Trees
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ORIGINAL ARTICLE

Could different structural features affect flammability traits in Mediterranean forest ecosystems?

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Abstract

Key message **Mediterranean forest stands manifest diverse flammability traits according to their potential ecological successional stage and promoting a gradient from flammable to less flammable ecosystem.**

From a general consideration of vegetation as 'fuel', it has been well proven that plant traits have the potential to promote the forest stand gradient from flammable to less flammable. While the ever-growing literature helps to assess the relationship between plants and their flammability at species level, at the landscape scale this relationship should be evaluated along with a variety of forest features such as structural and stand parameters and from the perspective of successional forest stages. To this end, we clustered several forest stands in Southern Europe (Apulia region, Italy), characterized by oaks, conifers, and arboreal shrub species, according to their flammability traits. We hypothesized that flammability traits change along different horizontal and vertical structural features of forest stands, shifting from high to low-flammability propensity. The results confirmed that forest stands with greater height and diameter classes are associated with traits with a low-flammability propensity. It is worth highlighting the importance of shrub coverage in differentiating the clusters denoting their strong influence in increasing fuel load (litter and fuel bed traits). Finally, our findings lead us to assume that high-flammability propensity traits are associated with typical pioneer successional stages, supporting the notion that later successional forest stands are less flammable and, therefore, that flammability decreases along with succession.

Keywords Flammability traits · Forest · Wildfire · Forest successional stages · Pioneer species · Structural features · Late successional forest · PAM clusterization

Introduction

Wildfires are one of the most important natural threatening events that alter landscapes and forest ecosystems worldwide (Bowman et al. 2020). At the European level, wildfires mostly affect the Mediterranean regions of Southern Europe where climate change, land abandonment and human pressure are triggering changes in fire regimes (Ganteaume et al. 2013; Hagmann et al. 2021). These changes generate feedback on the ecological processes of plant growth and vegetation successional stages, acting as internal controls on forest flammability (Kitzberger et al. 2016). Plant feedback on fire regimes has the potential to result in forest stand gradients shifting from flammable to less flammable. Both reproductive and vegetative traits, affecting forest flammability, have been widely analyzed in many fire-prone ecosystems (Pausas et al. 2017; Keeley and Pausas 2022). Plants do not only react to fire but can create structural stands that prevent and protect themselves from wildfire (Burger and Bond 2015).

From a general consideration of vegetation as 'fuel', it has been well proven that plant flammability varies between and within species, determining a great variety of vegetation flammability-related responses in fire-prone ecosystems (Pausas et al. 2017; Cui et al. 2020). Plant traits linked to flammability are genetically determined, but can be considerably modified by environmental and biotic factors (Rowe and Speck 2005) and vary depending on tree size and forest stands (Babl et al. 2020).

In particular, the continuous growing literature reveals how plant traits can be related to flammability (Schwilk

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and Caprio 2011; Fernandes and Cruz 2012; Pausas and Moreira 2012; Burton et al. 2021; Scarff et al. 2021). Many authors (see Popović et al. 2021 for a consistent synthesis) have attempted to associate flammability traits to classify species from low to high-flammability levels empirically, improving the understanding of fire behavior and promoting species selection for appropriate forest management. For example, Kane et al. (2021) used leaf litter traits to understand the potential of red maple to reduce community flammability in North America. Babl et al. (2020) found a strong relationship between four oak species and five non-oak species with flammability in western Kentucky, United States. They found that non-oak tree species have canopy, bark, and leaf litter traits associated with low flammability and that the range of non-flammable traits changes with tree size, resulting in a potential fire-mitigation capacity. Other studies (Bianchi et al. 2019; Barberá et al. 2023) have compared the live fuel moisture content (FMC) of different conifers in Argentina, to understand the ignitability of each investigated species. Curt et al. (2011) compared the flammability of litter within a mosaic of different oak forests in south-eastern France to test if litter flammability traits vary according to vegetation typology. Krix et al. (2022) attempted to link plant trait-based ignition to different forest habitats, meteorological conditions, and biotic pressures in south-eastern Australia.

