 10–60 cm			Precipitation (mm)			Temperature (°C)			Relative humidity (%)		
	r	Period (days)	*P*-value	*r*	Period (days)	*P*-value	*r*	Period (days)	*P*-value	*r*	Period (days)	*P*-value
Ñire	0.56	20–30	0.04	0.75	30	0.07	0.42	30	0.070	−0.44	20	0.04
Laura	0.51	20–30	0.07	0.64	30	0.04	0.80	60	0.006	−0.71	60	0.02
Caña colihue	0.82	20–30	<0.001	0.57	30	0.07	−0.82	60	0.004	0.73	60	0.01
Cypress	−0.38	90	0.14	0.55	90	0.01	0.38	90	0.190	−0.29	90	0.21
Radal	−0.32	20–30	0.22	0.62	30	0.05	0.80	60	0.030	0.75	60	0.04
Black poplar	–[A]	–[A]	–[A]	0.58	20	0.13	−0.40	90	0.230	0.46	10	0.21

[A] Soil moisture in poplar sites was not measured.

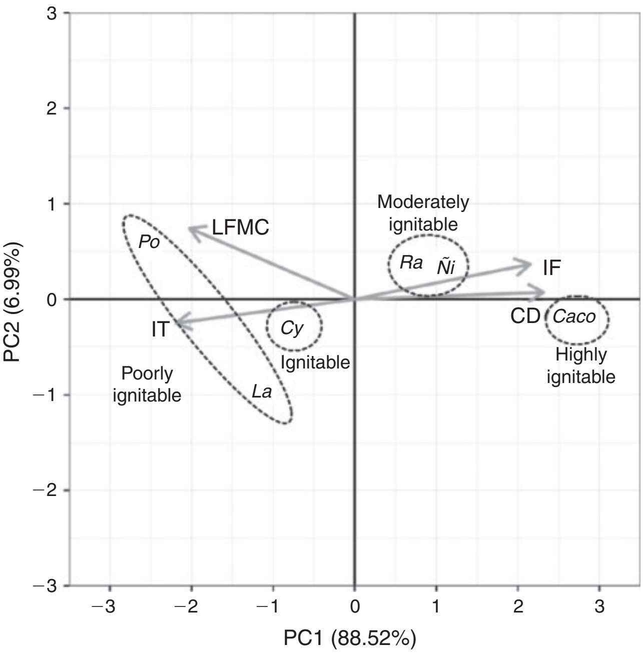

Fig. 3. PCA and hierarchical cluster results. Vectors represent correlations between ignition parameters and principal components 1 and 2. CD, combustion duration; IF, ignition frequency; IT, ignition time; LFMC, live fuel moisture content. Dotted circles group species according to their ignitability. Cy, cypress; Caco, caña colihue; Ra, radal; Ñi, ñire; La, laura; Po, poplar.

leaf ignition of six key fire-prone species of Patagonian forest–steppe ecotone and their relationships with environmental variables. With the exception of the 2008–09 growing season, the dominant trees ñire and cypress had similar LFMC dynamics among the seasons analysed. Differences in LFMC values for ñire (110–130%) as compared with those of cypress (180–220%) during the hot and dry conditions of the 2008–09 growing season may have been related to the intrinsic characteristics of each species (cypress is a perennial, and ñire a deciduous tree), and to the structural and physiological adaptations to water stress that characterise both species. The severe water stress experienced during this particular season may have greatly affected LFMC in ñire, being almost inconsequential for cypress. This hypothesis may be supported with other data, such as when LFMC of both species was correlated with meteorological and soil moisture content variables. While LFMC of cypress was only correlated with 90 days of accumulated precipitation, ñire LFMC was significantly correlated with soil moisture content, temperatures and precipitation values measured during the previous 30 days (Table 1).

