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► **To cite this version:**

Anne Ganteaume. Does plant flammability differ between leaf and litter bed scale? Role of fuel characteristics and consequences for flammability assessment. *International Journal of Wildland Fire*, 2018, 27 (5), pp.342-352. 10.1071/WF17001 . hal-02067991

HAL Id: hal-02067991

<https://hal.science/hal-02067991>

Submitted on 14 Mar 2019

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1 **Does plant flammability differ between leaf and litter bed scale? Role of fuel**
2 **characteristics and consequences for flammability assessment**

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6

7 **Running head**

8 Plant flammability can differ between fuel scales

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11

12 **Abstract.**

13 The increasing concern regarding fire in the wildland-urban interface (WUI) around the world
14 highlights the need to better understand the flammability of WUI fuels. Research on plant
15 flammability is rapidly increasing but commonly only considers a single fuel scale. In some
16 cases, however, different fuel scales (e.g. leaf and litter bed) have greater influence on fire, for
17 instance, when it spreads from the litter bed to the lower canopy. Examining fuel flammability
18 at these different scales is necessary to better know the overall flammability but also provides
19 insights into the drivers of flammability. To investigate if leaf and litter bed flammability
20 differed, laboratory experiments were conducted on fifteen species (native or exotic)
21 commonly found in WUI of southeastern France. Species were ranked and the association of
22 fuel characteristics with flammability sought at both scales. For most species, leaf and litter
23 bed flammability differed due to strong fuel characteristics (e.g. leaf thickness or litter bulk
24 density), entailing differences in rankings based on fuel scale and potentially leading to a
25 misrepresentation of flammability of the species studied. Favoring species with lower
26 flammability at both scales in WUI, especially near housing, may help reduce undesired
27 impacts during wildfires.

28

29

30 **Brief summary**

31 For most species, leaf and litter bed differed in flammability; leaf thickness and litter bulk
32 density being among the main drivers. Low flammable species, at both scales, should be
33 favored in WUI to mitigate damage on housing during wildfires.

34

35 **Key-words:** fuel scale, wildland-urban interface, leaf characteristics, flammability
36 component, litter bulk density, litter composition.

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42 **Introduction**

43 Around the world, and especially in the Mediterranean region, concerns about the impact of
44 wildland fires are increasingly focusing on the wildland-urban interface (WUI) (Cohen 2000;
45 Lampin-Maillet 2009). Fire occurrence in WUI is highest, being mainly human-induced, and
46 the risks to human lives and property are greatest (Bar Massada *et al.* 2009). Furthermore, the
47 on-going higher incidence of extreme climate events (e.g. high summer temperatures, strong
48 winds, and drought) is expected to worsen under climate change. This combined with the high
49 flammability of Mediterranean fuels (Valette 1990; Dimitrakopoulos and Papaioannou 2001)
50 implies a higher probability of ignition. Fire propagation throughout WUI vegetation is a
51 growing concern in many regions of the world, especially regarding the structure of
52 ornamental vegetation around housing which can affect its vulnerability. Indeed, this
53 vegetation can act as a vector of fire propagation from wildland fuels to buildings, as well as
54 from one building to another (Etlinger and Beall 2004).

55 These circumstances led to recommendations for using less flammable species as
56 ornamental plants (Monroe *et al.* 2003; Long *et al.* 2006; White and Zipperer 2010).
57 According to Dimitrakopoulos (2001) and to Dimitrakopoulos and Papaioannou (2001), the
58 classification of fuels, in relation to its expected flammability, is an essential component of
59 fire risk assessment (specifically regarding fire hazard). In previous works, flammability
60 rankings of species were mostly performed using ground samples (Dimitrakopoulos and
61 Papaioannou 2001; Liodakis *et al.* 2002), litter samples (Ganteaume *et al.* 2013a), leaf and
62 shoot samples (Weise *et al.* 2005; Ganteaume *et al.* 2013b; Wyse *et al.* 2016), and were based
63 only on leaf and litter traits (Behm *et al.* 2004) or only on experts' opinions (Fogarty 2001).
64 However, none of these works compared litter bed and leaf flammability rankings of species.

65 Plant flammability has been widely studied and experimentally assessed under laboratory
66 conditions, through different flammability parameters (e.g. time-to-ignition, flaming duration,
67 flame height, flame propagation) recorded during burning experiments, for various purposes
68 and following several methods (Anderson 1970; Martin *et al.* 1993; Liodakis *et al.* 2002;
69 Etlinger and Beall 2004; Weise *et al.* 2005; White and Zipperer 2010). Most works have
70 focused on assessing flammability at the leaf (Dimitrakopoulos and Papaioannou 2001;
71 Liodakis *et al.* 2002) or the litter bed scale (Scarff and Westoby 2006; Kane *et al.* 2008;
72 Ganteaume *et al.* 2011a, 2014; de Magalhães and Schwilk 2012). Litter beds are composed of
73 one or several types of particles and are highly involved in surface fires, or can act as a
74 receptor for firebrands from spot fires (Ganteaume *et al.* 2009). In some cases, however,
75 different fuel scales are relevant to ignition and fire spread, for example, when it propagates
76 from the litter bed to the lower canopy, transitioning from a surface fire to a crown fire. In this
77 case, the flammability assessment of both live fuel and dead surface fuel (litter) needs to be
78 considered. Moreover, flammability has mostly been assessed using only one flammability
79 variable usually related to fuel ignitability (Valette 1990; Dimitrakopoulos and Papaioannou

80 2001), time-to-ignition for instance, thereby lacking evaluation of other variables. The results
81 obtained have also differed depending on the fuel scale considered (Etlinger and Beall 2004;
82 Madrigal *et al.* 2013) and on the sampling methodology (Ganteaume *et al.* 2014).
83 Furthermore, the flammability drivers also differed according to flammability parameters and
84 fuel scales examined. Usually, these drivers encompassed morphological and chemical traits
85 at the leaf scale, as well as factors taking into account fuel structure (e.g. bulk density,
86 packing ratio, fuel depth) and fuel composition (proportion of the different fuel components)
87 at the multi-particle scale (Scarff and Westoby 2006; Ganteaume *et al.* 2011a; Engber and
88 Varner 2012; de Magalhães and Schwilk 2012; Ganteaume *et al.* 2013a, 2013b, 2014).
89 However, some leaf traits continue to affect litter flammability, scaling up from leaf to litter
90 (Varner *et al.* 2015).

91 In order to improve the characterization of species flammability, several flammability
92 parameters across the main fuel scales typically involved in fire propagation should be taken
93 into account. The live leaf and litter bed scales are often among the main fuel scales involved
94 in fire propagation (related to crown fires, surface fires, and spot fires) in WUI and the
95 combination of different methods for assessing their flammability was thus necessary. The
96 objectives of the current work were: (i) to determine the main drivers of flammability (e.g.
97 fuel characteristics) at the leaf and litter bed scales, (ii) to examine if leaf characteristics
98 explained flammability at the litter bed scale, and (iii) to assess whether the ranking of
99 flammability among species differed between scales. These objectives were addressed using
100 fifteen commonly occurring species in WUI of southeastern France. The results can also be
101 relevant in other fire-prone regions, especially given the fact that plant flammability might
102 differ between fuel scales. At a finer scale, results from the current work will also provide a
103 better characterization of the flammability of WUI plants, allowing selection of firesmart
104 species for landscaping. Equally, these results can be of interest outside the framework of
105 WUI, given the range of native and exotic species.

106

107

108 **Material and methods**

109 This work was conducted in the “département” Bouches du Rhône, located in the eastern part
110 of SE France, which is among the areas most affected by wildfires (223 fires and 1266
111 hectares burned per year during the 2000-2016 period according to the regional forest fire
112 database Prométhée; www.promethee.com). A survey of the most common species planted in
113 WUI was made throughout the study area. I selected 15 of the 20 most representative species
114 of the study area: *Viburnum tinus* Linnaeus, *Prunus laurocerasus* Linnaeus (cherry laurel),
115 *Cotoneaster franchetii* Bois, *Pyracantha coccinea* Roemer (scarlet firethorn), *Elaeagnus*
116 *ebbingei* Doorenbos, *Cupressus sempervirens* Linnaeus (Italian cypress), *C. arizonica* Greene,

117 *Cupressocypris leylandii* (Jacks. & Dallimore) Farjon, *Thuja occidentalis* Linnaeus, *Nerium*
118 *oleander* Linnaeus (oleander), *Photinia fraseri* Dress (Christmas berry), *Ligustrum japonicum*
119 Thunberg (Japanese privet), *Euonymus japonicus* Thunberg, and *Pittosporum tobira*
120 (Thunberg) Aiton (Pittosporum). *Phyllostachys* sp. (bamboo) was also chosen because of its
121 uniqueness, as it was the only monocotyledon recorded during the survey and may present
122 particular flammability characteristics. Most species are native to different regions of the
123 Mediterranean basin (*Viburnum tinus* common throughout the entire Mediterranean area,
124 *Nerium oleander* in Spain and Portugal, and *Cupressus sempervirens* can form monospecific
125 forest stands in Italy and Greece). Other species are native to non-Mediterranean areas
126 (*Cupressus arizonica*, *Thuja occidentalis*, or *Phyllostachys* sp.).