While these studies may help to assess the relationship between plants and flammability at species levels, at the landscape scale this relationship should be evaluated considering other forest features such as structural and stand parameters and from the perspective of successional forest stages. For instance, intrinsic flammability traits, such as litter moisture content, surface-to-volume ratio (S/V), and bulk density determining different consequences in terms of ignitability, consumability and sustainability, can be strongly affected by tree height, tree diameter class, and shrub coverage at a larger scale (Varner et al. 2022).

In this paper, we explored if flammability traits change along different horizontal and vertical structural features of several forest stands, shifting from high to low-flammability propensity. In particular, we hypothesized that (i) greater height classes of forest stands would have traits associated with low-flammability propensity; (ii) ampler tree diameter classes have traits related to low-flammability propensity; and (iii) forest stands with a wider abundance of understory vegetation have traits associated with high-flammability propensity.

Studies linking flammability traits to forest stands play a key role in better understanding fire-related ecological processes and providing effective information for restoration programs, especially in the Mediterranean region. In addition, understanding whether horizontal and vertical structural features of forest stands are associated with a gradient from low to high-flammability propensityis useful to explore the evolution of new forests or reforestation areas.

Materials and methods

Study area

The study was conducted in forested landscapes of the Apulia region, a peninsula located in southern Italy at a latitude of 39°50′–41°50′N and a longitude of 15°50′–18°50′E (Fig. 1). Most of the landscape is characterized by plains (53%) while rolling hills and low mountains are found North-West, reaching a mean altitude of 565 m a.s.l. Average temperatures are around 15 °C and 16 °C, with higher average values in the Ionian-Salento area and lower values in the Dauno and Gargano Sub-Apennines. Summers are hot, with average temperatures between 28 °C and 33 °C and peaks up to 40 °C on the hottest days. Precipitation is mostly concentrated in the fall (November–December) and winter (range between 450 and 650 mm/yr) seasons, while the summer season is relatively dry, with lacks of rainfall even for long periods (Elia et al. 2016, 2020).

The Apulia region is mostly agricultural territory, where olive trees and vineyards dominate (36%). Only 10% of the landscape is covered by forests: broadleaved forests (*Quercus ilex* L., *Q. pubescens* Willd., *Q. cerris* L., *Fagus Sylvatica* L.) are mainly located in hilly and mountainous areas, while conifers (*Pinus pinea* L., *P. halepensis* Mill. and *P. pinaster* Ait.) are limited to coastal areas where, historically, reforestation was carried out for different purposes. Despite the low amount of forest cover, this region experiences on average 460 forest fires per year, with a mean annual burnt area of 2433 ha (2006–2020 data). These data depict a region characterized by high-wildfire occurrence with 70% of the events cover an area of less than 5 ha. Almost 3% of the events, on the other hand, involve an area of more than 50 ha, with some extraordinary events occurring in wooded areas of more than 600 ha.

Field sampling and flammability traits

A total of 209 circular plots (13-m radius) were randomly selected from the Apulian land-cover layer (http://www.sit.puglia.it, accessed Dec. 06, 2022) provided by the regional government. The vegetation characteristics were collected according to Elia et al. (2015) and Brown (1982). We collected data on trees, shrub characteristics, herbaceous components, litter parameters and the fallen dead woody material (for a better description of the sampling plot, see the supplementary material—Fig. S1). According to the large review by Popović et al. (2021) and other studies (see Table 1) we derived our flammability traits by field data such as: canopy

