

Research Paper

Flammability of Patagonian invaders and natives: When exotic plant species affect live fine fuel ignitability in wildland-urban interfaces

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ABSTRACT

The increasing influx of people moving to woodland environments in order to access social and natural amenities is generating conflicts which are becoming ever more intense and complex. Urban-forest interface issues are currently among the most serious and problematic issues for forest managers. The wildland-urban interface has grown in size in Patagonia because of an increase in area of human settlements intermingled with natural vegetation, giving rise to a disturbing new landscape dynamic associated with wildfires. Through laboratory tests we produced the first flammability plant list for northwest Patagonia, which includes exotic species that can frequently be found in wildland-urban interface areas. We identified groups of species according to live fine fuel characteristics and detected different types of flammability, based on ignitability and heat release. Our plant list allows comparison of native and exotic species, and the formulation of precautionary action to minimize environmental and economic risks.

1. Introduction

In many ecosystems it is difficult to distinguish the effects of climate variation from the influence of changes in land use (Veblen et al., 2011), for example, the introduction of exotic species (for instance, through cattle browsing, exotic pine plantations). In this context, fire plays a major role in determining future landscape patterns (Gardner, Hargrove, Turner, & Romme, 1996). Changes in land use practices or the introduction of ornamental species for hedging or gardening that alter fuel conditions may change fire regimes in natural environments, as well as in the surrounding cities and towns, producing irreversible changes. This ecological damage represents considerable economic loss to human populations, and especially to the rural communities that live in these landscapes. Urban development in natural areas presents an environmental challenge in a broad sense, involving habitat fragmentation, introduction of invasive species into natural areas, alteration of hydrological cycles (Radeloff et al., 2005) and the creation of a new risk-prone area: the wildland-urban interface.

The extension of the wildland-urban interface in Patagonia, due to an increase in area of human settlements inserted within natural vegetation, constitutes a disturbing new landscape dynamic in relation to wildfires. Here (Bühler, de Torres Curth, & Garibaldi, 2013), as in other parts of the globe (Chas-Amil, Touza, & García-Martínez, 2013; Mercer & Prestemon, 2005), fire events over recent decades have increased in

parallel with the spatial and temporal rise in human population density. For example, approximately 45% of fires recorded in the extended region of Patagonia occur in the surroundings of Bariloche, the most populated city in Andean Patagonia, which is located in the conservation area of Nahuel Huapi National Park (de Torres Curth, Ghermandi, & Pfister, 2008). These fires are mainly associated with a wildland-urban interface dominated by a mixture of shrublands, forests and old pine plantations. Furthermore, the number of these fires is correlated with low-income neighborhoods, thus increasing the negative social impact (de Torres Curth, Biscayart, Ghermandi, & Pfister, 2012). In addition to a low social perception of this new risk, the sprawling, disorganized expansion of these wildland-urban interfaces is likely to continue its upward trend in the region. For instance, the population growth rate of Bariloche is twofold greater than the national mean (Medina, 2017). On the other hand, climate-change models for the second half of the XXI century for the Patagonian region show trends characterized by an extension of the warmer season, and an increase in drought due to an increase in temperature and a decrease in rainfall (Holz et al., 2017). These climatic conditions, together with the increase in interface areas, make it necessary to obtain information on the flammability of native and introduced species growing in natural and rural environments, so as to enable prevention or reduction of interface fires in the short and medium term. Over recent years, pioneer studies in the region have explored fire dynamics in the wildland-urban

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interface. These studies have contributed valuable information on the demographic and socioeconomic influence of local human populations on fire regime (Bühler et al., 2013; de Torres Curth et al., 2012), and proposed methodologies for assessing fire hazard in regional neighborhoods located in fire-prone areas (Ghermandi, Beletzky, de Torres Curth, & Oddi, 2016). However, to our knowledge, no previous extended flammability plant lists have been reported for Patagonia. Plant lists can provide basic information that contributes to the understanding of landscape complexity in relation to changing environmental conditions, particularly in interface fire areas, and can play an important part in management and policy discussions (Murray, Martin, Brown, Krix, & Phillips, 2018; White & Zipperer, 2010).

Plant lists have been the subject of debate over recent decades, particularly due to their usually restricted information (e.g. number of species, species characteristics, regional or seasonal limitations), and their usefulness is also in question, as most plants will burn in a high-intensity fire (White & Zipperer, 2010). However, using them with caution (e.g. considering regions and seasons of origin) can offer a useful guideline to homeowners and gardeners in terms of recommending low-flammability horticultural species, thus reducing fire risk close to houses and urban landscapes, and providing an initial guide for the establishment of broader policies and regulations (Murray et al., 2018; White & Zipperer, 2010). Published plant flammability lists usually differ in types of plant properties or the components of flammability considered when classifying species, but they all basically agree on the general definition of individual plant flammability as “the capacity for plant biomass to burn; that is, to start and sustain fire” (Pausas, Keeley, & Schwilk, 2017). Flammability can be measured on different scales (e.g. tissues, plants, communities or landscapes) and for different types of fuel (e.g. dead/live, fine/coarse, canopy/litter). This multidimensionality also encompasses different components such as ignitability, sustainability, combustibility and consumability (Anderson, 1970; White & Zipperer, 2010), or as proposed more recently, flammability might comprise different dimensions or a combination of axes such as ignitability, heat release, rate of heat release (i.e., flame spread rate) and fuel density or packing ratio (Pausas et al., 2017; Prior, Murphy, & Bowman, 2018; Schwilk, 2015). However, appropriate methods for assessing flammability efficiently on different scales is still an area of active research. With respect to type of fuel, fine fuel material may be the best correlate of overall surface area:volume ratio, and hence a critical component dictating much fire behavior: the greater the surface area in relation to fuel volume, the faster the fuel will be heated and burned during a fire (Countryman & Philpot, 1970). On the other hand, the general consensus is that moisture content (defined by the water and dry matter weights) is one of the main drivers of fuel flammability across all study scales, including live and dead fuels. Live fuel moisture content is a complex and dynamic trait, with the change in live fuel water and dry matter content being influenced by the carbon and water cycles (Jolly & Johnson, 2018). Moreover, changes in the dry matter of live tissues that directly influence the flammability of fuel can be modulated by physiological variations in different components such as photosynthetic, defensive, structural and non-structural compounds. Aside from these factors that determine fuel quality, the load and spatial arrangement of the fuel in the landscape can further determine individual or community flammability (e.g. horizontal and vertical continuity of fuel).