127

128 *Field sampling*

129 Sampling was carried out in summer during the fire season (most severe climate conditions).
130 Following the protocol described in Ganteaume *et al.* (2013a), litter samples (18 x 20 cm)
131 were collected undisturbed (thereby containing both litter and duff layers) under hedges to
132 take into account the intact fuel structure and composition. Previous work has highlighted that
133 fuel microstructure affects litter flammability (Ganteaume *et al.* 2011a). Litter samples were
134 verified to be mainly composed of particles coming from the species studied. Before burning,
135 samples were oven-dried for 48 h at 60°C to reduce fuel moisture content (FMC) that could
136 impact flammability (Chuvienco *et al.* 2004), and to increase consistency across species.
137 Working with samples with low FMC (<5%) was also consistent with that of severe summer
138 climatic conditions (see Ganteaume *et al.* 2013a). Litter bulk density (BD, in kg m⁻³,
139 calculated for each sample by dividing the weight by the volume of the litter sample) was
140 measured and litter components (proportions¹ of evergreen leaves, scale-leaves, fine and
141 coarse particles, fine and coarse² debris, and non-combustible particles) were sorted from sub-
142 samples (for the litter component classes; see Ganteaume *et al.* 2013a).

143 Leaves of similar size were collected on mature plants, excluding the newly developed
144 tissues at the top of the twigs. In order to create the worst case scenario in terms of fire risk,
145 each species was sampled in summer at the hottest time of day (between 1200 and 1400),
146 avoiding days following rainfall events. The leaves sampled were placed in plastic bags and
147 stored in a cool box for transportation to the laboratory, minimizing changes in water content.
148 Just before burning, a 5 g sample of live leaves (fresh weight) of each species was oven-dried
149 for 24h at 60°C to enable the calculation of FMC.

¹ Proportions based on the dry weight of each class of particle.

² Debris or particles were defined as fine, when their thickness or diameter was less than 2 mm, and as coarse, when it was higher.

150 Immediately before burning, the following physical characteristics of the live leaves³
151 were measured because of the importance of particle geometry in determining their
152 combustion: weight (W, in g); total⁴ and contact⁵ surface areas (Stot and Sctc, in cm²);
153 volume (V, in cm³), calculated for the broadleaved species by multiplying leaf thickness by
154 the upper or lower leaf surface area (e.g. contact surface area); weight-to-volume ratio,
155 hereafter referred to as leaf density (D, in g cm⁻³); specific leaf area (SLA in cm² g⁻¹),
156 calculated as the surface area-to-weight ratio; surface area-to-volume ratio (SVR, in cm⁻¹).
157 Because of its impact on fuel ignitability (Montgomery and Cheo 1971), leaf thickness (Thi,
158 in cm) was measured at the middle of the leaf (excluding the midrib), using a 10⁻⁴ m accuracy
159 micrometer. Leaf surface area and scale-leaf volume were measured using a 2400 dpi scanner
160 and image analysis software (WinFOLIA for leaf surface area and WinSEEDLE for the
161 volume of scale-leaves; Regent Instruments, Canada).

162

163 *Flammability experiments*

164 The burning experiments were conducted at the Irstea Aix-en-Provence facility. Air
165 temperature and relative humidity in the laboratory were measured (respectively $27.6 \pm 1.6^\circ\text{C}$
166 and $47.2 \pm 5\%$) throughout the experiment period but they did not affect flammability
167 (Fisher's LSD test, $p > 0.05$).

168 To assess the flammability of live leaves, fifty 1 ± 0.1 g samples of each species were
169 burned on an epiradiator that consisted of a 500 W electric radiator with a 10 cm diameter
170 radiant disk, as described in previous works (e.g. Hernando-Lara 2000; Ganteaume *et al.*
171 2013b). Using heavier samples may increase the possibility that other fuel properties, such as
172 fuel height, would be involved in flammability changes (Ormeño *et al.* 2009). The surface
173 temperature achieved with the device at a steady-state regime was 420°C and the samples
174 were in direct contact with the radiant disk. The contact surface area depended on species
175 whose leaves could shrink and curl up (and even flicker), especially during pyrolysis.
176 However, this contact surface area was assumed to be close enough to the heat source to
177 undergo homogeneous heat transfer effects (mostly by radiation and conduction). A pilot
178 flame which did not take part in the sample decay was located 4 cm above the centre of the
179 disk; it allowed more regular ignition of the gases emitted during leaf combustion. When the
180 leaf samples were placed on the electric radiator, time-to-ignition (Lv_TTI, in s), then time-
181 to-flame extinction were recorded to enable calculation of flaming duration (Lv_FD, in s).

³ The shape of scale-leaf was approximated as an ellipsoid.

⁴ For ordinary flat, non-succulent leaves, the surface area S of the upper surface is approximately equal to that of the lower surface and the total leaf surface = $2S$.

⁵ The contact surface area was the part of the total surface area in contact with the radiant disk (e.g. one-sided projected area).

182 Ignition frequency (Lv_IF, in %) was calculated as the percentage of tests in which the
183 samples successfully ignited.

184 Litter burning experiments (30 undisturbed litter samples by species) were conducted to
185 estimate litter flammability characteristics among species, including ignition and initial fire
186 propagation. To represent similar conditions as during a spot fire, a “standard” glowing
187 firebrand made of *Pinus sylvestris* wood (2 × 2 × 1 cm, weighing 1.44±0.05 g) was used as
188 the ignition source and a 9.8 km h⁻¹ wind speed was added to the burning device to favor
189 ignition, as described in Ganteaume *et al.* (2013a). Once flaming ended, the glowing firebrand
190 was placed in the centre of the sample and the timer was initiated. For each litter sample, up
191 to three successive ignition trials were performed until the sample ignited and, as in previous
192 studies (Plucinski and Anderson 2008; Ganteaume *et al.* 2009, 2011a, 2011b), ignition was
193 considered successful if a flame lasted at least 10 s to ensure that the ignition was sufficient to
194 allow propagating flames. The variables recorded during the burning experiments were: (i)
195 ignition frequency (Lit_IF, in %) which was computed as the percentage of tests in which the
196 samples successfully ignited; (ii) time-to-ignition (Lit_TTI, in s) which corresponded to the
197 time necessary for the appearance of a flame after the firebrand had been placed on the
198 sample; (iii) flame propagation which was approximated by the number of opposite directions
199 of the sample reached by flames (Lit_FS, 0 to 4), and (iv) flaming duration (Lit_FD, in s)
200 between the ignition and the end of the flaming combustion (when the timer was stopped).

201

202 *Data analysis*

203 In order to highlight the best flammability drivers for both fuel scales, relationships between
204 fuel characteristics and flammability variables were sought using bivariate regression analyses
205 (either the correlation coefficient R or the adjusted R² were given in the analyses).

206 Principal components analysis (PCA) was run on the leaf, then on litter characteristics of
207 the fifteen species to determine their most significant characteristics. The same analysis was
208 also used to investigate flammability patterns across species, regarding both fuel scales, in
209 identifying which litter or leaf flammability variable(s) better characterized the species
210 studied.

211 Multivariate redundancy analysis (RDA) was performed to examine if leaf characteristics
212 explained flammability at the litter bed scale and to account for the interrelatedness between
213 leaf and litter characteristics in contributing to litter flammability. This analysis summarizes
214 linear relationships between components of dependent variables (flammability) that were
215 "explained" by a set of explanatory factors (fuel characteristics), only when they were
216 significantly correlated.