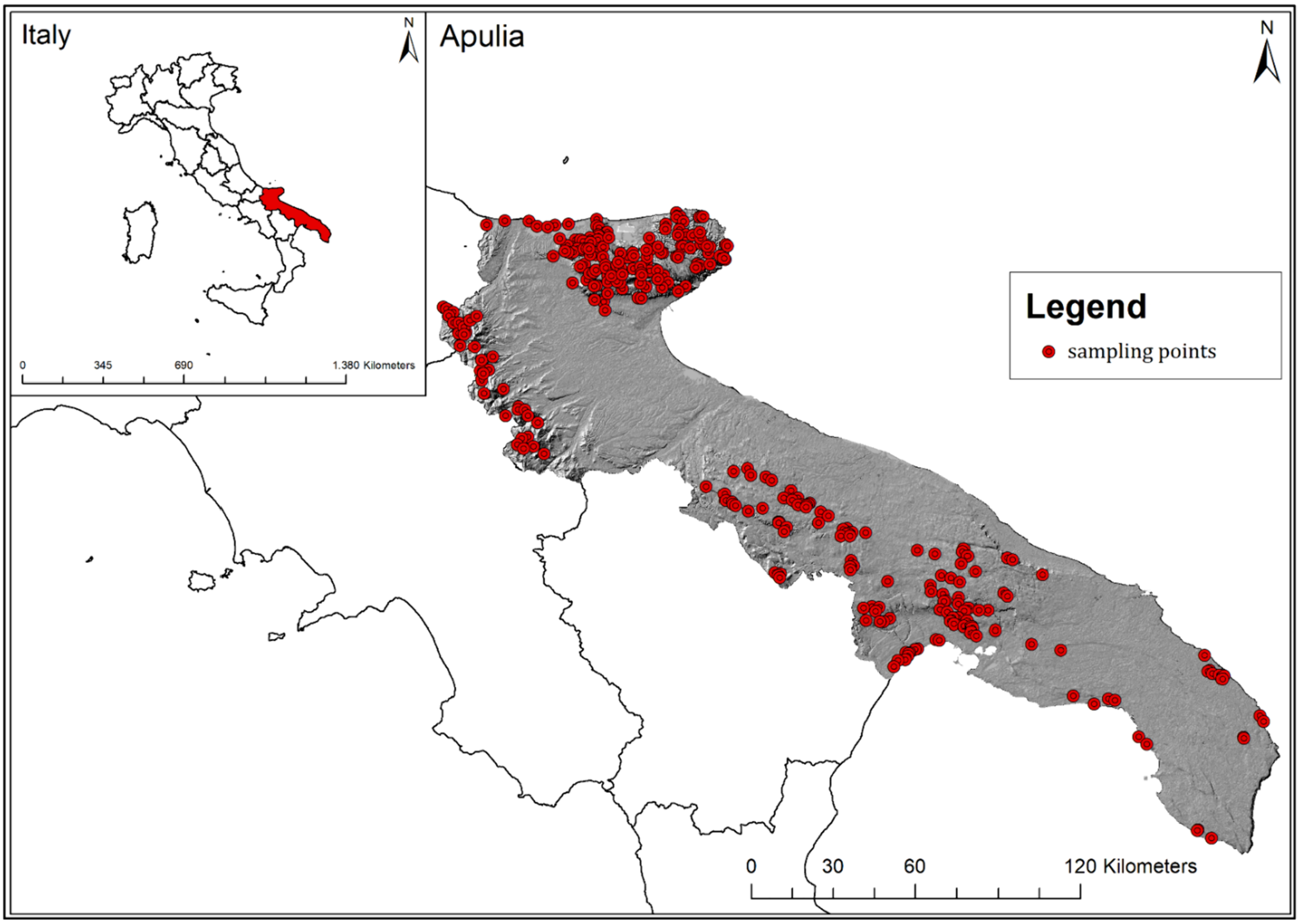

Fig. 1 Location of the Apulia region and the 209 field sampling plots

depth (m), canopy bulk density (CBD) (kg/m^3), fuel bed depth (m) litter compactness (dimensionless), and litter leaf thickness (cm). Furthermore, Litter FMC (%) and litter surface area-to-volume ratio (RA S/V) (m^2/m^3) were determined in the laboratory following the protocol developed by Pollet and Brown (2007). These plant traits and their positive (+) and/or negative (−) relationship with flammability components are described in Table 1.

A number of structural features of forest stands were selected to explore changes in flammability traits. According to Spies (1998) the following horizontal and vertical structural features of forest stands were derived: diameter (cm), tree height (m), crown base height (m), canopy cover (%), abundance of shrub (%), shrub height (m), abundance of herbs (%), herb height (m).

Cluster and statistical analyses

To understand if flammability traits change along different horizontal and vertical structural features of forest stands, we first clustered all the 209 circular plots randomly located within the study area. This approach allows to classify vegetation attributes, thus avoiding errors stemming from vegetation-type-based classification and considers fuel parameter variations caused by different agents such as logging, insects, disease, etc.

