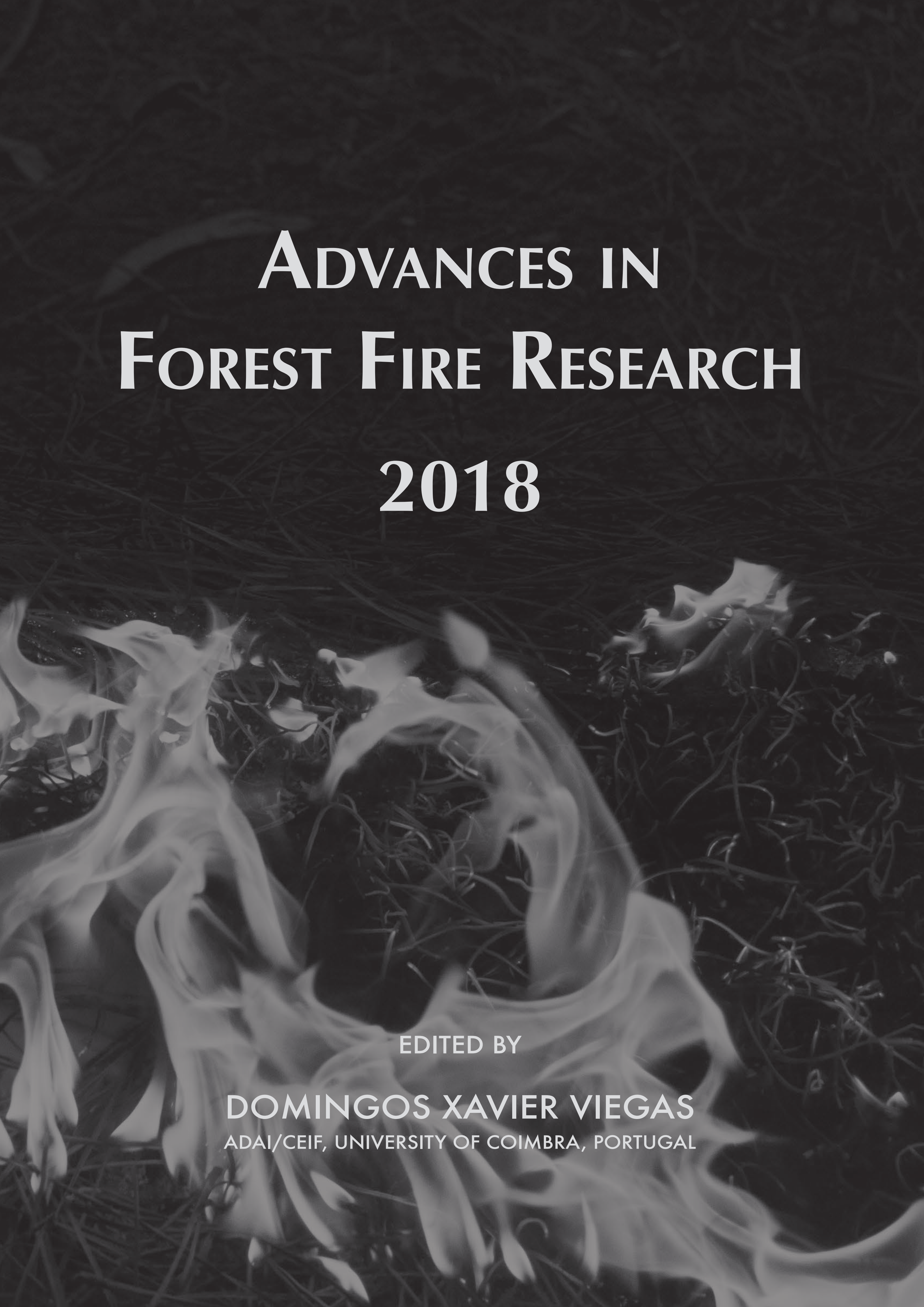

Advances in Forest Fire Research 2018

EDITED BY

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https://doi.org/10.14195/978-989-26-16-506_93

Terpene-containing species vs terpeneless species: what best drives flammability of ornamental species used in WUI?

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Abstract

In wildland-urban interfaces (WUI), the vegetation surrounding housing can be an efficient vector of fire propagation towards buildings possibly resulting in extensive damage. The current work aimed at highlighting the most flammable species in WUI and the driving factors of their leaf flammability among a set of leaf characteristics including terpene content supposed to enhance plant flammability. This hypothesis needed to be clarified and the role of the three main classes (mono-, sesqui-, and diterpenes) determined in the species that contained such molecules.