217 Using hierarchical cluster analysis (Ward method, based on squared Euclidian distance),
218 the species studied were ranked according to their leaf and litter flammability. For each fuel

219 scale, this analysis was used to group species into categories of flammability in such a way
220 that two species from the same cluster were more similar than two species from different
221 clusters, regarding their flammability variables. A total ranking was also obtained, combining
222 all the flammability variables of both fuel scales to obtain an overall “relative” flammability.
223 To account for any difference in flammability, the leaf and litter rankings were compared
224 together, via a Spearman’s rank-order correlation which measured the strength of the
225 association between two ranked variables (H_0 : no association between the two variables).

226 Except for RDA which was performed in the “vegan” package (R Development Core
227 Team, 2005), the other analyses were performed using Statgraphics® Centurion XV (StatPoint
228 Technologies, Inc, USA).

229

230

231 **Results**

232 *Drivers of leaf and litter flammability*

233 Significant relationships between flammability variables and fuel characteristics were sought
234 for both fuel scales. Regarding leaf flammability, the significant predictors of time-to-ignition
235 were leaf thickness and specific leaf area ($R^2=0.55$, $p<0.001$; $R^2=0.24$, $p<0.05$, respectively;
236 Fig. 1a and 1b). In contrast to thickness, specific leaf area was negatively related to time-to-
237 ignition, meaning that thin leaves presenting a high specific leaf area quickly ignited whereas
238 thick leaves (mainly scale-leaves of Cupressaceae species), whose specific leaf area was
239 lower, took longer to ignite. Significant negative relationships (but quite moderate) were also
240 detected between leaf flaming duration and both leaf weight and total surface area ($R^2=0.23$,
241 $p<0.05$; $R^2=0.22$, $p<0.05$, respectively; Fig. 1c and 1d), meaning that small light leaves (e.g.
242 *Cotoneaster franchetii* or *Pyracantha coccinea*. Suppl. Mat. 1) burned longer than large heavy
243 ones (e.g. *Prunus laurocerasus* or *Cupressus arizonica*. Suppl. Mat. 1). Ignition frequency
244 was unrelated to any leaf characteristics. FMC ranged between 72 and 213% among species
245 but was surprisingly not significantly related to any of the leaf flammability variables.
246 However, when the scale-leaved species were excluded from the analyses, a significant
247 positive relationship between time-to-ignition and FMC was highlighted (Table 1),
248 confirming that leaves with high moisture content took longer to ignite (e.g. *Ligustrum*
249 *japonicum* and *Nerium oleander*. Suppl. Mat. 1). In that case, leaf ignition frequency became
250 negatively correlated with leaf time-to-ignition (Table 2), among the broadleaved species,
251 leaves igniting frequently also ignited quickly (e.g. *C. franchetii* or *Photinia fraseri* contrary
252 to *Pittosporum tobira* and *L. japonicum*. Suppl. Mat. 1). Leaf characteristics significantly
253 correlated with each other, except FMC (only correlated with specific leaf area when the
254 Cupressaceae species were excluded from the dataset) and leaf density (only correlated with
255 leaf thickness for the complete dataset) (Suppl. Mat. 2).

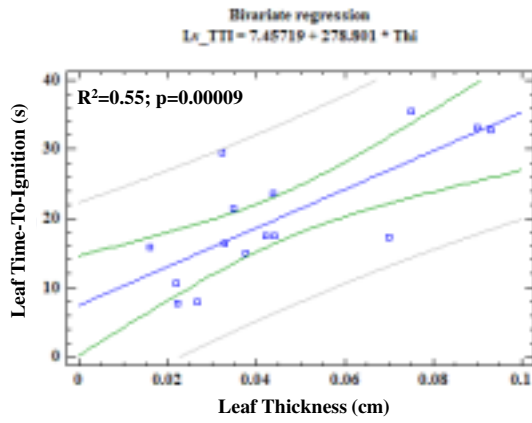
256 Regarding litter flammability, bulk density and proportion of fine debris were the best
257 predictors of flaming duration (but with quite moderate relationships: $R^2=0.29$, $p<0.05$;
258 $R^2=0.25$, $p<0.05$, respectively; Fig. 1e and 1f). Compacted litter (corresponding especially to
259 that of Cupressaceae species) tended to have a higher residency time for the fire (Suppl. Mat.
260 3). These two litter characteristics were positively correlated with each other (Suppl. Mat. 4).
261 Litter that was more compacted tended to have a higher proportion of fine debris. Ignition
262 frequency was negatively correlated with proportion of evergreen leaves ($R^2=0.25$, $p<0.05$.
263 Fig. 1g), meaning that litter presenting a large amount of evergreen leaves (e.g. *Eleagnus*
264 *ebbingei*) ignited less frequently compared to scale-leaved species litter (Suppl. Mat. 3).
265 Ignition frequency, time-to-ignition, and flame spread were not significantly related to any
266 litter characteristics although some of the correlations were moderate (correlation coefficients
267 around 0.5; Table1). Considering only the broad-leaved species, a significant positive
268 correlation was highlighted between flame spread and proportion of coarse debris (Table1). It
269 is worth noting the positive correlation between litter ignition frequency and flaming duration
270 ($R^2=0.59$, $p<0.05$; Table 2), showing that species that frequently ignited also burned the
271 longest (e.g. *Cupressus* species or *Photinia fraseri*. Suppl. Mat. 3).

272 The main fuel characteristics of each species were sought for both fuel scales using
273 principal component analyses. For leaves, component 1 explained 52% of the variation and
274 opposed species with high leaf surface area-to-volume ratio and specific leaf area (such as *P.*
275 *coccinea* and *C. franchetii*) to those with high leaf volume and surface areas (such as *P.*
276 *laurocerasus*). Component 2 explained 25% of the variation and opposed species
277 characterized by leaf thickness and density (Cupressaceae species presenting the highest
278 values contrary to most broadleaved species). FMC best characterized component 3
279 (explaining only 10% of the variance) which opposed species, such as *L. japonicum*, *N.*
280 *oleander* or *P. tobira* (high leaf moisture content), to species, such as *Photinia fraseri* and *C.*
281 *franchetii*, whose leaves presented lower values of FMC (Suppl. Mat. 5). For litter,
282 component 1 explained 38% of the variation and opposed the Cupressaceae species (scale-
283 leaved species), whose litter presented the highest bulk density and proportion of fine debris,
284 to the broadleaved species whose litter presented high proportion of evergreen leaves (e.g.
285 *Elaeagnus ebbingei* and *Euonymus japonicus*). Component 2 (explaining 22% of the
286 variation) displayed species opposed by the proportion of coarse debris in the litter (e.g. the
287 lowest values were obtained by *C. sempervirens* contrary to *L. japonicum* and *Phyllostachys*
288 sp.). Component 3 (explaining 19% of the variation) best displayed litter of *C. franchetii* and
289 *P. tobira* that presented the highest proportion of coarse particles and the lowest proportion of
290 non-combustible particles (that showed the highest scores on this component) (Suppl. Mat. 6).

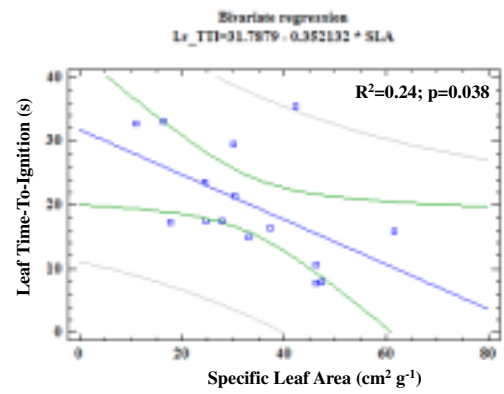
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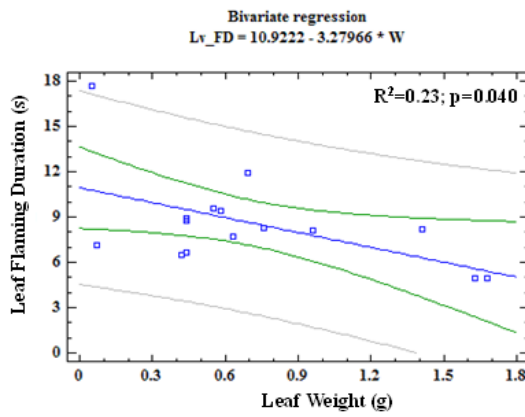
(a)