Black poplar was the only species that had non-significant correlations with meteorological variables (Table 1). The lack of correlations may be due to black poplar's own structural and physiological characteristics, particularly to its extensive deep root system that taps water from the water table. These characteristics make its LFMC independent from its surrounding environmental factors or the upper soil moisture conditions. At the other extreme is caña colihue: LFMC of this shallow-rooted

Table 2. Leaf ignition parameters and mean live fuel moisture content (LFMC) for each species analysed in Patagonia

Mean values of leaf ignition parameters determined for each of the species analysed. Mean LFMC is the average moisture content value of $n = 70$ samples during leaf ignition tests

Species	Ignition time (s)	Combustion duration (s)	Ignition frequency (%)	Mean LFMC (%)
Caña colihue	11.2	18.6	97.7	74.9
Ñire	15.0	12.6	91.1	135.6
Radal	17.2	13.5	89.9	151.9
Cypress	23.3	7.5	72.7	153.1
Laura	22.8	7.2	42.8	144.5
Black poplar	22.9	3.1	40.4	252.0

Table 3. Linear regression statistics of live fuel moisture content (%) and leaf ignition parameters

The intercept (*a*) and slope (*b*) parameters, the coefficient of determination (R^2) and the significance levels (P) of the regressions are shown. n.s., not significant at $P > 0.05$

Species	Ignition frequency				Ignition time				Combustion duration			
	a	*b*	R^2	*P*	*a*	*b*	R^2	*P*	*a*	*b*	R^2	*P*
All combined	130.38	−0.37	0.43	<0.001	8.57	0.07	0.38	<0.001	22.76	−0.08	0.61	<0.001
Caña Colihue	110.26	−0.16	0.02	n.s.	−13.49	0.33	0.22	n.s.	1.18	0.24	0.14	n.s.
Ñire	152.07	−0.45	0.19	n.s.	−18.99	0.25	0.51	0.02	49.75	−0.28	0.65	0.008
Radal	229.23	−0.91	0.29	n.s.	−20.45	0.25	0.52	n.s.	42.88	−0.19	0.33	n.s.
Cypress	251.33	−1.16	0.65	0.008	−20.28	0.28	0.74	0.002	21.49	−0.09	0.49	0.03
Laura	211.56	−1.23	0.28	n.s.	18.21	0.03	0.02	n.s.	23.83	−0.13	0.42	n.s.
Black poplar	218.10	−0.71	0.45	0.07	2.62	0.08	0.25	n.s.	13.79	−0.04	0.50	0.05

bamboo was highly correlated with all the environmental and soil variables measured (Table 1). LFMC of laura, which possesses a shallow root system as compared with those of radal and cypress, was also significantly correlated with soil moisture at 10–60-cm soil depth. For the latter two species, whose roots penetrate deep into the soil profile, LFMC was not correlated with upper soil moisture fluctuations (Table 1).

Blackhall *et al.* (2012), reported LFMC values for ñire, laura and radal that were similar to those found in our study. However, when LFMC of these species are compared with those of related species grown in other Mediterranean ecosystems, results showed similarities and also discrepancies. LFMC values of Patagonian cypress were higher than those reported for *Juniperus phoenicia*, *Cupressus arizonica* and *C. sempervirens* grown in the Mediterranean basin (Valette 1990; Pellizzaro *et al.* 2007), or for *J. pinchotii* Sudw. grown in North America (Bunting *et al.* 1983). Cypress, however, had similar LFMC trends to those of related species of the European basin during the summer season (Valette 1990; Pellizzaro *et al.* 2007). The LFMC dynamics of ñire closely followed those of the related species *Quercus ilex* and *Castanea sativa* during the summer. Absolute LFMC values of ñire, however, lie between those reported for both European species (Valette 1990). In the case of black poplar, a comparison could be made with trembling aspen (*Populus tremuloides* Michx.), widely distributed in western North America (Fowells 1965). Although we did not find specific LFMC values for this North American species, trembling aspen has long been considered as the 'asbestos forest' because it does not readily burn during summer conflagrations when its leaves are green (Wright and Bailey 1982; DeByle *et al.* 1987; Keyser *et al.* 2005; Alexander 2010). This fire behaviour coincides with observations made when fires reached black poplar plantations in Patagonia, in which their intensity and rate of spread diminished (Dentoni *et al.* 1999). This behaviour is, however, completely different to what usually occurs when wildfires involve nearby native vegetation or pine plantations in this region. The fact that black poplar had very high LFMC and low levels of leaf ignition (according to the parameters measured), makes it promising for use as a firebreak in pine afforestations being developed in Patagonia. However, and since we presented results for only one season, an extension of data sampling of LFMC and leaf ignition along other seasons may be necessary to fully recommend it as firebreak barrier.