After the screening of the live leaf terpene contents in 16 of the most common species in WUI of SE France, only five presented terpenes: *Pinus halepensis, Cupressus arizonica, C. sempervirens, Cupressocyparis leylandii,* and *Thuja occidentalis.* Burning experiments provided data allowing the species to be ranked from the most to the least flammable. *P. halepensis* belonged to the most flammable species contrary to the four others. Relationships between flammability and leaf characteristics (terpene contents, leaf thickness, surface-to-volume ratio, mass-to-volume ratio, and FMC) were tested to highlight the most significant flammability drivers. Except for ignition frequency hindered by diterpene content, the flammability of species containing terpenes was mostly driven by sesquiterpene content (positive effect), sometimes combined to other leaf characteristics; *P. halepensis* best characterized these relationships. Leaf thickness best predicted flammability of the terpeneless species (negative effect) but when all species were pooled, sesquiterpene content was still one of the best predictors.

P. halepensis containing the highest amount of sesquiterpenes and being among the most flammable species should be avoided in WUI, along with species with low FMC and leaf density. The other species presenting high monoterpene and diterpene contents were characterized by less flammable thick and dense leaves; however, the amount of dead fuel trapped in the canopy of *Cupressus sempervirens* strongly increases its flammability and should also be avoided near housing.

Keywords: WUI, leaf flammability, terpenes, ornamental vegetation, Pinus halepensis

1. Introduction

In wildland-urban interfaces (WUI), where the fire risk is high, the vegetation surrounding housing (i.e. WUI vegetation also called ornamental vegetation composed of both native and strictly ornamental species) can be an efficient vector of fire propagation towards structures, possibly resulting in damaging or destroying these buildings. Consequently, to better understand the role of the ornamental vegetation in this propagation, either due to spot fires or to the radiant heat emitted by the flame front, previous studies have focused on the assessment of this vegetation's flammability (Ganteaume *et al.* 2013a, 2013b), targeting live and dead surface fuels but without taking into account chemical characteristics. Others works showed that some of these characteristics (i.e. nitrogen, phosphorus, and tannin contents) could affect plant flammabilty (Grootemat *et al.* 2015, 2017). Terpenes are among the most frequent chemical compounds hypothesized or even assumed to promote flammability but results were not always significant or differed between studies (Dimitrakopoulos 2001; Alessio *et al.* 2008; Ormeño *et al.* 2009; Pausas *et al.* 2016). To increase knowledge on the WUI vegetation's flammability and to be able to select "firewise species" for landscaping in these areas, the current work aimed at highlighting the most flammable species that can be deleterious in WUI and the driving factors of their flammability among a set of leaf characteristics including leaf terpene content characterized by three classes (monoterpenes, sesquiterpenes, and diterpenes). The terpene content is supposed to enhance plant flammability (Pausas *et al.* 2016; Alessio *et al.* 2008) but this hypothesis needed to be clarified and the role of the different classes determined in species that contained such molecules.

2. Methodology

2.1. Study Species and Sampling

The 16 species studied in the current work (Table 1) are common in WUI of SE France and this WUI vegetation is composed of both native (such as *Viburnum tinus, Pinus halepensis*) and exotic species (such as *Thuja occidentalis*), some being created for strictly ornamental purposes (i.e. *C. Leylandii*). Depending on their location, these species can be involved in fire propagation to the nearby buildings, especially those used in ornamental hedges characterized by a strong horizontal fuel continuity. During a fire, some of these species (e.g. *Pinus halepensis, Cupressus sempervirens*) can also be responsible for damage and even for the destruction of buildings when the plants are too close to buildings, as often witnessed by the firefighters.

The live leaf sampling was carried out on five individuals per species, in summer (July 2016), when the climate conditions were the most severe in SE France and avoiding 48h following precipitations to avoid any impact of the recent rain on FMC.