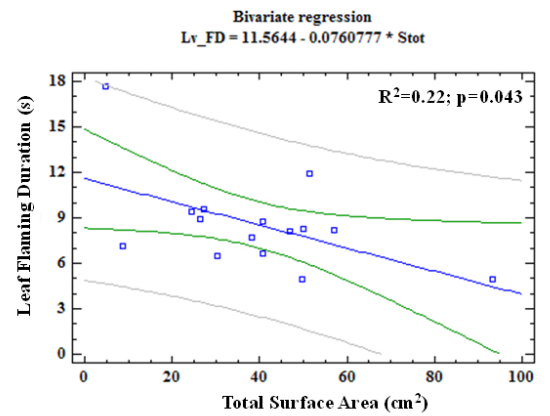
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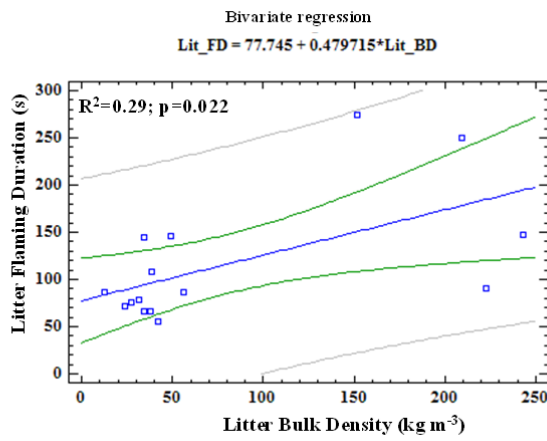
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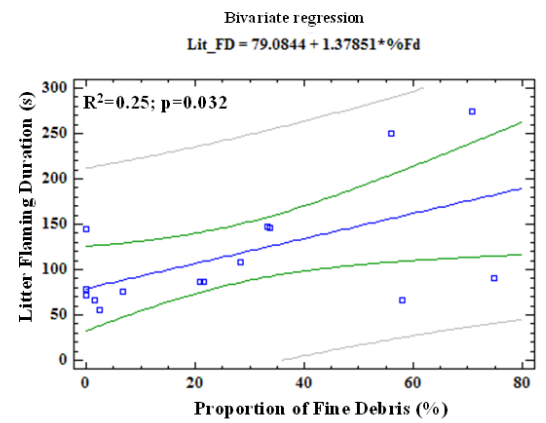
(d)



(e)



(f)



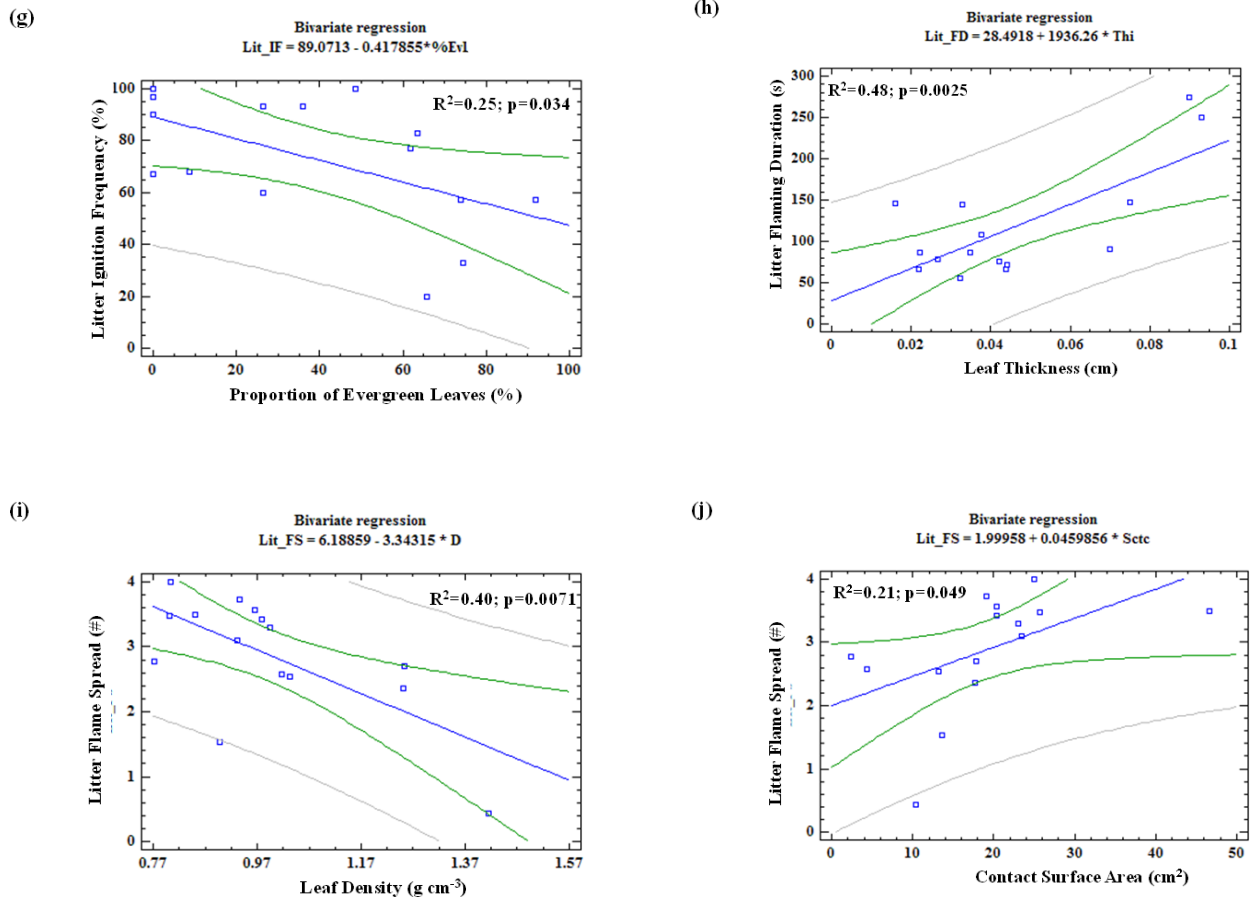


Fig. 1. Significant relationships between leaf and litter characteristics and flammability variables: at the leaf scale (a) leaf thickness (Thi) and leaf time-to-ignition (Lv_TTI), (b) Specific leaf area (SLA) and leaf time-to-ignition (Lv_TTI), (c) leaf weight (W) and leaf flaming duration (Lv_FD), (d) leaf total surface area (Stot) and leaf flaming duration (Lv_FD); at the litter scale (e) litter bulk density (Lit_BD) and litter flaming duration (Lit_FD), (f) proportion of fine debris (%Fd) and litter flaming duration (Lit_FD), (g) proportion of evergreen leaves (%Ev) and litter ignition frequency (Lit_IF); at both scales (h) leaf thickness (Thi) and litter flaming duration (Lit_FD), (i) leaf density (D) and litter flame spread (Lit_FS), (j) leaf contact surface area (Sctc) and litter flame spread (Lit_FS).

(Bivariate regressions, $p=p$ -value, R^2 mentioned is the adjusted regression coefficient)

295

296 *Influence of leaf characteristics on litter flammability*

297 Some leaf characteristics were significant drivers of litter flammability, but only regarding
298 flaming duration and flame spread (Table 1). Leaf thickness which drove leaf time-to-ignition
299 was also positively related to litter flaming duration ($R^2=0.48$, $p<0.01$; Fig. 1h). This entailed
300 a significant relationship between leaf time-to-ignition and litter flame duration ($R^2=0.28$,
301 $p<0.05$; Table 2), meaning that species whose leaves took longer to ignite also had litter that
302 burned the longest (e.g. Cupressaceae species). Leaf thickness was also highly related to the
303 flaming duration's drivers previously highlighted, especially litter bulk density ($p<0.0001$,
304 correlation coefficient higher than 0.70. Suppl. Mat. 7). When the scale-leaved species were
305 removed from the dataset, leaf time-to-ignition became negatively correlated with litter
306 ignition frequency (Table 2), meaning that broadleaved species whose leaves took longer to
307 ignite also had litter that did not ignite frequently (e.g. *P. tobira*). On the contrary, when
308 considering only the scale-leaved species, leaf surface area-to-volume ratio became positively
309 related to litter time-to-ignition as well as leaf total surface area to litter flaming duration and
310 flame spread (Table 1).