Clustering is a technique that, given a set of data points, uses an algorithm to classify each data point into a specific group. In theory, data points belonging to the same group should have similar properties, while data points in different groups should exhibit dissimilar properties. According to Elia et al. (2022), a consistent grouping process should include: (1) representative points from the original dataset and (2) an algorithm strictly built on the characteristics of the issue under study.

After a complex and detailed review of the main clustering techniques (Xu and Tian 2015), we opted to use a clustering algorithm based on partitioning where the core idea is to consider the center of data points as the center of the corresponding cluster. Among these, Partitioning Around Medoids (PAM) is known to be a robust version of k-means, as it is considered to be less sensitive to outliers (Jain et al.

Table 1 Canopy, litter, and shrub traits and their influence on forest flammability and fire behavior

Trait	Role in flammability	Relationship with flammability	Citation
Canopy			
Canopy depth	Light intensity decreases with increasing canopy depth, leading to shadier undergrowth. A shadier undergrowth can lead to cooler and wetter conditions, reducing flammability	–	Kozlowski and Pallardy (1997), Tanskanen et al. (2005)
Canopy bulk density	Canopy bulk density (CBD) describes the density of fuel available in the canopy of a stand. In some cases is positively correlated with flammability and the likelihood of active canopy fire, whereas in other cases, it is negatively correlated, as it delays the burning process due to the distribution among a greater number of solid particles and a higher moisture content of these	+ or –	Dahale et al. (2013), Balaguer-Romano et al. (2020)
Litter			
Litter compactness	Compact litter can remain wet and inhibit fuel consumption during fires	–	Herwitz (1985), Hengst and Dawson (1994), Aboal et al. (1999), Dimitrakopoulos (2002), Plucinski et al. (2008), Kreye et al. (2012), Cornwell et al. (2015), Dickinson et al. (2016), Zhang et al. (2022), Dimitrakopoulos and Panov (2001), Weise et al. (2005), Saura-Mas et al. (2010), Engber and Varner (2012), Simeoni et al. (2012)
Litter leaf thickness	Thin litters burn with lower maximum temperatures. Litter leaf thickness is negatively correlated with the initial moisture content of litter beds	+	
Litter fuel moisture content	High fuel moisture content can reduce both the susceptibility to ignition and the rate at which a fuel burns	–	
Litter RA S/V	High litter surface area-to-volume ratio is associated with higher rates of energy and mass exchange, resulting in short ignition delays and rapid fire spread	+	
Herb and Shrub			
Fuel bed depth	Fuel bed depth have a significant effect on the probability of fire spread, as the distribution of available combustible fuels increases	+	Berry et al. (2011), Dickinson et al. (2013)

The signs describe the directly (+) and/or inversely (–) proportional relationship of traits with one or more flammability components (ignitability, combustibility, sustainability, consumability)

2020). Despite the elevated time complexity, this method has an overall high computing efficiency (Velmurugan and Santhanam 2011). As part of the PAM algorithm, we analyzed several indices to determine the optimal number of clusters, such as the Average Silhouette Method, the Hubert index and the D-index, as well as the total sum of squares within the cluster. The Silhouette co-efficient estimates the average distance between clusters, the Hubert index and D-index are graphical methods to determine the number of clusters. All analyses were performed in R (Team, 2016) the NbClust package (Charrad et al. 2014).

A one-way ANOVA followed by Tukey's HSD (honestly significant difference) was performed to test the differences between clusters according to structural features of forest stands such as tree diameter class, tree height class, crown base height, abundance of shrub, shrub height, abundance of herbs, herb height (see Sect. 2.2). All data concerning tree diameter and height were previously grouped in frequency classes of 5 cm (5, 10, 15, 20 …) according to the protocol developed by the Italian National Forest Inventory (INFC) (Gasparini et al. 2022).