Table 1 - List of the 16 species studied: abbreviations (Abb.), terpene content (yes or no), mean leaf thickness and mean ($\pm$SD) leaf moisture content (FMC)

Latin name	**Abb.**	**Terpene content**
Viburnum tinus	*Vt*	*No*
Cupressus sempervirens	*CuS*	*Yes*
Cotoneaster franchetii	*Co*	*No*
Prunus laurocerasus	*Pr*	*No*
Elaeagnus ebbingei	*El*	*No*
Cupressus arizonica	*CuA*	*Yes*
Phyllostachys sp.	*Phy*	*No*
Pyracantha coccinea	*Py*	*No*
Cupressocyparis leylandii	*CuL*	*Yes*
Nerium oleander	*Ne*	*No*
Pinus halepensis	*Ph*	*Yes*
Photinia fraseri	*Pho*	*No*
Euonymus japonicus	*Eu*	*No*
Ligustrum japonicum	*Lj*	*No*
Pittosporum tobira	*Pi*	*No*
Thuja occidentalis	*To*	*Yes*

2.2. Terpene analyses

The content of the three main terpene classes (monoterpenes, sesquiterpenes, diterpenes) was screened in the leaves of the 16 species studied. The analyses were conducted on 10g leaf samples using a GC-MS (GC System 7890B – Agilent Technologies®).

2.3. Burning experiments

Just after sampling, the flammability of the 16 species studied was assessed burning thirty 1g leaf samples per species using a 500W epiradiator. Ignition frequency (IF, %), time-to-ignition (TTI, s), and flaming duration (FD, s) were recorded during the burning experiments.

Just before the experiments, 5 g of leaves of each individual were oven-dried for 48 h at 60 °C in order to measure their moisture content at the time of burning. Along with the terpene content and FMC, leaf characteristics – thickness (Thi), surface-to-volume ratio (SVR), density or mass-to-volume ratio (D) were also taken into account as flammability explanatory factors.

2.4. Data analyses

In order to check if flammability and terpene contents varied according to species, intra- and inter-specific variations in leaf flammability were tested with variance analysis (one-way ANOVA, Fisher test). According to the flammability variables recorded during the burning experiments, species were ranked from the most flammable to the least flammable performing Hierarchical Cluster Analysis. Then relationships between flammability and leaf characteristics (monoterpene, sesquiterpene, and diterpene contents, leaf structural characteristics, and FMC) were tested to highlight the most significant drivers of each flammability variable performing regression and co-inertia analyses.

3. Results and discussion

3.1. Terpene Contents

Out of the 16 species studied, only five presented terpenes: *Pinus halepensis, Cupressus arizonica, C. sempervirens, Cupressocyparis leylandii,* and *Thuja occidentalis.* These species present storage structures for volatile organic compounds, such as resin ducts (Yani *et al.* 1993; Ormeño *et al.* 2008)

Regarding terpene diversity, a total of 54 different compounds were identified in the leaves and litter of the species studied. Sesquiterpenes presented the higher diversity in terpenes (24 compounds) mostly in *Cupressocyparis leylandii* and *Cupressus arizonica,* compared to diterpenes (19 compounds) mainly found in *C. leylandii* and in *Cupressus sempervirens,* and to monoterpenes (11 compounds), mostly in *C. Leylandii*. This latter species presented the highest terpene diversity with 34 different compounds.

Regarding terpene contents, *C. leylandii* presented the highest monoterpene content (2.54 mg g^{-1}), *P. halepensis* presented the highest sesquiterpene content (1.2 mg g^{-1}), mostly due to caryophyllene, and diterpene content was the highest in *Thuja occidentalis* (1.04 mg g^{-1}), mostly due to nezukol.

The intra-specific variation in the terpene content (31%) was not considered as significant. The inter-specific variations in the terpene content were significant regardless of the class of terpene (One way ANOVA, $p<0.0001$).

3.2 Species Flammability

Within the same species, flammability variables varied only slightly between individuals (the coefficient of variation was, on average, 25.6%). Inter-specific differences were tested for each flammability variable and all the flammability variables significantly differed between species (One-way Anova, $p<0.001$). When the flammability of species containing terpenes was compared to that of terpeneless species, results were contrasted; the former presenting longer flaming duration and time-to-ignition. The ranking of species according to their flammability revealed that the terpene-containing species were split into two groups of different flammability (Fig. 1). Agreeing with previous works (Trabaud, 2000; Dimitrakopoulos, 2001), *P. halepensis* belonged to the most flammable species, along with two terpeneless species *Cotoneaster franchetti* and *Elaeagnus ebbingei* (mostly due to high ignition frequency and long flaming duration) while the four others were ranked as not very flammable (mostly due to long time-to-ignition).