311 Litter flame spread (found unrelated to litter characteristics) was negatively related to leaf
312 density ($R^2=0.40$, $p<0.01$; Fig. 1i and Table 1) and positively related to contact surface area
313 ($R^2=0.21$ $p<0.05$; Fig. 1j and Table 1). In litter mainly composed of small dense leaves (e.g.
314 *T. occidentalis*), flames did not propagate well compared to litter composed of large and less
315 dense leaves (e.g. *P. laurocerasus*, *E. ebbingei*, or *P. fraseri*). Several other significant
316 relationships were also highlighted between leaf and litter characteristics that had not been
317 taken into account in the previous analysis as they did not correlate with flammability
318 variables (Suppl. Mat. 7). Most relationships highlighted differences between Cupressaceae
319 species and broadleaved species, such as the positive relationships between the proportion of
320 scale-leaves (characterizing litters of the Cupressaceae species) and both leaf thickness and
321 density (scale-leaves being thicker and denser than evergreen leaves), or between the
322 proportion of fine particles (that better characterized the litter of broadleaved species than
323 those of scale-leaved species) and surface area-to-volume ratio (higher for broadleaves than
324 for scale-leaves).

325 The interrelatedness among leaf and litter characteristics which was not highlighted in the
326 bivariate regression analyses complicated identifying the contribution of each leaf
327 characteristic to litter characteristics and flammability. The redundancy analysis (RDA)
328 helped to quantify the proportion of variance in flammability explained by all parameters
329 combined for each fuel scale (Fig. 2). The first two RDA axes together explained 83% of the
330 total variance; 66% being explained by RDA 1. This axis displayed the litter flaming duration
331 which was constrained by the combined influence of leaf thickness and weight (the latter to a
332 lesser extent) as well as of litter bulk density and proportion of fine debris. The proportion of

333 evergreen leaves in the litter was negatively related to this variable. Component 1 was best
334 characterized by *Cupressus arizonica* and *C. leylandii* whose litter burned the longest,
335 contrary to that of *P. tobira*, for instance. The score of litter time-to-ignition was higher on
336 RDA 2 (explaining 18% of the variance) and this variable was mostly constrained by the
337 influence of proportion of fine particles and specific leaf area, to a lesser extent. Litter of *P.*
338 *coccinea* and *L. japonicum* best characterized this component, the former presenting the
339 highest proportion of fine particles and taking longer to ignite contrary to the latter.

340

341 *Characterization of live leaf and litter flammability*

342 The fifteen species had contrasting flammability but this was not consistent across all
343 parameters and fuel scales (Suppl. Mat. 1 and 3; Fig. 3). Leaf flammability was mainly driven
344 by time-to-ignition and flaming duration which were displayed on opposite sides of the first
345 component (explaining 31% of the variance), along with litter flaming duration (best
346 characterizing litter flammability). Leaves of *C. arizonica* (longest time-to-ignition) and *C.*
347 *franchetii* (longest flaming duration) as well as litter of *C. leylandii* (longest flaming duration)
348 were best characterized by these flammability variables (highest scores on the first
349 component). Leaf and litter ignition frequencies were displayed on the second component
350 (explaining 24% of the variance); leaves of *P. tobira* and *L. japonicum* (lowest leaf ignition
351 frequency) as well as litter of *P. fraseri* (highest litter ignition frequency) were best
352 characterized by these variables (highest scores on the second component). Finally, litter
353 time-to-ignition and flame spread were opposed on the third component (explaining 17% of
354 the variation); litter of *E. japonicus* and *P. coccinea* (longest time-to-ignition and low flame
355 spread) as well as those of *L. japonicum* (shortest time-to ignition and highest flame spread)
356 best characterized these variables (highest scores on the third component).

357

358

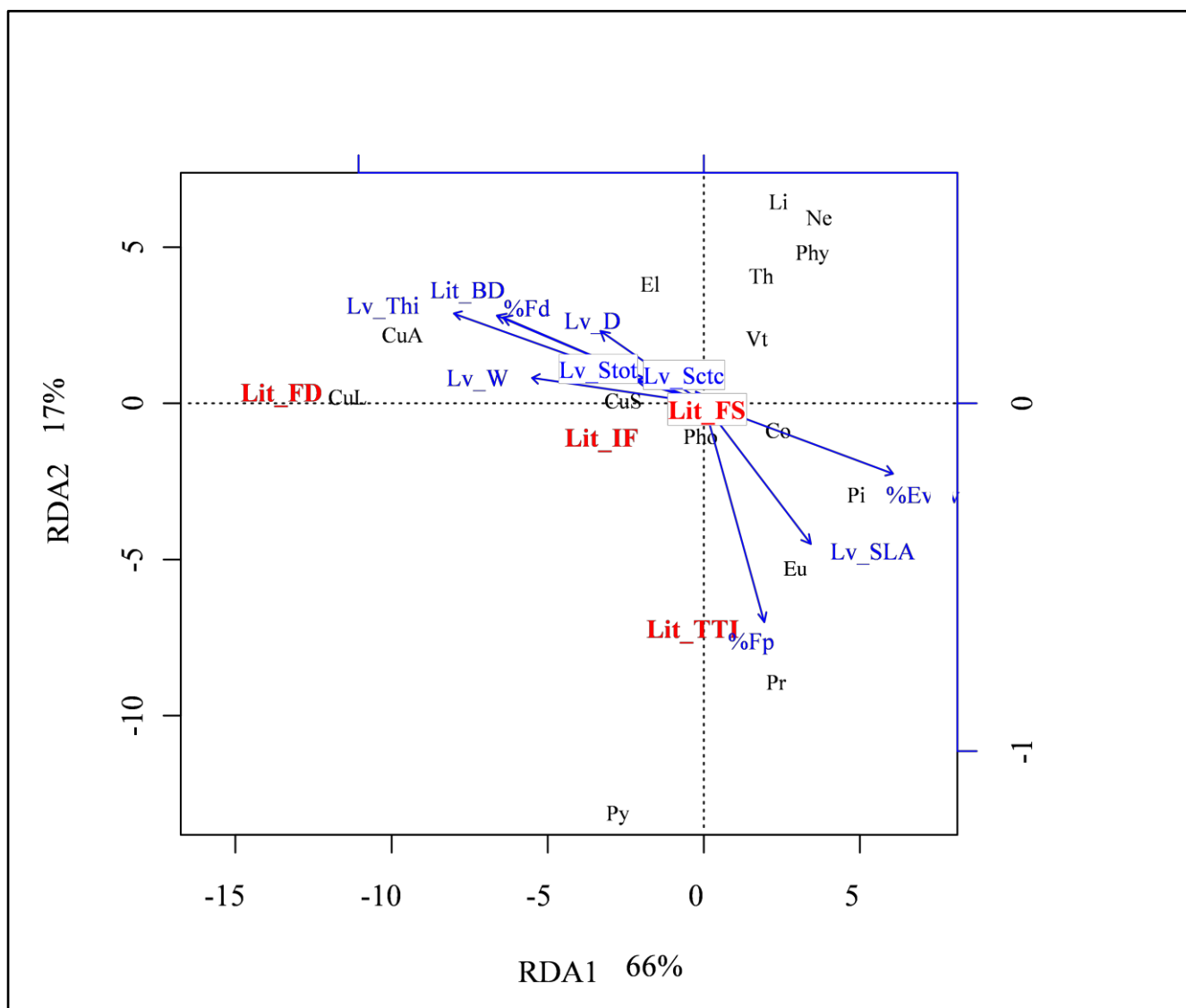


Fig. 2. Redundancy analysis plot run on the litter flammability variables (in bold) as constrained by the litter and leaf characteristics (only those presenting a significant relationships with flammability where taken into account) of the 15 ornamental species.

(Lv: leaf, Lit: litter, Sctc: leaf contact surface area, Stot: leaf total surface area, Thi: leaf thickness, W: leaf weight, SLA: specific leaf area, D: leaf density, BD: litter bulk density, %Ev: proportion of evergreen leaves, %Fp: proportion of fine particles, %Fd: proportion of fine debris, Co: *Cotoneaster franchetii*, CuA: *Cupressus arizonica*, CuL: *Cupressocyparis leylandii*, CuS: *Cupressus sempervirens*, El: *Elaeagnus ebbingei*, Eu: *Euonymus japonicus*, Li: *Ligustrum japonicum*, Ne: *Nerium oleander*, Pho: *Photinia fraseri*, Phy: *Phyllostachys* sp., Pi: *Pittosporum tobira*, Pr: *Prunus laurocerasus*, Py: *Pyracantha coccinea*, Th: *Thuja occidentalis*, Vt: *Viburnum tinus*).