The scale analyzed and the type of fuel generally determine the methodology used for determining flammability. In laboratory settings, a great diversity of techniques has been developed for the study of plant properties that affect flammability metrics (Pérez-Harguindeguy et al., 2013; Valette, 1992; White & Zipperer, 2010). These studies generally obtain data on species-level fine fuel traits, which have greatly improved fire behavior models that otherwise only consider conventional fuel parameters, such as understory cover or surface fuel load (Zylstra et al., 2016). Under a specific fire regime, intra- and inter-specific variations in organ and individual flammability scales can lead to

different evolutionary plant flammability strategies, as natural selection pressures occur on these scales (Pausas et al., 2017). As outlined in Pausas et al. (2017), estimating variance in flammability across scales is a challenge, and determining to what extent flammability information on one scale can be used to predict flammability on another scale is still an area which has been little explored (e.g. Pausas, Alessio, Moreira, & Corcobado, 2012; Zylstra et al., 2016).

Some exotic species introduced with different aims (economic and ornamental) over the last century have contributed towards a shift in the frequency and extent of high-severity fires (Pauchard et al., 2008; Raffaele, Nuñez, Eneström, & Blackhall, 2016). In this environment, exotic species appear to interact with fire events in a way that can change fuel properties and generate positive feedback that might transform fire regimes. Over the last few decades, the area planted with introduced tree species has increased rapidly in Argentinean Patagonia and Southern Chile, a trend that is expected to continue during the XXI century (Raffaele, Nuñez, & Relva, 2015; Veblen et al., 2011). Pine invasions and plantations (historically settled and dispersed in natural and wildland-urban interface areas) significantly alter the amount and structure of fuels, potentially promoting more severe fires (Paritsis et al., 2018) and lead to positive feedback between species adapted to fire, for example, setorinous pines, and thus greater invasion (Franzese & Raffaele, 2017). Likewise, urban and suburban areas can act as foci of alien species propagules. For example, it has been documented that distance to the closest town or city (i.e. increased human densities) has a consistent positive correlation with alien species richness and density (e.g. in Chile and in Argentinean Patagonia; Arroyo, Marticorena, Matthei, & Cavieres, 2000; Speziale & Ezcurra, 2011). Considering the trend of population growth in populated areas of the region, a rise in alien species richness and density could be expected.

Plant flammability lists do exist in other regions of the world, and are useful guides for home owners to use when seeking non-flammable or less flammable plants (White & Zipperer, 2010). In this study we present the first species list with flammability ranking, considering species in the wildland-urban interface areas surrounding principally the most populated city in the region, Bariloche. On the basis of this plant flammability list, we discuss the following questions: 1) Do flammability patterns associated with laboratory experiments (i.e. epiradiator tests) reflect regional flammability patterns on the wildland-urban interface scale level? 2) Could exotic species affect the flammability of these wildland-urban interface ecosystems?

The list encompasses species diversity along a strong precipitation gradient from semi-arid steppe through xeric woodlands to mesic forests in northern Patagonia (Veblen, Kitzberger, Raffaele, & Lorenz, 2003). Our analysis of 31 different species (26% exotic species) covered four woody and semi-woody life forms. Using a Principal Components Analysis, we identified groups of species according to four plant characteristics commonly associated with live fine fuel flammability: moisture, time to ignition, maximum temperature reached by the flame and heat released.

2. Methods

2.1. Study area and studied species

The study was carried out in wildland-urban interface areas in northwest Andean Patagonia, Argentina, including the city of Bariloche (41°09'S 71°18'W) and other areas with small populations (e.g. El Hoyo, El Bolsón). Bariloche, the most densely populated area in this region (area: 220.27 km², population: 113,000 inhabitants) is located within Nahuel Huapi National Park. The area occupied by Bariloche is long and thin in shape, its perimeter being 40 km in length, and it holds extensive wildland-urban interface areas. These areas contain diverse vegetation, as influenced by precipitation gradient and topographic heterogeneity, and include dry steppes of cushion shrubs and bunchgrasses, xeric woodlands of *Austrocedrus chilensis*, and mosaics of tall

shrublands and mesic forest patches dominated by *Nothofagus* species (Veblen et al., 2003). Across approximately 50 km, the mean annual precipitation in the region ranges between 700 and 1500 mm, and occurs mainly during autumn and winter. Precipitation is scarce in summer, and it is thus a season with water deficit tied to high temperatures and a consequent period of high probability of fire. These climatic characteristics place Bariloche and the surrounding area at the limit of the Mediterranean-type climate regions of the world, which are typically characterized by the dominance of fire-prone communities (Keeley, Bond, Bradstock, Pausas, & Rundel, 2012).

The native and exotic species studied coexist in the wildland-urban interface landscape, are common and abundant in the region, and include shrubs, shrubby trees, trees and woody climbers (Table 1). Among the most important exotic plant species in the region—economically and in predominance—are pines that were introduced for plantations some decades ago; they were planted mainly in the surroundings of Bariloche and other rural populations. Some of these exotic conifers have spread outside their plantations (Orellana & Raffaele, 2010; Sarasola, Rusch, Schlichter, & Ghersa, 2006), and others are in the process of invasion, largely after fire occurrence (Franzese & Raffaele, 2017; Raffaele, Nuñez, et al., 2016). In addition, other exotic species studied have been introduced into the region for hedging and ornamental use, such as *Cytisus scoparius*, *Rosa rubiginosa*, *Crataegus monogyna*, or *Juniperus communis* (Rovere, Molares, & Ladio, 2013); over the years these species have become problematic invaders (Damascos & Gallopin, 1992; Ledniuk, Damascos, Puntieri, & Svriz, 2014; Simberloff, Relva, & Nuñez, 2003).

2.2. Live fine fuel sampling and ignitability measurements

We sampled 15 individuals per species from the wildland-urban interface in the last two weeks of February 2016 (in the season of maximum fire probability). The number of replicates was selected based on other studies (e.g. Blackhall et al., 2017; Blackhall, Raffaele, & Veblen, 2012; Saura-Mas & Lloret, 2007; Saura-Mas, Paula, Pausas, & Lloret, 2010). Fresh samples from the live fine fuel fraction (10 g of well-developed healthy leaves attached to < 2.5 mm diameter twigs) were enclosed in airtight bags and stored in coolers. Within 24 h of field sampling, 3.5 g of each sample were used to determine live fine fuel moisture percentage based on dry mass (Saura-Mas & Lloret, 2007; Wyse et al., 2016), as follows: $[(\text{fresh mass} - \text{dry mass}) / \text{dry mass}] \times 100$. For this procedure, the fresh leaves and fine twigs collected were oven-dried at 60 °C for 72 h and re-weighed (all weights were obtained with a precision of 0.001 g).