Our results revealed a close relationship between LFMC and most leaf ignition parameters. In general for the six species analysed, and despite some non-significant correlations, when LFMC decreased, leaf ignition increased (Tables 2 and 3). This is also shown by the PCA analysis, which revealed that it may be redundant to analyse a parameter different from LFMC to estimate the ease of leaf ignition for these six species (Fig. 3). These results agree with those of previous studies carried out in other regions and with different plant species (Trabaud 1974; Xanthopoulos and Wakimoto 1993; Dimitrakopoulos and Papaioannou 2001). However, some species are more flammable than others and may present differences in ignitability even at the same water content (Trabaud 1976; Massari and Leopaldi 1998). For example in our study, laura had LFMC values similar to those of more flammable species, but according to the ignition tests and the cluster analysis, it was classified as a poorly ignitable species (Tables 2, Fig. 3). Of the other species analysed, those having low LFMC were classified as highly ignitable, and those having high LFMC were classified as poorly ignitable species (Table 2, Fig. 3). Ignition parameters of cypress were negatively related to changes in LFMC; low LFMC levels imply high leaf ignitability and high levels in LFMC low leaf ignitability. For ñire leaves, in contrast, LFMC was not significantly correlated with ignition frequency. This parameter was always high despite changes in LFMC. For radal, laura and caña colihue, leaf ignition was poorly or not correlated with changes in LFMC. Independent of their changes in LFMC, laura leaves always had poor ignitability, whereas leaves of radal and caña colihue were always highly ignitable. For caña colihue, LFMC varied around very low values, making it a highly flammable species despite the non-significant relationship found between LFMC and its ignition parameters. On the other hand, changes in LFMC of black poplar are highly related to its ignition parameters, showing that it is a poorly flammable species that consistently has high LFMC values (Table 3). Although our results on leaf ignition for the six Patagonian species studied could give a rough idea of their flammability, they should not be used as a substitute for this parameter. As mentioned before, leaf traits, leaf chemical compounds and the retention and variation of dead branches and dead leaves' position in the canopy may produce different local temperatures and heat release, and change flammability even for the same species (Schwilk 2003; Kuljian and Varner 2013).

The regression equations and the relationships between LFMC and the leaf ignition parameters seemed to be species specific, confirming findings reported by other authors that studied leaf flammability (Valette 1990; Dimitrakopoulos and Papaioannou 2001; Pellizzaro *et al.* 2007). Our results add new information about LFMC, leaf ignition and their relationships with environmental factors of key species of Andean Patagonia. These confirm the importance of these two parameters in determining crown ignition. These results also contribute to add and expand this knowledge for comparison with other fire-prone Mediterranean ecosystems around the world.

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References

Agee JK, Wright CS, Williamson N, Huff MH (2002) Foliar moisture content of Pacific Northwest vegetation and its relation to wildland fire behavior. *Forest Ecology and Management* **167**, 57–66. doi:10.1016/S0378-1127(01)00690-9

Alessio GA, Peñuelas J, Llusià J, Ogaya R, Estiarte M, De Lillis M (2008) Influence of water and terpenes on flammability in some dominant Mediterranean species. *International Journal of Wildland Fire* **17**, 274–286. doi:10.1071/WF07038

Alexander ME (2010) Surface fire spread potential in trembling aspen during summer in the Boreal Forest Region of Canada. *Forestry Chronicle* **86**, 200–212. doi:10.5558/TFC86200-2

Alexander ME, Cruz MG (2013) Assessing the effect of foliar moisture on the spread rate of crown fires. *International Journal of Wildland Fire* **22**, 415–427. doi:10.1071/WF12008

Anderson HE (1970) Forest fuel ignitability. *Fire Technology* **6**, 312–319. doi:10.1007/BF02588932

Bertiller MB, Beeskow AM, Coronato F (1991) Seasonal environmental variation and plant phenology in arid Patagonia (Argentina). *Journal of Arid Environments* **21**, 1–11.