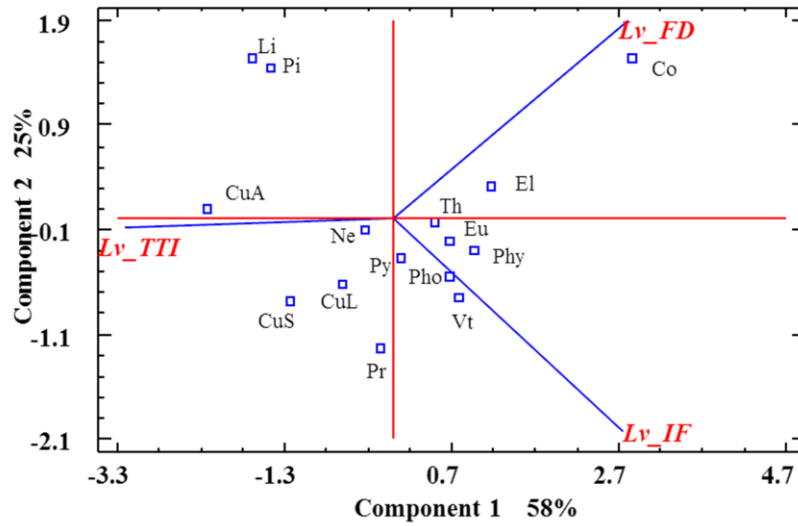
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361

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a

Biplot PCA



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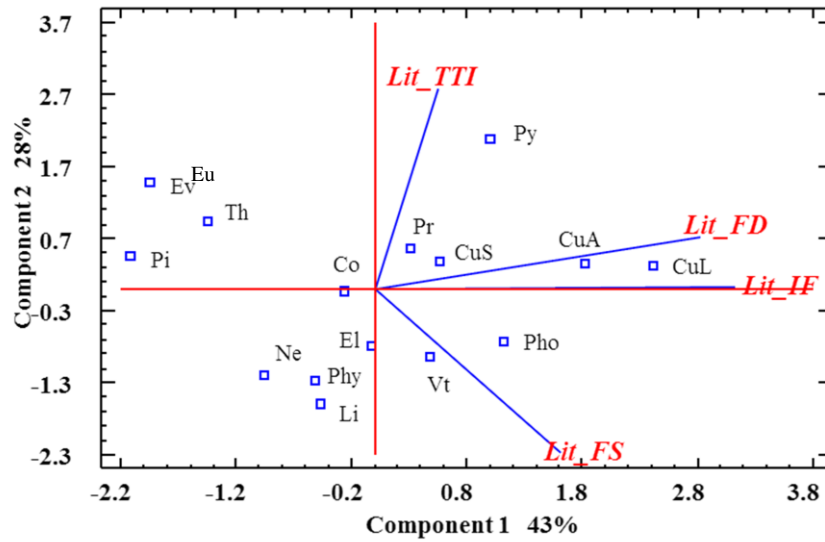
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b

Biplot PCA



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385 **Fig.3.** Biplots of the principal component analysis showing relationships between the 15 ornamental species and
 386 leaf (a) and litter (b) flammability variables (Lv: leaves, Lit: litter, IF: ignition frequency, TTI: time-to-ignition,
 387 FD: flaming duration, FS: flame spread, Co: *Cotoneaster franchetii*, CuA: *Cupressus arizonica*, CuL:
 388 *Cupressocyparis leylandii*, CuS: *Cupressus sempervirens*, El: *Elaeagnus ebbingei*, Eu: *Euonymus japonicus*,

389 Li: *ligustrum japonicum*, Ne: *Nerium oleander*, Pho: *Photinia fraseri*, Phy: *Phyllostachys* sp., Pi: *Pittosporum*
390 *tobira*, Pr: *Prunus laurocerasus*, Py: *Pyracantha coccinea*, Th: *Thuja occidentalis*, Vt: *Viburnum tinus*).

391

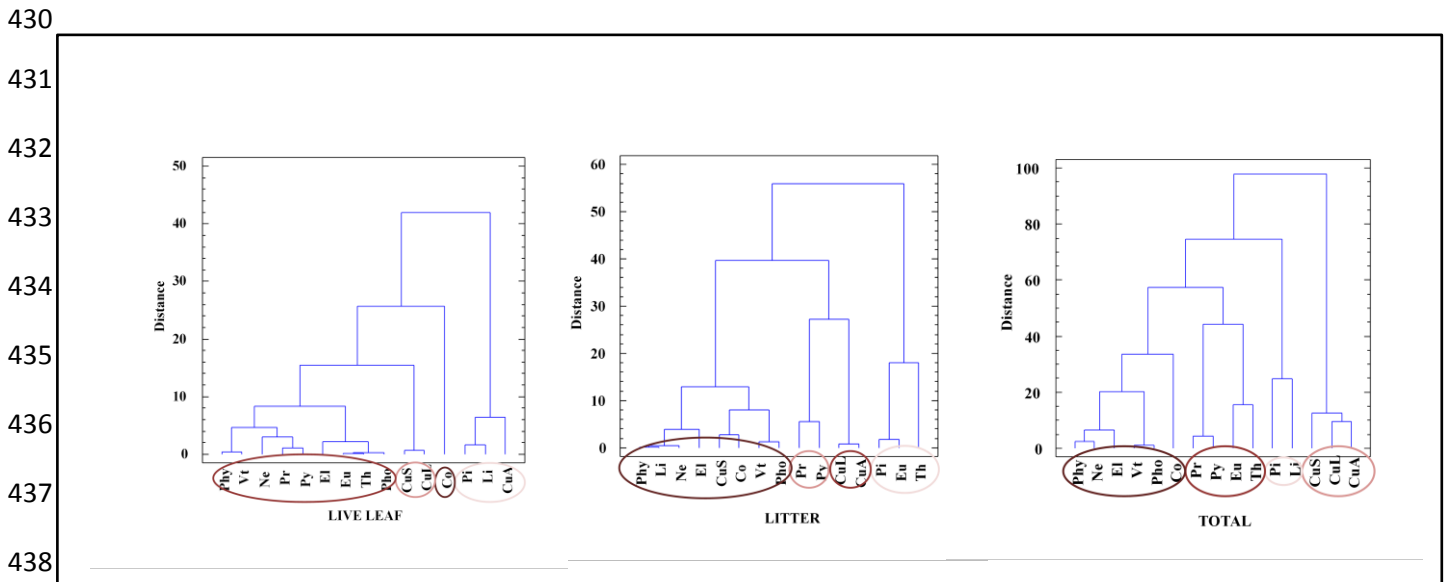
392 *Ranking species according to their flammability*

393 For each ranking (leaf, litter, and total), hierarchical cluster analyses highlighted four groups
394 of species from the most flammable to the least flammable; the composition of these groups
395 differed from one analysis to the other (Fig. 4). For live leaves (Fig. 4a), *C. franchetii* had the
396 highest flammability (mainly due to long flaming duration and short time-to-ignition) whereas
397 *P. tobira*, *C. arizonica*, and *L. japonicum* belonged to the group of the least flammable species
398 (mostly due to longer time-to-ignition and lower ignition frequency). The other species
399 belonged to the two groups of intermediate flammability: leaves of *C. sempervirens* and *C.*
400 *leylandii* took longer to ignite and the eight other species presented intermediate values of
401 flammability and/or short time-to-ignition or high ignition frequency.

402 For litter (Fig. 4b), three species composed the group of the least flammable species (*P.*
403 *tobira*, *E. japonicus*, and *T. occidentalis*) which, except for *P. tobira*, differed from the
404 previous ranking. These species had low ignition frequency and/or long time-to-ignition, short
405 flaming duration, and low flame propagation. The species composing the two groups of
406 intermediate flammability were also different from those of the leaf ranking: *P. coccinea* and
407 *P. laurocerasus* presented long time-to-ignition but high flame spread whereas *C. arizonica*
408 and *C. leylandii* were characterized by long flaming duration and high ignition frequency.
409 The eight other species composed the group of the most flammable species which, except for
410 *C. franchetii*, were different from the leaf ranking (in which this group was composed of this
411 latter species only). These species presented intermediate values of flammability and short
412 time-to-ignition or high flame propagation.