A sub-sample fraction of 3.5 ± 0.1 g from each of the 15 individuals sampled (including leaves and fine twigs) was used to perform flammability tests using an infrared quartz-silica epiradiator (500 W, Helios Italquartz, Italy). The epiradiator consists of an electric heating resistance that reaches a standard surface temperature of 420 °C. The appropriate amount of biomass for running epiradiator tests was selected based on previous studies (e.g. Blackhall et al., 2017) and pre-testing. These preliminary tests determined that 3.5 g sample material allowed us to achieve flaming combustion across all the species (smaller masses failed to ignite), thus allowing comparison of flaming properties between all species. As observed by Kauf, Fangmeier, Rosavec, and Španjol (2015) for litter samples, smaller samples of most species were not sufficient to form a layer covering the whole disk. Covering the disk completely ensured similar heat exposure for all tested samples, reducing the influence of variations in temperature on the epiradiator surface. A thermocouple (Type K; with range 50–1000 °C) was placed 6 cm above the 10 cm diameter epiradiator silica disk and connected to a data-logger (Model 1384, TES Corp., Taiwan) using a time resolution of 2 s following Blackhall et al. (2017). Each sample was placed in the center of the disk, and using the data-logger's digital timer, we recorded the time to appearance of first flame (time to ignition/ignitability (s) reflects how easily fuel can catch fire when exposed to an ignition

source, and hence how easily fire should spread within and between individuals (Pausas et al., 2017)), and time to flame extinction (flame duration (s)). Additionally, we recorded the maximum temperature reached (°C) at 6 cm height and the heat released (proxy for energy released ($\text{C}^\circ \text{s g}^{-1}$)) during flame occurrence (estimated as the area under the temperature-time curve throughout flame duration divided by fresh biomass), following Pausas et al. (2017). All experiments were conducted in a fume hood, which maintained a closed environment to prevent any draught disturbance during tests. In general, ignition frequency (percentage of samples that ignited, producing flame) was 100%, except for a small number of samples of *C. scoparius*, *Discaria chacaye*, *Pinus contorta* and *Ribes magellanicum* (< 7% failed ignitions); these failed tests were not considered when computing the variables used in subsequent data analyses.

2.3. Data analysis

We performed principal component analysis (PCA) to evaluate which species could be considered more flammable according to their live fine fuel ignitability. Mean values for each species were organized in a data matrix of four live fine fuel traits (moisture, time to ignition, maximum temperature reached and heat released), and the analysis was performed via the correlation matrix based on Pearson coefficients (Legendre & Legendre, 1998). Prior to this PCA ordination, we had carried out PCAs that considered two more variables—flame duration and ignition frequency; however, lower Kaiser-Meyer-Olkin (KMO) values for these ordinations indicated that the four traits selected for analysis of live fine fuel ignitability were the most suitable combination for application of the data reduction technique. For the selected PCA, we retained the principal components with eigenvalue > 1 according to the Kaiser-Guttman criterion, and components were interpreted according to variable loadings (Legendre & Legendre, 1998). Given that flammability traits determined a “low-high flammable axis” for the first axis of the PCA, and a “type of flammability axis” for the second axis (see Results and Discussion), we used the position of species on each axis to generate a flammability ranking related to the variables studied that best characterized each axis (considering factor loadings > 0.40; adapted from Wyse et al., 2016). To explore the relationships between all the fine fuel traits studied, we examined Pearson's correlation coefficients, which were computed considering species' mean values.

3. Results

The PCA showed great variation in species flammability and revealed some general associations between the live fine fuel traits studied. The first two components of the analysis had a cumulative explained flammability variation of 76% (Fig. 1). The best KMO measure of sampling adequacy was obtained considering four variables (moisture, time to ignition, maximum temperature and heat released; KMO = 0.7), and Bartlett's test of sphericity was significant ($p < 0.01$). For PC1, the factor loads of the four selected traits mainly characterized a “low-high flammability axis”, specifically represented by decreasing values of live fine fuel moisture and time to ignition, and increasing values of maximum temperature reached during flame, and total heat released. According to the values of the factor scores of species across PC1, we determined a flammability ranking (Table 1), such that flammable species (species factor scores for PC1 > 0) were characterized by low values for live fine fuel moisture, and times to ignition, and high values for maximum temperatures reached and heat released. In contrast, less flammable species (species factor scores for PC1 < 0) were characterized by high values for moisture and longer times to ignition, and low values for maximum temperatures reached and heat released. This ranking placed, for example, *Mulinum spinosum*, *Chusquea culeou*, *Pinus ponderosa* and *Fabiana imbricata* among the most flammable species, and *Pseudotsuga menziesii*, *Araucaria araucana*, *Embothrium coccineum* and *Aristotelia chilensis* among the least flammable species.