Blackhall M, Raffaele E, Veblen TT (2012) Is foliar flammability of woody species related to time since fire and herbivory in northwest Patagonia, Argentina? *Journal of Vegetation Science* **23**, 931–941. doi:10.1111/J.1654-1103.2012.01405.X

Bran D, Pérez A, Barrios D, Pastorino M, Ayesa J (2002) Eco-región valdiviana: distribución actual de los bosques de 'ciprés de la cordillera' (*Austrocedrus chilensis*)-Escala 1 : 250.000. INTA – Administración de Parques Nacionales – Fundación Vida Silvestre Argentina. (Bariloche, Río Negro)

Bunting SC, Wright HA, Wallace WH (1983) Seasonal variation in the ignition time of redberry juniper in West Texas. *Journal of Range Management* **36**, 169–171. doi:10.2307/3898155

Byram GM (1959) Combustion of forest fuels. In 'Forest Fire: Control and Use' (Ed. KP Davis) pp. 61–89. (McGraw-Hill: New York)

Castro FX, Tudela A, Sebastià MT (2003) Modeling moisture content in shrubs to predict fire risk in Catalonia (Spain). *Agricultural and Forest Meteorology* **116**, 49–59. doi:10.1016/S0168-1923(02)00248-4

Curt T, Schaffhauser A, Borgniet L, Dumas C, Estève R, Ganteaume A, Jappiot M, Martin W, N'Diaye A, Poilvet B (2011) Litter flammability in oak woodlands and shrublands of southeastern France. *Forest Ecology and Management* **261**, 2214–2222. doi:10.1016/J.FORECO.2010.12.002

De Lillis M, Bianco PM, Loreto F (2009) The influence of leaf water content and isoprenoids on flammability of some Mediterranean woody species. *International Journal of Wildland Fire* **18**, 203–212. doi:10.1071/WF07075

DeByle NV, Bevins CD, Fischer WC (1987) Wildfire occurrence in aspen in the interior western United States. *Western Journal of Applied Forestry* **2**, 73–76.

Defossé GE, Loguercio GA, Oddi FJ, Molina JC, Kraus PD (2011) Potential CO_2 emissions mitigation through forest prescribed burning: a case study in Patagonia, Argentina. *Forest Ecology and Management* **261**, 2243–2254. doi:10.1016/J.FORECO.2010.11.021

Dentoni MC, Defossé GE, Rodríguez NF, Muñoz MM, Colomb H (1999) Estudio de Grandes Incendios: El caso de la Ea. San Ramón en Bariloche, Río Negro – Patagonia Argentina. Plan Nacional de Manejo del Fuego – CIEFAP–GTZ. (Esquel, Chubut)

Dentoni MC, Defossé GE, del Valle HF, Labraga JC (2001) Atmospheric and fuel conditions related to the Puerto Madryn Fire of January 21, 1994. *Meteorological Applications* **8**, 361–370. doi:10.1017/S1350482701003127

Dimitrakopoulos AP, Bemmerzouk AM (2003) Predicting live herbaceous moisture content from a seasonal drought index. *International Journal of Biometeorology* **47**, 73–79.