Results

Cluster analysis

The PAM analysis indicated that the optimal number of clusters is 3. Figure 2 shows the components of the dataset and the grouping of the points. The algorithm divided the initial 209 plots into 74 points for Cluster-1, 87 points for Cluster-2, and 48 points for Cluster-3, displaced along a single vertical axis. Cluster-1 and Cluster-3 are clearly

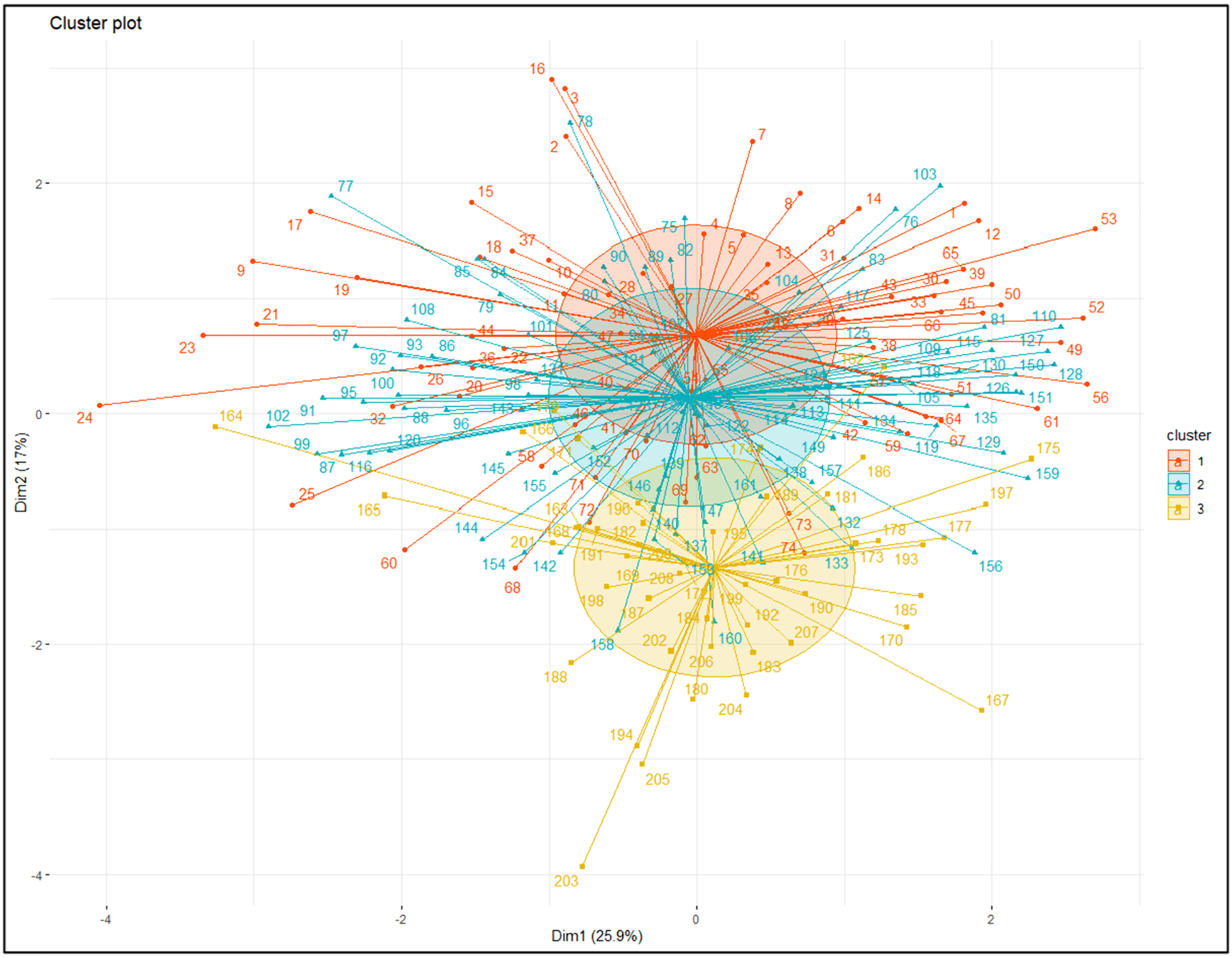

Fig. 2 Cluster plot on the base of flammability traits: canopy depth, canopy bulk density, litter compactness, litter leaf thickness, litter fuel moisture content, surface-to-volume ratio (S/V) and fuel bed depth

distinguished, while Cluster-2 is shown as an intermediate cluster tending more toward Cluster-1.