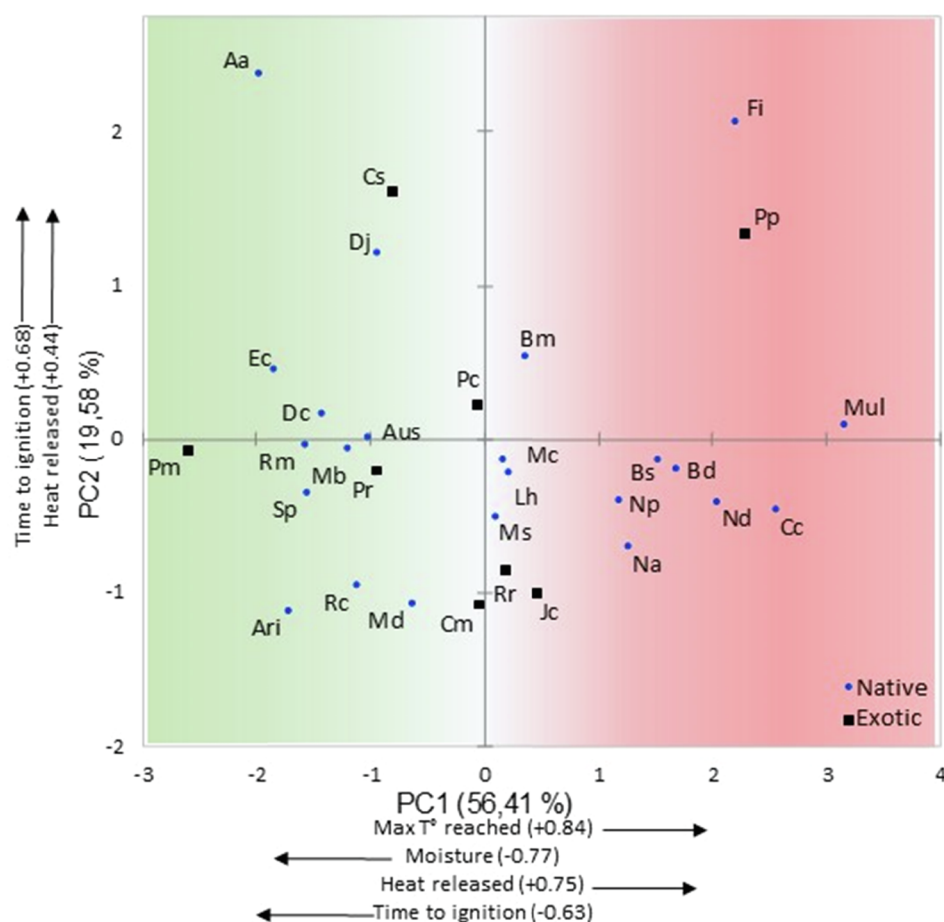


Fig. 1. Principal components analysis of live fine fuel flammability traits for 31 common native and exotic woody and semi-woody species in wildland-urban interface areas in northwest Patagonia, on the basis of the following traits: live fine fuel moisture, time to ignition, maximum temperature reached during flame and heat released. PC1 (eigenvalue: 2.3) and PC2 (eigenvalue 0.8) presented a cumulative explained flammability variation of 76%. Codes for species are detailed in Table 1. Labels on each axis show traits with the highest eigenvectors scores for each axis (factor loadings > 0.40). Correlations between traits and PCA axes are given in parentheses, and arrows indicate the direction of each correlation. Colors varying across PC1 indicate level of flammability, increasing from left (green) to right (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

PC2 mainly represented increased values for time to ignition and heat released, thus revealing the general association of this axis with two different, interesting groups of species, particularly considering the highly flammable species determined by PC1 (i.e. species situated on positive values for PC1; see Table 1). This “type of flammability axis” showed a first group including species with higher values for heat release and longer times to ignition (i.e. lower ignitability), such as *F. imbricata*, *P. ponderosa*, *Berberis microphylla* or *M. spinosum* (species factor scores for PC2 > 0). Conversely, a second group included species with lower values of heat release and shorter times to ignition (i.e. higher ignitability), such as *C. culeou*, *Nothofagus spp.*, *B. serrato-dentata*, *B. darwinii* or the exotic *J. communis* and *R. rubiginosa* (species factor scores for PC2 < 0).

The spatial ordination of the species through the PCA and the derived flammability ranking showed great variation for exotic species with regard to the four selected live fine fuel traits. Several exotic species occupied extreme positions among all the native and exotic species studied; for example, *P. menziesii* was the least flammable species and *P. ponderosa* among the most flammable species (PC1). Moreover, both species presented the lowest and the highest values for heat release, respectively, across the complete species list (see Appendix A). *Juniperus communis*, *R. rubiginosa* and *C. monogyna* showed particularly short times to ignition in comparison with most of the species. *Pinus contorta* and *P. radiata* were positioned among the mean values for all studied traits, hence showing intermediate live fine fuel flammability. Finally, *C. scoparius* was characterized by a particularly low flammability value, determined basically by the highest value for fuel moisture of all the species on the list.

We observed significant relationships among the six fine fuel flammability traits measured initially (Table 2). Fine fuel moisture was positively correlated with time to ignition ($r = 0.40$, $p = 0.02$) and

negatively correlated with frequency of ignitions ($r = -0.37$, $p = 0.04$), and maximum temperature reached during flame occurrence ($r = -0.54$, $p = 0.002$). Similarly, heat release was positively correlated with flame duration ($r = 0.82$, $p < 0.001$) and with maximum temperature reached ($r = 0.59$, $p = 0.001$).

4. Discussion

Our results enabled the identification of major groups of species based on live fine fuel characteristics related to tissue flammability. From this ordination, we were able to compose a species flammability list, establishing a high-to-low flammability ranking. We also detected different “types of flammability” according to ignitability and heat released. The list includes the most common species that form native communities and exotic conifer plantations that are frequently found in the wildland-urban interface zones. With a low population density in comparison to larger cities across the globe (Bühler et al., 2013), many Bariloche neighborhoods are surrounded by a mosaic of diverse vegetation landscapes, each characterized by ecologically diverse communities with different probabilities of ignition, depending on landscape models (e.g. steppes vs. *Nothofagus* forests vs. shrublands; Kitzberger et al., 2016). In addition, a socially and economically heterogeneous human population also affects annual ignition rates across the wildland-urban interface (Bühler et al., 2013).

Results also showed that live fine fuel with low moisture had a lower probability of ignition (i.e. frequency of ignitions), took longer to dry and begin ignition (i.e. time to ignition), and reached higher temperatures while burning (i.e. maximum temperature reached). Moreover, the heat released by samples during flame occurrence was higher, as shown by the longer flame duration and higher maximum temperatures reached. Similar findings have been reported by other

Table 1

Ranking list of the 31 studied species, indicating the code used for PCA analysis, family, growth form (GF: Tree (T), Shrubby Tree (ST), Shrub (S), Climber (C) and Bamboo (B)); following [Ezcurra & Brion, 2005](#)); origin (native (N) or exotic (E)), and factor scores for PC1 for each species, arranged from high values (i.e. high flammability) to lower values (i.e. low flammability). On the right, a new ranking arrangement is shown for species according to scores for PC2; this re-arrangement is only detailed for species with positive factor scores for PC1 (species with high flammability), and associated with two flammability groups (hot-high ignitability) according to PCA results. Exotic species in the list on the right are indicated with (E).