413 Regarding the total ranking (Fig. 4c), combining both leaf and litter flammability, two
414 species belonged to the group of the least flammable species, including *P. tobira* (as in the
415 two previous rankings) and *L. japonicum* (as in the leaf ranking) which had the lowest
416 ignitability (e.g. long time-to-ignition and low ignition frequency). In the two groups of
417 intermediate flammability, species differed from those of the previous rankings: the group of
418 the three *Cupressus* species presented long leaf time-to-ignition but long flaming duration. *E.*
419 *japonicus*, *T. occidentalis*, *P. coccinea*, and *P. laurocerasus* composed the other group,
420 characterized by short flaming duration and low flame spread but differing in their ignitability
421 (for both time-to-ignition and ignition frequency). The group of the most flammable species
422 was composed of the six other species, still including *C. franchetii*, which were mostly
423 characterized by higher litter and leaf ignitability, long leaf flaming duration, high flame
424 spread or by intermediate values of flammability.

425 According to the Spearman's rank-order correlation, the rankings obtained for leaf and
 426 litter flammability were not correlated (results would not change when each flammability
 427 variable was taken separately) (Table 3), confirming the results of the hierarchical cluster
 428 analyses. This result highlighted a significant difference in the species composition of the
 429 different groups of flammability.



439 **Fig. 4.** Rankings of the 15 ornamental species from the most flammable (darkest outline) to
 440 the least flammable (lightest outline) species according to the flammability of live leaves (a),
 441 litter (b), and both fuels (c) (Co: *Cotoneaster franchetii*, CuA: *Cupressus arizonica*, CuL:
 442 *Cupressocyparis leylandii*, CuS: *Cupressus sempervirens*, El: *Elaeagnus ebbingei*, Eu:
 443 *Euonymus japonicus*, Li: *Ligustrum japonicum*, Ne: *Nerium oleander*, Pho: *Photinia fraseri*,
 444 Phy: *Phyllostachys* sp., Pi: *Pittosporum tobira*, Pr: *Prunus laurocerasus*, Py: *Pyracantha*
 445 *coccinea*, Th: *Thuja occidentalis*, Vt: *Viburnum tinus*).

446

447

448 Discussion

449 Drivers characterizing leaf and litter flammability

450 The leaf characteristics that drive flammability are well known. Vegetation characteristics can
 451 have large effects on fire behavior (Schwilk 2015) and scaling up from leaf to fuel bed would
 452 be an important step in predicting surface fire behavior (Varner *et al.* 2015). Results showed
 453 that leaf flammability was best characterized by leaf time-to-ignition which was mainly
 454 driven by leaf thickness (especially for *C. arizonica*) and, in part, by FMC (when considering
 455 only the broadleaved species, especially *L. japonicum* and *P. tobira*). On the other hand, litter

456 flammability was best characterized by litter flaming duration which was mainly driven by
457 bulk density and proportion of fine debris (especially for *C. arizonica* and *C. leylandii*). In
458 addition, litter flammability was also characterized by litter ignition frequency which was
459 negatively related to the proportion of evergreen leaves in the litter (especially for *P. tobira*
460 and *E. japonicus*). Thick leaves with low specific leaf area (e.g. scale-leaves) took longer to
461 ignite in contrast to thinner leaves with higher specific leaf area, such as those of *C.*
462 *franchetii*, agreeing with previous works (Montgomery and Cheo 1971; Murray *et al.* 2013;
463 Grootemaat *et al.* 2015). Specific leaf area as well as surface area-to-volume ratio (the latter,
464 however, was not significant in the analyses) are essential factors driving ignitability, as with
465 FMC (Bond and Van Wilgen 1996; Anderson and Anderson 2009; White and Zipperer 2010;
466 Marino *et al.* 2011; Madrigal *et al.* 2013; Murray *et al.* 2013; Santoni *et al.* 2014; Grootemaat
467 *et al.* 2015). FMC was not a significant predictor of leaf flammability, mostly because it was
468 overridden by leaf thickness, but, when considering only the broad-leaved species (thinner
469 leaves), FMC significantly increased leaf time-to-ignition (as for *L. japonicum* and *N.*
470 *oleander*). The range of FMCs recorded in the species studied covered the range of live FMCs
471 in Bond and Van Wilgen (1996; 50-205%) or in Grootemaat *et al.* (2015; 68-231%).
472 Surprisingly, the results also showed that heavy leaves characterized by high total surface area
473 (e.g. *P. laurocerasus* or *C. arizonica*) burned for a shorter time than lighter and smaller leaves
474 (e.g. *C. franchetii* which also ignited faster) contrary to the results of Grootemaat *et al.*
475 (2015). However, the variation in leaf flaming duration among species explained by leaf
476 weight and total surface area was moderate in the current work ($R^2=0.22$ and 0.23).

477 The most important drivers of litter flammability have been sought among fuel bed
478 characteristics (e.g. “*in situ*” bulk density and litter components, as litter samples were
479 collected undisturbed) but also among those of leaves. Given their importance in the
480 flammability of surface fuels, the need to scale up from leaf to litter bed characteristics has
481 already been highlighted in previous works (Scarff and Westoby 2006; de Magalhães and
482 Schwilk 2012; Varner *et al.* 2015). Leaf thickness was among the main drivers of leaf time-to-
483 ignition and was also a significant predictor of litter flaming duration: litter of thick-leaved
484 species (Cupressaceae species) took longer to burn. This result was not always consistent with
485 other experimental studies (Kane *et al.* 2008; de Magalhães and Schwilk 2012) in which litter
486 beds composed of thick leaves either were characterized by lower residence time for fire or
487 did not present a specific pattern of flaming duration (results not significant). These thick
488 scale-leaved species also had the most compacted litter (e.g. the highest bulk density). Litter
489 bulk density was positively related to flaming duration, agreeing with the results of de
490 Magalhães and Schwilk (2012) who found that the leaf surface area was also a significant
491 predictor of flaming duration. In the current work, this latter parameter was unrelated to
492 flaming duration (except for the scale-leaved species dataset, but with a positive effect). It is
493 worth noting that leaf thickness (along with leaf density) significantly correlated with litter
494 bulk density because of the thickness (and high density) of scale leaves, scaling up from leaf

495 to litter bed characteristics according to other works (Scarff and Westoby 2006; Cornwell *et*
496 *al.* 2015). However, leaf density was not related directly to flaming duration as was leaf
497 thickness. Accordingly, these leaves can be easily broken into fine debris (e.g. very small
498 elements) and produce more tightly packed litter that took longer to burn because of the slow
499 combustion mostly due to the lack of oxygen in the samples (Scarff and Westoby 2006;
500 Schwilk and Caprio 2011; de Magalhães and Schwilk 2012). This result also showed the
501 importance of decomposed materials on litter flaming duration (Zhao *et al.* 2014); this large
502 amount of fine debris resulted from the slow decomposition process characterizing
503 gymnosperms compared to angiosperms (Cornwell *et al.* 2008). Bulk density was unrelated
504 to litter time-to-ignition, as already highlighted by Santoni *et al.* (2014). Oxygen limitation in
505 compacted litter samples (high bulk density) should have mitigated the flame propagation, as
506 found in other works (Scarff and Westoby 2006; Santoni *et al.* 2014) but, surprisingly, flame
507 spread and bulk density were not significantly related. In contrast, leaf contact surface area
508 and density turned out to be significant predictors of flame spread, the former increasing
509 flammability contrary to the latter. In fact, denser leaves presented more fuel to burn,
510 mitigating flame propagation. This result agreed with previous works that showed that litter
511 flammability was often strongly influenced by litter particle (e.g. leaf) size, larger particles
512 leading to greater aeration, faster flame spread rate, and higher rate of heat release (Scarff and
513 Westoby 2006; Kane *et al.* 2008; van Altena *et al.* 2012; de Magalhães and Schwilk 2012;
514 Cornwell *et al.* 2015).

515

516 *Flammability ranking*

517 Results showed that only two species had the same flammability, regardless of the fuel
518 scale: the poorly flammable species *P. tobira*, agreeing with White and Zipperer (2010, based
519 on Baptiste 1992), and the highly flammable *C. franchetii*. However, for most species, the
520 rankings differed between the two fuel scales, some species having more flammable litter than
521 the live leaf scale (e.g. *C. sempervirens*) and other species demonstrating the opposite pattern
522 (e.g. *E. japonicus*). In contrast, using a different burning devices, Dimitrakopoulos (2001)
523 ranked *C. sempervirens*' leaves among the most flammable (but measuring only the mean
524 volatilization rate) and Etlinger and Beall (2004, based on the work of Lubin and Shelly 1997)
525 recommended *N. oleander* to be used in high fire hazard areas (but measuring only the peak
526 heat released). Their assessment of the species' flammability would have been more accurate
527 if several flammability components had been taken into account.