Table 2 shows the average values of each cluster's flammability traits: canopy depth, CBD, litter compactness, litter leaf thickness, litter FMCS/V and fuel bed depth for each of the three clusters. Except for RA S/V, Cluster-1 exhibited the highest values for each trait. On the contrary, Cluster-3 showed the highest value of RA S/V and the second highest value of litter FMC.

The three clusters are significantly different according to the algorithm performed and the applied indices. Figure 3 summarizes the values of each cluster after data normalization (Minimum–Maximum Value Based Normalization Methods) (Han et al. 2011). The radar charts (Fig. 3) were

Table 2 Average values of the flammability traits used to perform the PAM analysis grouped per cluster

Cluster	Canopy depth (m)	Canopy bulk density (kg/m^3)	Litter compactness	Litter leaf thickness (cm)	Litter FMC (%)	RA S/V (m^2/m^3)	Fuel bed depth (m)
1	4.952	0.447	1.473	18.060	30.671	1288.594	0.320
2	4.808	0.428	1.368	19.849	27.741	2368.957	0.274
3	4.827	0.415	1.298	16.405	30.003	5477.337	0.289

PAM Partitioning Around Medoids, *FMC* Fuel moisture content, *RA S/V* litter surface area-to-volume ratio

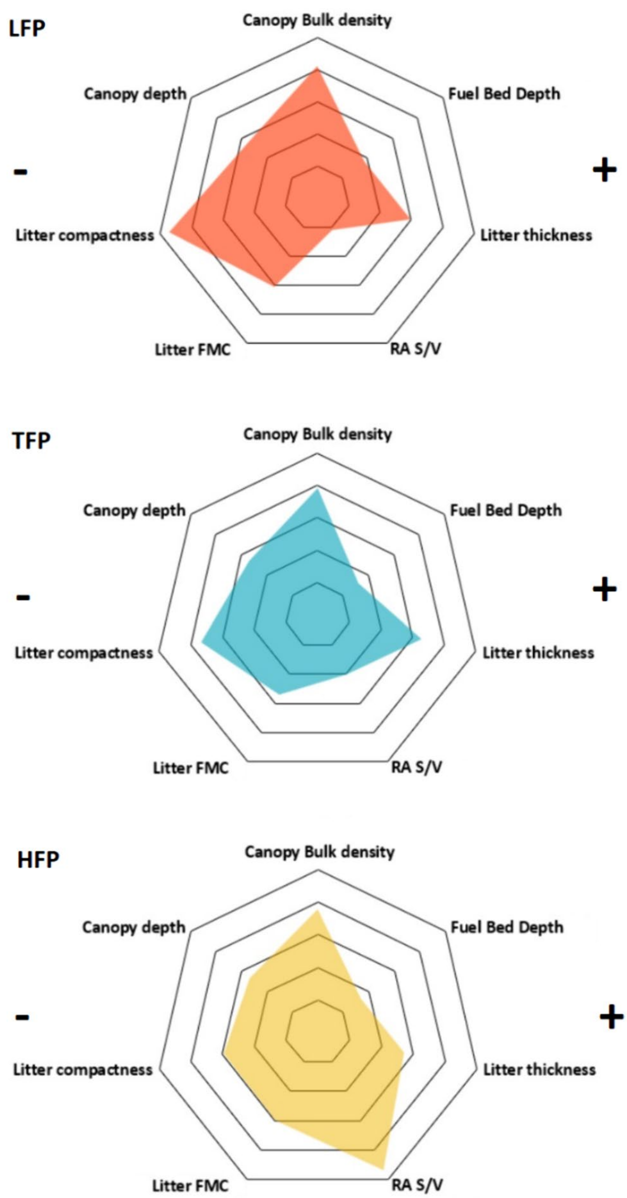

Fig. 3 Radar chart of flammability traits: canopy depth, canopy bulk density, litter compactness, litter leaf thickness, litter fuel moisture content (FMC), litter surface area-to-volume ratio (RA S/V) and fuel bed depth for the three clusters. LFP, forest stand with low flammable propensity (Cluster-1); TFP, forest stand with transitional flammable propensity (Cluster-2); and HFP, forest stand with high flammable propensity