Code	Family	GF	O	Species	PC1	Species	PC2
Mul	Apiaceae	S	N	<i>Mulinum spinosum</i>	+3.15	<i>Fabiana imbricata</i>	+2.07
Cc	Poaceae	B	N	<i>Chusquea culeou</i>	+2.56	<i>Pinus ponderosa</i> (E)	+1.34
Pp	Pinaceae	T	E	<i>Pinus ponderosa</i>	+2.30	<i>Berberis microphylla</i>	+0.54
Fi	Solanaceae	S	N	<i>Fabiana imbricata</i>	+2.20	<i>Mulinum spinosum</i>	+0.09
Nd	Nothofagaceae	T	N	<i>Nothofagus dombeyi</i>	+2.04	<i>Maytenus chubutensis</i>	-0.14
Bd	Berberidaceae	S	N	<i>Berberis darwinii</i>	+1.69	<i>Berberis serratodentata</i>	-0.14
Bs	Berberidaceae	S	N	<i>Berberis serratodentata</i>	+1.53	<i>Berberis darwinii</i>	-0.20
Na	Nothofagaceae	T/ST/S	N	<i>Nothofagus antárctica</i>	+1.27	<i>Lomatia hirsuta</i>	-0.23
Np	Nothofagaceae	T	N	<i>Nothofagus pumilio</i>	+1.19	<i>Nothofagus pumilio</i>	-0.40
Jc	Cupressaceae	ST/S	E	<i>Juniperus communis</i>	+0.45	<i>Nothofagus dombeyi</i>	-0.41
Bm	Berberidaceae	S	N	<i>Berberis microphylla</i>	+0.36	<i>Chusquea culeou</i>	-0.46
Lh	Proteaceae	T	N	<i>Lomatia hirsuta</i>	+0.21	<i>Mutisia spinosa</i>	-0.51
Rr	Rosaceae	S	E	<i>Rosa rubiginosa</i>	+0.18	<i>Nothofagus antarctica</i>	-0.71
Mc	Celastraceae	T	N	<i>Maytenus chubutensis</i>	+0.16	<i>Rosa rubiginosa</i> (E)	-0.87
Ms	Asteraceae	C	N	<i>Mutisia spinosa</i>	+0.10	<i>Juniperus communis</i> (E)	-1.01
Cm	Rosaceae	T	E	<i>Crataegus monogyna</i>	-0.02		
Pc	Pinaceae	T	E	<i>Pinus contorta</i>	-0.06		
Md	Asteraceae	C	N	<i>Mutisia decurrens</i>	-0.63		
Cs	Fabaceae	S	E	<i>Cytisus scoparius</i>	-0.81		
Dj	Verbenaceae	S	N	<i>Diostea juncea</i>	-0.94		
Pr	Pinaceae	T	E	<i>Pinus radiata</i>	-0.95		
Aus	Cupressaceae	T	N	<i>Austrocedrus chilensis</i>	-1.02		
Rc	Grossulariaceae	S	N	<i>Ribes cucculatum</i>	-1.11		
Mb	Celastraceae	T	N	<i>Maytenus boaria</i>	-1.20		
Dc	Rhamnaceae	T/ST/S	N	<i>Discaria chacaye</i>	-1.43		
Sp	Anacardiaceae	ST/S	N	<i>Schinus patagonicus</i>	-1.55		
Rm	Grossulariaceae	S	N	<i>Ribes magellanicum</i>	-1.57		
Ari	Elaeocarpaceae	ST/S	N	<i>Aristotelia chilensis</i>	-1.71		
Ec	Proteaceae	ST/S	N	<i>Embothrium coccineum</i>	-1.84		
Aa	Araucariaceae	T	N	<i>Araucaria araucana</i>	-1.97		
Pm	Pinaceae	T	E	<i>Pseudotsuga menziesii</i>	-2.59		

authors for single species or a set of diverse species (e.g. [Bianchi & Defossé, 2015](#); [Hachmi, Sesbou, Benjelloun, El Handouz, & Bouanane, 2011](#); [Pausas et al., 2012](#); [Pellizzaro, Duce, Ventura, & Zara, 2007](#); [Saura-Mas et al., 2010](#)). In the future, detailed investigation should be carried out to explore these relationships, including further fine fuel traits in the analyses, such as leaf morphology or the presence and concentration of chemical compounds, as well as the eco-physiological role of fuel water in the specific mechanisms determining flammability patterns.

Table 2

Pearson correlation coefficients (r) for the six fine fuel flammability traits explored in this study. Significant correlations are indicated: *P < 0.05, **P < 0.01.

Traits	Live fine fuel moisture	Max T [°] reached	Time to ignition	Flame duration	Heat release
Live fine fuel moisture (%)					
Max T [°] reached (°C)	-0.54**				
Time to ignition (s)	0.40*	-0.31			
Flame duration (s)	-0.08	0.06	-0.28		
Heat release (°C s g ⁻¹)	-0.34	0.59**	-0.30	0.82**	
Frequency of ignitions (%)	-0.37*	0.12	-0.23	-0.02	0.06

4.1. Native interface live fine fuel flammability

Species with low flammability, determined by their high values for live fine fuel moisture, longer time to ignition and low values for temperature reached and heat released, were in general, species which are able to grow in diverse habitats and are also associated with communities characterized by low fire frequency. Examples are *Ar. chilensis*, *Ribes* spp., *Schinus patagonicus* or *Maytenus boaria*. Across wildland-urban interface zones, these species commonly grow in the understory

of tall *N. dombeyi* forests, or mixed *N. dombeyi* and *Au. chilensis* forests, where the closed tree canopy results in higher moisture microclimatic conditions and lower desiccation rates of plant tissues (Blackhall, Raffaele, & Veblen, 2012, 2015).

Araucaria araucana was the species that showed the lowest live fine fuel flammability, determined basically by the longest time to ignition (95% longer than the mean of all species) and low maximum temperature reached. This low flammability of the live fine fuel can be added to the list of fire characteristics associated with *A. araucana*: its fine fuel arranged in an umbrella crown shape (i.e. placing foliage distant from surface fires), thick bark, post-fire resprouting capacity, seeds that survive fire, and flammable litter (Boberg et al., 2010; Burns, 1993; González, Veblen, & Sibold, 2005). All these traits characterize a fire resistant or tolerant strategy (Pausas et al., 2017), and give this long-lived conifer the ability to survive repeated superficial fires (Veblen et al., 2003).

Fire-prone *A. araucana* habitats are typically co-dominated in lower canopy layers by the resprouters *N. antarctica* and *C. culeou*. Similar to the results of Bianchi and Defossé (2015), our results show that these resprouting species present moderate and highly flammable live fine fuel, respectively. *Chusquea culeou*, a key species of *Nothofagus* forests (Kitzberger et al., 2016), was the second highest species in the flammability ranking, showing the lowest moisture content (86%), and along with *N. antarctica*, very low values for time to ignition and high values for maximum temperature reached. These species form dense, fire-prone, tall shrublands, and although they can be accompanied by considerably less-flammable species according to our results (e.g. *E. coccineum*, *Ribes* spp., *S. patagonicus*, *M. boaria*), prevailing microclimatic conditions (e.g. high solar insolation; Blackhall et al., 2012, 2015) contribute to the occurrence of more frequent fires in shrublands in comparison with juxtaposed forests. Since the most highly flammable components of shoot-level species mixtures are the drivers of the net flammability of combined species (Wyse, Perry, & Curran, 2017), we can place highly flammable *C. culeou* and *N. antarctica* as the main flammability engineers of fire-prone shrublands.