Dimitrakopoulos AP, Papaioannou KK (2001) Flammability assessment of Mediterranean forest fuels. *Fire Technology* **37**, 143–152. doi:10.1023/A:1011641601076

Dimitri MJ (1972) 'La región de los Bosques Andino-Patagónicos.' (INTA: Buenos Aires)

Dunteman GH (1989) 'Principal Components Analysis.' Vol. 69. (Sage Publications: Newbury Park, CA)

Elvira LM, Hernando C (1989) Inflamabilidad y energía de las especies de sotobosque: estudio piloto con aplicación a los incendios forestales. Monografías INIA N°68. (Ministerio de Agricultura Pesca y Alimentación: Madrid)

Engber EA, Varner JM, III (2012) Patterns of flammability of the California oaks: the role of leaf traits. *Canadian Journal of Forest Research* **42**, 1965–1975. doi:10.1139/X2012-138

Fonda RW (2001) Burning characteristics of needles from eight pine species. *Forest Science* **47**, 390–396.

Fowells HA (1965) Silvics of forest trees of the United States. USDA Forest Service, Agriculture Handbook No. 271. Prepared by the Division of Timber Management Research, Forest Service (Washington, DC)

Fuglem PL (1979) Foliar moisture content of Central Alberta conifers and its implications in crown fire occurrence. MSc thesis, University of Alberta, Edmonton.

Ganteaume A, Guijarro M, Jappiot M, Hernando C, Lampin-Maillet C, Pérez-Gorostiaga P, Vega JA (2011) Laboratory characterization of firebrands involved in spot fires. *Annals of Forest Science* **68**, 531–541. doi:10.1007/S13595-011-0056-4

Gill AM, Zylstra P (2005) Flammability of Australian forests. *Australian Forestry* **68**, 87–93. doi:10.1080/00049158.2005.10674951

Gyenge JE, Fernández ME, Dalla Salda G, Schlichter T (2005) Leaf and whole plant water relations of the Patagonian conifer *Austrocedrus chilensis* (D. Don) Pic.Serm. & Bizarri: implication on its drought resistance capacity. *Annals of Forest Science* **62**, 297–302. doi:10.1051/FOREST:2005024

Gyenge JE, Fernández ME, Schlichter T (2007) Influence of radiation and drought on gas exchange on *Austrocedrus chilensis* seedlings. *Bosque* **28**, 220–235. doi:10.4067/S0717-92002007000300006

Keyser TL, Smith FW, Shepperd WD (2005) Trembling aspen response to a mixed-severity wildfire in the Black Hills, South Dakota, USA. *Canadian Journal of Forest Research* **35**, 2679–2684. doi:10.1139/X05-180

Kitzberger T (2005) Hacia una tipología forestal basada en procesos dinámicos: el caso Ciprés de la Cordillera. In 'Actas de 1er Reunión sobre Ecología, Conservación y Uso de los Bosques de Ciprés de la Cordillera – Ecociprés'. (Ed. CIEFAP) pp. 13–18 (Esquel, Chubut)

Kuljian H, Varner JM (2013) Foliar consumption across a sudden oak death chronosequence in laboratory fires. *Fire Ecology* **9**, 33–44. doi:10.4996/FIREECOLOGY.0903033

La Manna L, Bava J, Collantes M, Rajchenberg M (2006) Características estructurales de los bosques de *Austrocedrus chilensis* afectados por "mal del ciprés" en Patagonia, Argentina. *Bosque* **27**, 135–145. doi:10.4067/S0717-92002006000200008

Larcher W (1983) 'Physiological Plant Ecology.' (Springer-Verlag: Berlin)

Madrigal J, Marino E, Guijarro M, Hernando C, Díez C (2012) Evaluation of the flammability of gorse (*Ulex europaeus* L.) managed by prescribed burning. *Annals of Forest Science* **69**, 387–397. doi:10.1007/S13595-011-0165-0

Martin RE, Gordon DA, Gutierrez ME, Lee DS, Molina DM, Schroeder RA, Sapsis DB, Stephens SL, Chambers M (1994) Assessing the flammability of domestic and wildland vegetation. In 'Proceedings of the 12th Conference on Fire and Forest Meteorology', 26–28 October 1993, Jekyll Island, GA. pp. 130–137 (Society of American Foresters: Bethesda, MD)