structured to observe (on the left) the flammability traits having an inversely proportional relationship with one or more flammability components (e.g., ignitability, combustibility, sustainability, consumability) (Popović et al. 2021) and (on the right) to observe the flammability traits having a directly proportional relationship with one or more flammability components. CBD is a flammability trait that we preferred to keep in the middle as it can be both directly and inversely proportional to the flammability components (see Table 1). Structuring the radar charts in this way, we clarified whether a cluster is more inclined (higher values toward the right and lower values towards the left) or less inclined (higher values towards the left and lower values towards the right) to the flammability components.

In Cluster-1, the values for litter FMC, litter compactness and canopy depth were higher than in the other two clusters. In fact, Cluster-1 values shifted far to the left, thus classifying it as a cluster that is not very inclined to flammability. In Cluster-2, values such as litter FMC, litter compactness and canopy depths were slightly lower than in Cluster-1, with a significant increase, however, in the values of RA S/V and litter leaf thickness. Cluster-2, in fact, showed high values in both directions of the radar chart, thus classifying it as an inflammation-neutral cluster. In Cluster-3, the previously mentioned values drastically decreased in favor of other values such as RA S/V and litter leaf thickness which significantly increased. In contrast to Cluster-1, Cluster-3 values shifted far to the right, thus classifying it as a cluster highly inclined to inflammation. The CBD value was similar for the three clusters but higher in Cluster-1 than in Cluster-2 and lastly in Cluster-3. Based on the results described above, it is possible to define the three clusters as forest stands with low flammable propensity (LFP) (Cluster-1), forest stand with transitional flammable propensity (TFP) (Cluster-2), and forest stand with highly flammable propensity (HFP) (Cluster-3).

Figure 4 depicts forest-category classes among clusters according to the INFC (Gasparini et al. 2022). We found that LFP is characterized by a predominance of multi-species forests with an abundance of broadleaf trees. TFP (located in the center) is characterized by a slight predominance of multi-species forests but still with an abundance of broadleaf trees. Conifers are present in both LFP and TFP, but in less abundance than broadleaf trees. Also, in these two clusters there are forest categories such as arboreal shrubs (shrub species having tree habit). HFP (on the left) is mostly characterized by equal numbers of single-species and multi-species forests and an absolute predominance of conifers. No arboreal shrubs are present in this cluster, and broadleaf species are minimal (Fig. 4).

Cluster comparison over structural features

The one-way ANOVA followed by Tukey's HSD test highlighted the main differences of the three clusters according to horizontal and vertical structural features of forest stands (Fig. 5). Clusters with the same letter were not significantly different ($P < 0.05$). We found significant differences in the clusters for the diameter classes (%), tree height classes (%), abundance of shrub (%), and shrub height (m). Considering all other variables such as crown base height (m), canopy