Around the neighborhoods on the moister end of the precipitation gradient, we observed that *N. dombeyi* live fine fuel was highly flammable, determined principally by one of the lowest values for fuel moisture and one of the shortest times to ignition. Similar results were found for this species by Ghermandi et al. (2016). Despite these findings, tall mesic forests dominated by *N. dombeyi* rarely burn (Kitzberger et al., 2016). Cool, moist microclimatic conditions beneath the tree canopy, the absence of vertical fuel continuity, and principally, the very low live fine fuel flammability of the common understory species (e.g. *Ribes* spp., *S. patagonicus*, *M. boaria*, *Ar. chilensis*) underpin the fire regime patterns observed at landscape level (Blackhall, Raffaele et al., 2015; Blackhall, Veblen, & Raffaele, 2015; Kitzberger et al., 2016). A similar situation was found for *N. pumilio* forests; the live fine fuel from the tree canopy and the common species in the understory—such as *Berberis* spp.—showed moderate flammability. However, the vertical discontinuity of dead and live fine fuel, combined with shady, moist microclimatic conditions (Paritsis, Veblen, & Holz, 2015) compensated for the dominance of flammable live fine fuel.

Finally, and coincidentally growing on the driest end of the precipitation gradient of the wildland-urban interface zone, *M. spinosum* and *F. imbricata* were placed first and fourth in the high-to-low flammability ranking, respectively. *Mulinum spinosum* registered the shortest time to ignition (30.4% shorter than the second species in the ranking list, *C. culeou*), and the highest value for heat released between native species (46% greater release than *C. culeou*). *Fabiana imbricata* also presented one of the highest values for heat release, and in particular, showed the highest value for maximum temperature reached during flame occurrence. Both species, which typically grow from steppe to mixed shrublands, are well adapted to fire events, showing diverse adaptations as well as high live fine fuel flammability. *Mulinum spinosum* accumulates a high proportion of dead fuel, has low mortality

by fire, and resprouts vigorously even after high fire intensity (Gonzalez, Ghermandi, & Peláez, 2015). Conversely, *F. imbricata* is a post-fire recycler which has a particularly persistent, long-lived and fire-resistant seed bank; heat, smoke and/or charcoal can stimulate its germination (Dudinszky & Ghermandi, 2013).

4.2. The introduction of new species

For several decades, numerous and diverse studies have documented and compiled the different impacts of exotic species when they invade, and potentially transform, new systems (Lockwood, Hoopes, & Marchetti, 2013; Rejmánek & Richardson, 1996), including the possible modification of fire regimes (Balch, Bradley, D'antonio, & Gómez-Dans, 2013; D'Antonio & Vitousek, 1992; Franzese & Raffaele, 2017; Pauchard et al., 2008; Raffaele, Nuñez, et al., 2016). Recently, Wyse et al. (2017) showed through laboratory assays that the introduction of highly flammable species into a less flammable habitat may increase the ignitability of the entire new community, promoting the occurrence of new fires. In this scenario, complete, exhaustive plant flammability lists or rankings take on greater significance, since new, exotic plant species to be introduced for different reasons can be compared to the flammability of regional species, in addition to evaluation of their invasiveness and other possible associated effects.

Pinus ponderosa was the exotic species that showed the highest live fine fuel flammability, and was positioned in third place in the high-to-low flammability ranking of all native and exotic species studied. It presented medium values for all live fine fuel flammability traits, but showed in particular the highest value for heat released, releasing approximately 5% more heat than the native *M. spinosum*. In its native range, *P. ponderosa* is characterized as being a fire tolerant species, associated with surface fire regimes, presenting thick bark and self-pruning of lower branches. However, their needles are highly flammable, as shown in our results, and this species can also produce highly flammable litter (de Magalhaes & Schwilk, 2012) which can feed more intense surface fires. Nowadays, *P. ponderosa* is extensively planted in steppe areas and transition areas between forests and steppes, and is the most recommended pine to plant in Patagonia due to its low level of invasion compared with other pine species (Sarasola et al., 2006). However, the high flammability of its fine live fuel should be seriously considered, as well as the amount and structure of fuels produced, especially in poorly managed plantations (Paritsis et al., 2018). This is important since *P. ponderosa* plantations are generally located in drier areas of the precipitation gradient, in zones that in many cases surround rural populations and/or interface areas, and are characterized by high fire frequency. Many species and/or varieties of Pinaceae are adapted to fire (Franzese & Raffaele, 2017; He, Pausas, Belcher, Schwilk, & Lamont, 2012), so it is expected that they could not only change the regime and type of fire, but also display positive feedback, causing high social, economic and ecological costs, as has been observed, for example, for *P. radiata* in wildland-urban interfaces in Patagonia (Raffaele, Moreyra, et al., 2016). Our results show that *P. radiata* and *P. contorta* have lower live fine fuel flammability compared to other native tree species (e.g. *Nothofagus* spp.); however, as in other Pinaceae species, general observations show that net plant flammability can be further increased by retained, accumulated dead leaves and twigs extending from the ground to the crown. This situation has often been observed in *P. radiata* plantations and invasions (Raffaele, Moreyra, et al., 2016) and *P. contorta* invasions (Paritsis et al., 2018). On the other hand, *P. menziesii* showed the lowest flammability of the complete species list—determined by high values of fuel moisture and time to ignition, and the lowest value for heat release (40% lower than *P. ponderosa*). Low flammability was also recorded for this species by Baker (2011), who observed that individuals with moisture content > 70% were unable to sustain burning.

Besides Pinaceae species, which are commonly used in commercial plantations, other exotic and invasive species frequently appear

intermingled in the wildland-urban interface. We observed that these species presented low or moderate live fine fuel flammability, and three of them, in addition to *P. menziesii*, were ranked on a list of the most-used woody species for hedging in the region: *C. scoparius*, *R. rubiginosa* and *C. monogyna* (Rovere et al., 2013). *Cytisus scoparius* presented low flammability, determined by the highest % fuel moisture and prolonged time to ignition, similar to results recorded by Wyse et al. (2017) and Ghermandi et al. (2016). High fire frequency often reduces the resprouting capacity of this species and close-interval repeated fires eliminate the dormant, fire-stimulated seedbank, thus potentially extirpating local populations (Keeley et al., 2012). In this context, the low live fine fuel flammability of this species could be associated with evolutionary convenience. On the other hand, *C. monogyna* and *R. rubiginosa*, two exotic species that resprout vigorously after fire (Blackhall, de Paz, Gobbi, & Raffaele, 2016; Saura-Mas & Lloret, 2007), presented moderate live fine fuel flammability, as did *J. communis*, a genus that is not particularly associated with fire regimes in its range of origin (Keeley et al., 2012). Despite the moderate flammability of these three species, they presented considerably short times to ignition in comparison with the other native and exotic species. This fact should be taken into particular consideration, since these species are commonly used for gardening and hedging, and high ignitability may be a determining factor when fire conditions are given (e.g. abundant dry/dead fuels and high climatic probability of fire occurrence).