528 Most species were ranked differently depending on the fuel scale: e.g. leaves of *L.*
529 *japonicum* were poorly flammable whereas this species' litter was highly flammable. Other
530 species presented the opposite pattern (e.g. *T. occidentalis*). Species composing these groups
531 could also differ from those of the total ranking; e.g. species such as *C. arizonica* or *C.*
532 *sempervirens* were ranked more flammable in the litter ranking than in the total ranking,

533 leading to an underestimation of their flammability if based only on both fuel scales
534 combined. To increase the robustness of flammability estimates, species rankings should
535 encompass multiple relevant scales, with the most severe ranking considered carefully. The
536 most accurate flammability ranking should thus be composed of three groups of species
537 (instead of the four groups previously identified). The group of the most flammable species
538 should be composed of species presenting a higher litter flammability: *Cotoneaster franchetii*
539 (always ranked as very flammable regardless of the fuel scale), *Phyllostachys* sp., *Photinia*
540 *fraseri*, *Viburnum tinus*, *Eleaegnus ebbingei*, *Nerium oleander* (moderate leaf flammability),
541 and *Cupressus sempervirens* and *Ligustrum japonicum* (lower leaf flammability). The group
542 of intermediate flammability should be composed of *Pyracantha coccinea*, *Prunus*
543 *laurocerasus*, *Euonymus japonicus*, and *Thuja occidentalis* (moderate leaf flammability) and
544 of *Cupressus arizonica* and *Cupressocyparis leylandii* (moderate litter flammability).
545 Regardless of the fuel scale, *Pittosporum tobira* was consistently poorly flammable and was
546 the only one to compose the group of the least flammable species. For landscaping, the most
547 conservative approach would be to select species that have lower flammability at both scales
548 (in this case, only *Pittosporum tobira*) or to avoid species with higher flammability (such as
549 *Cotoneaster franchetii*). Potential limitations of rankings could be underlined, e.g. species
550 burning quickly would likely provoke less damage to structures than others burning slowly
551 (yet ranked less flammable).

552 *C. sempervirens* (var. *pyramidalis*) had a large amount of dead leaves within its crown, due
553 to its fastigiated form (Ganteaume *et al.* 2013b; Della Rocca *et al.* 2015), resulting in a high
554 combustibility, thus burning with a far greater intensity when reached by the flames. This
555 result highlights the need to assess, along with the flammability, the proportion of dead and
556 fine particles that composes each species' crown (as in Ganteaume *et al.* 2013b). In their
557 work, Della Rocca *et al.* (2015) suggested to plant barrier systems of *C. sempervirens* var.
558 *horizontalis* in WUI to reduce the fire spread because of this species' low leaf flammability,
559 but without assessing litter flammability (the most flammable fuel scale for *C. sempervirens*
560 according to the current work) nor the amount of dead fuel in the canopy. Even if this amount
561 is smaller in this variety of cypress, the live biomass is still dense and thus could burn with
562 high intensity. Regardless of the variety, *C. sempervirens* should not be planted close to
563 housing that could be damaged if the plant ignites, as observed by the firefighters.

564

565 *Explaining differences in results between works*

566 The differences I found between studies could be explained by the differences in litter type
567 (undisturbed samples *vs* reconstructed samples), in experimental devices and ignition
568 processes, as well as in the flammability variables recorded (Weise *et al.* 2005; Madrigal *et al.*
569 2013). Laboratory-based flammability measurements are not perfect and may not entirely
570 represent the ecosystems (Fernandes and Cruz 2012), even if the experiments were carried out

571 on undisturbed litter samples whose structure and composition are kept intact.
572 Complementary information that could be provided at the whole plant scale is needed and
573 may help in the integration and discussion of such results. In the case of the assessment of the
574 whole plant flammability, the influence of plant geometry will have to be analyzed in addition
575 to the other characteristics. Indeed, it is helpful to distinguish between characteristics
576 influencing the flammability of the whole plant's canopy and those that influence the
577 flammability of the litter to which they contribute (Schwilk 2015).

578

579

580 **Acknowledgements**

581 The author wishes to thank the Irstea's technical staff, Roland Estève, Fabien Guerra and
582 Jean-Michel Lopez, for their contribution in the field and in the laboratory during the burning
583 experiments. The author also sincerely thanks Aimee Mac Cormack for English revision.

584

585

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Table 1. Significant relationships (correlation coefficients, R, and p-value) obtained between flammability variables and characteristics of leaf and litter bed (in bold: all species, in bold and italic: non-significant correlations but $R \geq 0.5$, in italic: excluding the Cupressaceae species, in underlined: only the Cupressaceae species).

	Lv_IF	Lv_TTI	Lv_FD	Lit_IF	Lit_TTI	Lit_FD	Lit_FS
Leaf scale							
FMC	NS	<i>0.65;p=0.031</i>	NS				
Sctc	NS	NS	NS	NS	<u>0.98;p=0.020</u>	NS	0.52;p=0.049
Stot	NS	NS	-0.53;p=0.043	NS	NS	<u>0.99;p=0.010</u>	<u>0.97;p=0.025</u>
Thi	NS	0.76;p=0.0009	NS	NS	NS	0.72;p=0.002	NS
W	NS	NS	-0.54;p=0.040	NS	NS	NS	NS

V	NS	NS	NS	NS	NS	NS	NS
SVR	NS	NS	NS	NS	NS	NS	NS
SLA	NS	-0.54;p=0.038	<u>0.98;p=0.022</u>	NS	NS	NS	NS
D	NS	NS	NS	NS	NS	NS	-0.66;p=0.007

Litter scale

%Ev				-0.55;p=0.034	NS	NS	NS
%Sca				NS	NS	NS	NS
%Cp				NS	NS	NS	NS
%Cd				NS	NS	NS	<i>0.63;p=0.036</i>

%Fp	NS	0.51;p=0.054	NS	NS
%Fd	0.50;p=0.057	NS	0.55;p=0.032	NS
%NC	NS	NS	NS	NS
BD	NS	NS	0.58;p=0.022	0.50;p=0.057

Lv: leaves, Lit: litter, IF: ignition frequency, TTI: time-to-ignition, FD: flaming duration, FS: flame spread, FMC: fuel moisture content, Sctc: leaf contact surface area, Stot: leaf total surface area, Thi: leaf thickness, W: leaf weight, V: leaf volume, SVR: leaf surface area to volume ratio, SLA: specific leaf area, D: leaf density, BD: litter bulk density, %Ev: proportion of evergreen leaves, %Sca: proportion of scale-leaves, %Fp: proportion of fine particles, %Cp: proportion of coarse particles, %Fd: proportion of fine debris, %Cd: proportion of coarse debris, %NC: proportion of non-combustible particles.

Table 2. Significant relationships (correlation coefficients, R, and p-value) obtained between leaf and litter bed flammability variables (in bold: all species, in italic: excluding the Cupressaceae species, in underlined: only the Cupressaceae species).

	Lv_IF	Lv_TTI	Lv_FD	Lit_IF	Lit_TTI	Lit_FD	Lit_FS
Lv_IF		<i>-0.71;p=0.014</i>	NS	NS	NS	NS	NS
Lv_TTI	<i>-0.71;p=0.014</i>		NS	<i>-0.68;p=0.023</i>	NS	0.58;p=0.024	NS
Lv_FD	NS	NS		NS	NS	NS	NS
Lit_IF	NS	<i>-0.68;p=0.023</i>	NS		NS	0.59;p=0.021	0.99;p=0.0066
Lit_TTI	NS	NS	NS	NS		NS	0.96;p=0.041
Lit_FD	NS	0.58;p=0.024	NS	0.59;p=0.021	NS		NS
Lit_FS	NS	NS	NS	0.99;p=0.0066	0.96;p=0.041	NS	

Lv: leaves, Lit: litter, IF: ignition frequency, TTI: time-to-ignition, FD: flaming duration, FS: flame spread.

Table 3. Spearman's rank-order correlation between the leaf and litter flammability rankings of species

H₀: no association between the two variables; ρ : Spearman's correlation coefficient, P: p-value; IF: ignition frequency, TTI: time to ignition, FD: flaming duration

Ranking of species	Spearman's rank-order correlation
Live leaf-Litter (all variables)	$\rho=0.17$; $P=0.52$: very weak
Leaf-Litter IF	$\rho=0.45$; $P=0.052$: moderate
Leaf-Litter TTI	$\rho=0.09$; $P=0.77$: very weak
Leaf-Litter FD	$\rho=-0.31$; $P=0.25$: weak