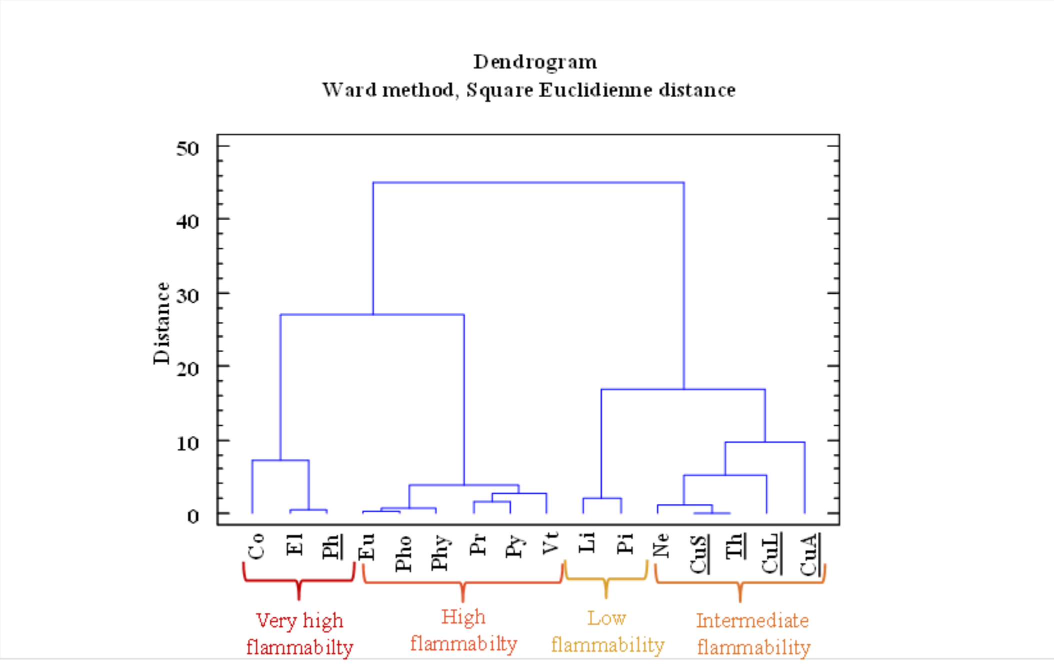

Figure 1 - Ranking of the 16 ornamental species from the most flammable to the least flammable species according to leaf flammability (underlined: species containing terpenes, Co: Cotoneaster franchetii, CuA: Cupressus arizonica, CuL: Cupressocyparis leylandii, CuS: Cupressus sempervirens, El: Elaeagnus ebbingei , Eu: Euonymus japonicus, Li: Ligustrum japonicum, Ne: Nerium oleander, Ph: Pinus halepensis, Pho: Photinia fraseri, Phy: Phyllostachys sp., Pi: Pittosporum tobira, Pr: Prunus laurocerasus, Py: Pyracantha coccinea, Th: Thuja occidentalis, Vt: Viburnum tinus).

Along with the high sesquiterpene, *P. halepensis*' leaves also presented high SVR as well as low density and FMC in contrast to less flammable species containing terpenes whose leaves were thicker and denser and presented higher monoterpene and diterpene contents. The least flammable species (*Pittosporum tobira* and *Ligustrum japonicum*) did not contain terpenes and presented low ignitability and sustainability, mostly due to higher leaf moisture content along with high density and low SVR (Fig. 2).

Except for ignition frequency significantly predicted by diterpene content (negative effect, logistic regression, $p=0.002$), the flammability of species containing terpenes was mostly driven by sesquiterpene content (positive effect), combined to leaf density (negative effect) regarding flaming duration (multiple regression, $p=0.002$) and to FMC and thickness (positive effect) regarding time-to-ignition (multiple regression, $p<0.0001$). *P. halepensis* was the species best characterizing these relationships, this species presenting the highest amount of sesquiterpenes (mostly due to caryophyllene: 0.905 mg g^{-1} which was the most concentrated molecule among the entire set of compounds identified). When this latter species was removed from the analyses, sesquiterpene content was not a significant driver of flammability anymore, replaced by diterpene content (negative effect on TTI). Several other fire-prone species also presented high sesquiterpene contents, such as the Australian *Malaleuca quinquenervia* (Ireland *et al.* 2002) or several Mediterranean species of *Cistus* (especially caryophyllene for *C. monspeliensis;* Llusià and Peñuelas 1998) whose germination is triggered by fire. In the current study, monoterpene content was not a significant driver of flammability contrary to the results of Pausas *et al.* (2016) obtained on *Rosmarinus officinalis*. This latter species produces monoterpenes (some presenting high contents such as camphrene) differing from those found in the species we studied; this could be an explaination to this difference. Other works showed, however, that monoterpenes were poorly related to flammability or were overridden by FMC (Alessio *et al*. 2008a, 2008b).