Massari G, Leopaldi A (1998) Leaf flammability in Mediterranean species. *Plant Biosystems* **132**, 29–38. doi:10.1080/11263504.1998.10654189

Matthews S, McCaw WL, Neal JE, Smith RH (2007) Testing a process-based fine fuel moisture model in two forest types. *Canadian Journal of Forest Research* **37**, 23–35. doi:10.1139/X06-207

Ormeño E, Céspedes B, Sánchez IA, Velasco-García A, Moreno JM, Fernandez C, Baldy V (2009) The relationship between terpenes and flammability of leaf litter. *Forest Ecology and Management* **257**, 471–482. doi:10.1016/J.FORECO.2008.09.019

Pellizzaro G, Duce P, Ventura A, Zara P (2007) Seasonal variations of live moisture content and ignitability in shrubs of the Mediterranean Basin. *International Journal of Wildland Fire* **16**, 633–641. doi:10.1071/WF05088

Peri PL, Martínez Pastur G, Lencinas MV (2009) Photosynthetic response to different light intensities and water status of two main Nothofagus species of southern Patagonian Forest, Argentina. *Journal of Forest Science* **55**, 101–111. Available at http://www.agriculturejournals.cz/web/jfs.htm?volume=55&firstPage=101&type=publishedArticle [Verified 18 December 2014]

R Core Team (2012). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available at http://www.R-project.org/ [Verified 18 December 2014]

Rothermel RC, Anderson HE (1966) Fire spread characteristics determined in the laboratory. USDA Forest Service, Intermountain Forest and Range Experiment Station, Research Paper INT-30 (Ogden, UT)

Scarff FR, Westoby M (2006) Leaf litter flammability in some semi-arid Australian woodlands. *Functional Ecology* **20**, 745–752. doi:10.1111/J.1365-2435.2006.01174.X

Schlichter T, Laclau P (1998) Ecotono estepa-bosque y plantaciones forestales en la Patagonia norte. *Ecología Austral* **8**, 285–296.

Schwilk DW (2003) Flammability is a niche construction trait: canopy architecture affects fire intensity. *American Naturalist* **162**, 725–733. doi:10.1086/379351

Trabaud L (1974) Experimental study on the effects of prescribed burning on a *Quercus coccifera* L. garrigue: early results. *Tall Timbers Fire Ecology Conference Proceedings* **13**, 97–129.

Trabaud L (1976) Inflammabilité et combustibilité des principales espèces de garrigues de la région méditerranéenne. *Acta Oecologica. Oecologica Plantarum* **11**, 117–136.

Valette JC (1990) Inflammabilité des espèces forestières Mediterranéennes. Conséquences sur la combustibilité des formations forestières. *Revue Forestiére Francaise* **42**, 76–92. doi:10.4267/2042/26171

Van Wagner CE (1977) Conditions for the start and spread of crown fire. *Canadian Journal of Forest Research* **7**, 23–34. doi:10.1139/X77-004

Veblen TT (1982) Growth patterns of Chusquea bamboos in the understory of chilean *Nothofagus* forests and their influences in forest dynamics. *Bulletin of the Torrey Botanical Club* **109**, 474–487. doi:10.2307/2996488

Villalba R (1995) Climatic influences on forest dynamics along the forest–steppe ecotone in northern Patagonia. PhD thesis, University of Colorado, Boulder, CO.

Walter H, Lieth H (1967) 'Klimmadiagram Weltatlas' (Fischer-Verlag: Jena)

White RH, Zipperer WC (2010) Testing and classification of individual plants for fire behaviour: plant selection for the wildland–urban interface. *International Journal of Wildland Fire* **19**, 213–227. doi:10.1071/WF07128

Wright HA, Bailey AW (1982) 'Fire Ecology. United States and Canada' (John Wiley and Sons: New York)

Xanthopoulos G, Wakimoto RH (1993) Time to ignition – temperature–moisture relationship for branches of three western conifers. *Canadian Journal of Forest Research* **23**, 253–258. doi:10.1139/X93-034