4.3. Exploring flammability as a multi-dimensional trait

Several authors have recently discussed the re-formulation of flammability as a multi-trait, or a trait composed of numerous dimensions and metrics (e.g. Jolly & Johnson, 2018; Pausas et al., 2017; Prior et al., 2018). Our study did not attempt to examine the recently proposed frameworks or hypotheses, but rather, apart from presenting a novel species flammability list for the region, our results might shed some light on the debate. Our PCA ordination showed that, as in other studies, live fine fuel traits allowed the organization of species in a low-to-high flammability direction, differentiating between species with extremely low (e.g. *P. menziesii* or *A. araucana*) or extremely high flammability (e.g. *M. spinosum*, *C. culeou* or *P. ponderosa*). Furthermore, we were able to associate highly flammable species with two “types of flammability” based on heat released and ignitability. In this way, two groups were detected: species with high ignitability and moderate heat release, and species that do not necessarily ignite rapidly, but release considerably more heat than average. For example, the exotic *J. communis* and *R. rubiginosa*, and the native *N. antarctica*, *Mutisia spinosa* and *C. culeou* were identified as species with high ignitability and moderate heat release, implying that natural areas or wildland-urban interface areas with sufficient fuel provided by these species may present higher probability of fire hazard and subsequent fire spread. In addition, the low to moderate heat released by this type of fuel might decrease the heat shock produced in soil properties and seed bank viability, as well as, on aerial meristems and plant roots. Except for *J. communis*, the fast-flammable strategy proposed by Pausas et al. (2017) resembles the characteristics observed for this group of species, which typically resprout vigorously after fire and present a high fine:coarse fuel ratio and fuel continuity. For example, at low-to-medium fire severity, a positive relation between the number of resprouted *N. antarctica* shoots and fire severity has been experimentally observed in burned individuals (Blackhall et al., 2016). Furthermore, microsite fire intensity was found to have a positive effect on the initial resprouting response of *C. culeou* seedlings (Cavallero & Blackhall, unpublished data).

On the other hand, species such as *F. imbricata*, *P. ponderosa*, *B. microphylla* or *M. spinosum* were ranked as species that not only present high live fine fuel flammability, but also high values for heat release, resembling the hot-flammable strategy proposed by Pausas et al. (2017). High levels of heat release can produce lethal effects in individuals and soil seed banks, as well as drastic changes in soil

properties (Keeley et al., 2012). This scenario can be catastrophic when we consider the introduction of high heat-releasing species (e.g. *P. ponderosa*) which can bring a vast new amount of flammable fuel (live fine fuel and litter) to a system where it was previously absent (e.g. wildland-urban interface steppes with low biomass net production; Paritsis et al., 2018). The frame by Pausas et al. (2017) posits that hot-flammable species often present high post-fire mortality, high post-fire recruitment, and/or fire stimulated germination, characteristics that perfectly describe the native *F. imbricata*, but not *P. ponderosa*, *B. microphylla* or *M. spinosum*. *Berberis microphylla* and *M. spinosum* can vigorously resprout after high fire intensity (Blackhall et al., 2016; Gonzalez et al., 2015), and *P. ponderosa* can successfully tolerate surface fires. Our results show that describing live fine fuel properties may sometimes be inadequate to describe species’ post-fire strategies, and that species found at the limit of the Mediterranean-type climate regions of the world might not necessarily fully adjust to the framework of Pausas et al. (2017).

4.4. What is next? Limitations, recommendations and urban planning implications

Although plant lists have evident limitations, we believe that they represent a first step in establishing guidelines and recommendations for homeowners, and contribute information that can be useful when enforcing regulations and policies. The limited feasibility of small-scale laboratory essays for simulating the flammability and reality of wild-fires is well recognized and still under discussion (e.g. Fernandes & Cruz, 2012). However, the implementation of a larger-scale approach is limited by the logistics and dimensions of burning entire individuals in field conditions, and under standardized measurements (Pausas & Moreira, 2012). We observed that our laboratory results, in general, did reflect large-scale flammability landscape patterns observed in north-west Patagonia. Flammability research in the region began only in the last decade, and further baseline datasets and studies are required. It has recently been demonstrated that data on small-scale fine fuel traits improve fire behavior models (e.g. thickness, length or width of leaves; Zylstra et al., 2016), in contrast to previous models which typically focused mainly on fuel loads and types (e.g. for the wildland-urban interfaces: Elia, Laforteza, Lovreglio, & Sanesi, 2015; Dimitrakopoulos, 2002). Hopefully, in the future, the new dataset presented here may help to generate or improve fuel and fire behavior models for the region, along with exhaustive data collection on vegetation structure and fuel biomass in the wildland-urban interface.

The present dataset focuses on the season of maximum fire probability; however, in the future it would be interesting to determine seasonal variations in tissue flammability, and study other types of fuel (e.g. standing dead fuel or litter). The flammability of dry fuels is driven by physiological processes which are different to those influencing live fuel (e.g. tissue decomposition or moisture balance; Jolly & Johnson, 2018); hence, examining these inter-specific variations should provide valuable information.

Recommendations should focus on promoting policies that restrict the location of newly afforested areas in the wildland-urban interface, or at least consider public subsidies for forestry only when efficient fuel and fire management are guaranteed (e.g. Gómez-González, Ojeda, & Fernandes, 2018). Strategic broad action lines should also focus on district policies that encourage and regulate nurseries in the promotion of low-flammability horticultural and commercially available species to homeowners, encouraging gradual replacement in their gardens. This conversion should also occur in public gardens and roadside planting in the wildland-urban interface area (Murray et al., 2018). An interesting scheme proposing a simple procedure for selecting worldwide species for the wildland-urban interface has recently been proposed by Murray et al. (2018). This scheme includes not only the selection of low flammability plants, but also considers avoiding allergenic or toxic species, and encourages the use of species that could promote biological

biodiversity or species with adaptations to the inclement conditions associated with climate change (Murray et al., 2018). As stated in Murray et al. (2018), globally, researchers are still in the pioneering stage of determining the properties associated with low-flammability and relating this knowledge to the vast diversity of species.