For the terpeneless species, leaf thickness best predicted flammability (negative effect) combined to surface-to-volume ratio and FMC (negative effect) regarding flaming duration, to leaf density (positive effect) regarding time-to-ignition, and to leaf density and surface-to-volume ratio (negative effect) regarding ignition frequency (for all relationships, p<0.0001). When all the species were pooled in the multiple regression analyses, sesquiterpene content was still one of the best predictors of time-to-ignition and flaming duration, highlighting the strong impact of *Pinus halepensis* in the relationships.

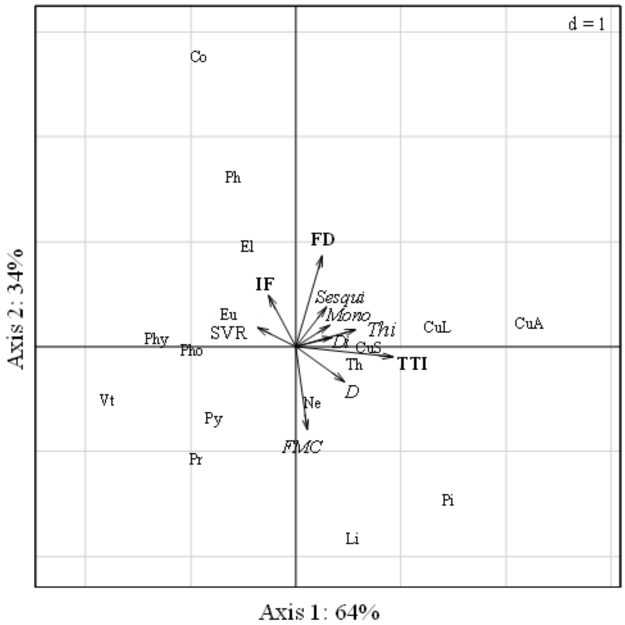

Figure 2 - Co-inertia analysis highlighting the relationships between the leaf characteristics of the 16 ornamental species and their flammability variables. The two first components together explain 98% of the total variance (D: leaf density, SVR: surface-to-volume ratio, FMC: fuel moisture content, Thi: leaf thickness, Mono: monoterpene content, Sesqui: sesquiterpene content, Di: diterpene content, Co: Cotoneaster franchetii, CuA: Cupressus arizonica, CuL: Cupressocyparis leylandii, CuS: Cupressus sempervirens, El: Elaeagnus ebbingei , Eu: Euonymus japonicus, Li: ligustrum japonicum, Ne: Nerium oleander, Ph: Pinus halepensis, Pho: Photinia fraseri, Phy: Phyllostachys sp., Pi: Pittosporum tobira, Pr: Prunus laurocerasus, Py: Pyracantha coccinea, Th: Thuja occidentalis, Vt: Viburnum tinus).

4. Conclusion

The present work showed that the sesquiterpene content (especially the caryophyllene content) was one of the strongest predictor of flammability highlighting that species containing high amount of this terpene (e.g. *P. halepensis*) would be among the most flammable and thus should be avoided in WUI, along with terpeneless species with low FMC and leaf density (e.g. *C. franchetti* and *E. ebbingei* contrary to *P. tobira* and *L. japonicum*). The other species that presented high monoterpene and diterpene contents were also characterized by thicker and denser leaves that were less flammable. However, the amount of dead fuel trapped in the canopy of some of these species (e.g. *Cupressus sempervirens*) strongly increases their flammability (Ganteaume *et al*. 2013a) and should also be avoided close to housing, especially when they form horizontal fuel continuity (as in ornamental hedge) that can easily propagate the fire. Moreover, as flammability can differ between live leaf and dead surface fuel within a given species (Ganteaume 2018), it will be important to also assess the role of terpene contents on litter flammability.

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