5. Conclusions

Our species flammability list constitutes a first step in identifying the role and potential fire hazard of numerous species in regional and diverse interface zones, as well as in relation to the inherent dynamics of native communities. In general, the patterns observed in our live fine fuel species flammability list are reflected in landscape level-fire regime patterns. As flammability lists already exist for other regions of the globe, this study may allow further future regional comparisons.

We found that introduced exotic species can potentially modify wildland-urban interface flammability. Regionally, intermingled with native communities across wildland-urban interface areas, the exotic species studied spread from homeowners' backyards and from com-

mercial pine plantations. *Pinus ponderosa*, *P. contorta*, *P. radiata* and *C. scoparius* are globally considered to be among the most invasive species (Rejmánek & Richardson, 1996). The existence of plant lists allows the evaluation of the introduction of new, foreign species, and the formulation of precautionary action to minimize environmental and economic risks. The information gathered should be used in land management and consider the replacement of highly flammable plants with non-flammable species within the ignition-fire risk zones so as to contribute to reducing fire hazard and spread, as well as limiting the damage caused by wildland-urban interface fires.

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Appendix A. Research data – Flammability variables values for each species

See Table A1.

Table A1

List of studied species detailing mean values and standard errors (ES) for each variable analyzed: live fine fuel moisture (%), frequency of positive ignitions (%; flame occurrence), time to ignition (s), maximum temperature reached during flame occurrence (C°), flame duration (s), and heat released during flame occurrence (C° s g⁻¹). Codes used for PCA analysis are also indicated.

Code	Species	Live fine fuel moisture (%)	Frequency of ignitions (%)	Time to ignition (s)	Max temp. reached (C°)	Flame duration (s)	Heat release (C° s g ⁻¹)
Aa	<i>Araucaria araucana</i>	142.7 (3.7)	100	60.9 (2.7)	204 (4)	43.7 (3.8)	2440 (227)
Ari	<i>Aristotelia chilensis</i>	177.5 (8.7)	100	25.5 (2.7)	198 (6)	38.3 (3.4)	1848 (166)
Aus	<i>Austrocedrus chilensis</i>	141.8 (6.8)	100	38.3 (2.1)	235 (7)	30.0 (2.3)	1805 (148)
Bd	<i>Berberis darwinii</i>	109.8 (4.9)	100	26.9 (1.4)	289 (13)	33.6 (1.9)	2318 (155)
Bm	<i>Berberis microphylla</i>	123.8 (12.4)	100	38.4 (2.3)	281 (18)	27.4 (2.3)	1996 (200)
Bs	<i>Berberis serratodentata</i>	120.0 (2.9)	100	24.9 (2.7)	263 (11)	41.1 (3.7)	2690 (254)
Cc	<i>Chusquea culeou</i>	86.0 (5.8)	100	24.7 (2.2)	305 (16)	31.4 (2.6)	2304 (193)
Cm	<i>Crataegus monogyna</i>	129.3 (8.1)	100	25.3 (2.3)	223 (10)	37.3 (2.7)	2070 (169)
Cs	<i>Cytisus scoparius</i>	186.8 (19.6)	93	40.8 (3.1)	283 (27)	31.3 (4.6)	2222 (319)
Dj	<i>Diostea juncea</i>	155.0 (8.9)	100	44.9 (3.3)	262 (14)	29.8 (2.6)	1994 (183)
Dc	<i>Discaria chacaya</i>	139.4 (6.5)	93	42.3 (3.3)	220 (7)	30.8 (3.2)	1780 (185)
Ec	<i>Embothrium coccineum</i>	185.0 (7.7)	100	37.2 (3.9)	219 (5)	37.6 (3.8)	2082 (185)
Fi	<i>Fabiana imbricata</i>	130.1 (9.3)	100	37.1 (2.8)	330 (19)	37.3 (3.2)	3004 (299)
Jc	<i>Juniperus communis</i>	112.5 (6.4)	100	27.5 (2.3)	252 (7)	27.9 (1.9)	1838 (116)
Lh	<i>Lomatia hirsuta</i>	146.0 (6.3)	100	27.6 (1.7)	252 (10)	36.9 (2.5)	2261 (159)
Mb	<i>Maytenus boaria</i>	164.2 (6.6)	100	34.3 (2.4)	237 (14)	27.9 (1.9)	1844 (182)
Mc	<i>Maytenus chubutensis</i>	116.1 (5.0)	100	35.1 (1.7)	250 (13)	32.1 (2.1)	2005 (174)
Mul	<i>Mulinum spinosum</i>	114.7 (9.5)	100	17.2 (4.3)	287 (9)	53.3 (3.8)	3357 (219)
Md	<i>Mutisia decurrens</i>	153.3 (12.0)	100	24.3 (2.1)	218 (8)	37.7 (3.0)	2006 (142)
Ms	<i>Mutisia spinosa</i>	145.2 (13.8)	100	26.5 (2.8)	251 (16)	33.7 (4.2)	2108 (312)
Na	<i>Nothofagus antarctica</i>	112.0 (4.0)	100	25.2 (2.5)	278 (12)	30.3 (2.3)	2066 (172)
Nd	<i>Nothofagus dombeiyi</i>	105.8 (2.5)	100	23.7 (1.3)	289 (12)	34.5 (2.7)	2423 (219)
Np	<i>Nothofagus pumilio</i>	112.4 (3.4)	100	26.4 (2.3)	245 (11)	43.7 (2.5)	2572 (156)
Pc	<i>Pinus contorta</i>	145.6 (4.4)	94	32.1 (2.3)	236 (7)	43.5 (2.9)	2466 (153)
Pp	<i>Pinus ponderosa</i>	127.0 (2.8)	100	29.3 (3.1)	276 (19)	53.0 (4.7)	3526 (398)
Pr	<i>Pinus radiata</i>	151.7 (4.3)	100	33.2 (3.4)	217 (10)	41.7 (3.9)	2097 (195)
Pm	<i>Pseudotsuga menziesii</i>	162.2 (4.7)	100	43.2 (2.6)	205 (6)	24.4 (3.1)	1425 (182)
Rc	<i>Ribes cucullatum</i>	148.2 (6.7)	100	30.0 (2.6)	223 (10)	28.7 (3.1)	1647 (180)
Rm	<i>Ribes magellanicum</i>	170.9 (8.8)	93	34.5 (2.3)	212 (11)	38.8 (4.3)	2033 (191)
Rr	<i>Rosa rubiginosa</i>	126.4 (4.3)	100	26.5 (1.6)	233 (11)	38.2 (3.4)	2113 (153)
Sp	<i>Schinus patagonicus</i>	126.8 (4.2)	100	41.7 (2.4)	209 (6)	27.8 (3.3)	1571 (199)

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