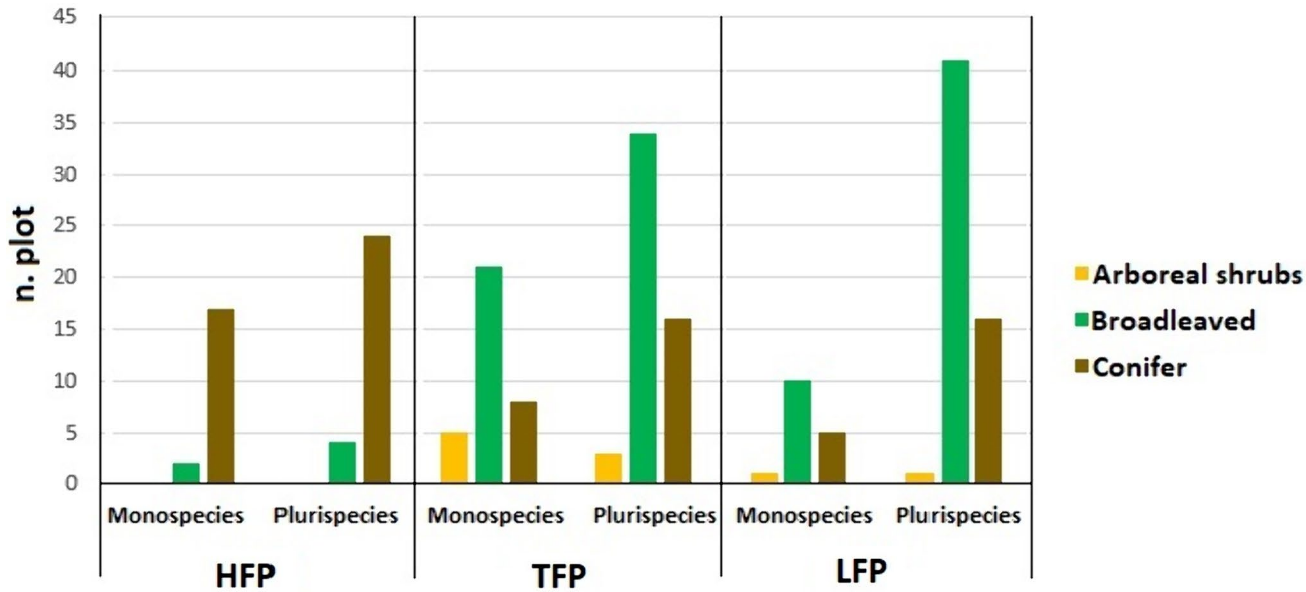

Fig. 4 Distribution of forest-category classes among clusters

cover (%), abundance of herbs (%) and herb height (m), no significant differences were found. LFP consists of trees with both diametric classes and greater height classes than the other two clusters (Figs. S1, S2). In contrast, HFP has both a higher percentage of shrubs and a greater height of shrubs. In all cases of analysis, TFP always displayed intermediate values between the other two clusters.

Discussion

The Climate-induced alteration of fire regimes and other human-derived changes have modified fire-related ecological processes with profound effects on many forest ecosystems worldwide (Lafortezza et al. 2013). In this study we attempted to cluster diverse forest stands according to their flammability traits. In particular, we demonstrated that flammability traits change along with forest structural and stand parameters following a gradient from low to high-flammability propensity.

Our analysis demonstrated a strong distinction between HFP and the other two clusters LFP and TFP, which are more similar in terms of structural parameters and forest categories. We strongly believe that our results seem to be consistent with the theory of ecological successions from pioneer species to later successional forests (Huston & Smith 1987; Keane et al. 2004; Marozas et al. 2007; Adámek et al. 2016), following a gradient from high to low-flammability propensity. Pioneer species distribution and stand features are closely linked to forest disturbance, such as wildfires (Goodale et al. 2009). Figure 4 and Table S1 emphasize the distinction between clusters in terms of forest category and species composition, as the HFP is mostly constituted by conifers such as *Pinus* spp. *and Cupressus* spp. (pioneer communities), while the other two are mostly composed of broadleaved species and shrubs having tree habit (i.e., arboreal shrubs) (later successional communities).

Our study supports the hypothesis that a gradient of flammability, from high to low, could be associated with successional forest stands at landscape scale, probably due to resource availability (e.g., light) during the successional path. In the early successional stages, the traditional dominant communities are short-lived, fast-growing, and shade-intolerant pioneers (e.g., conifers with shrub understory) that reproduce from seed. Over time, pioneer communities are replaced by more competitive ones (Huston and Smith 1987), and these changes in species composition along successional gradients similarly produce changes in flammability traits, depending on the characteristics of coexisting communities. In addition, it is worth noting that the flammability of this species have been recognized as a niche construction characteristic, since the retention of dead branches in the canopy greatly facilitate plant regrowth after a fire (Schwilk 2003).

Therefore, conifers are principally responsible for colonizing barren, lifeless habitats or are used for reforestation as is often made in Mediterranean ecosystems, especially in Southern Europe (Baeza et al. 2011; de las Heras et al. 2012; Vallejo et al. 2012). Through their interactions they build a simple initial biological community becoming more complex as new species arrive (e.g., broadleaved) which play a key role in the different phases of forest succession (Brokaw

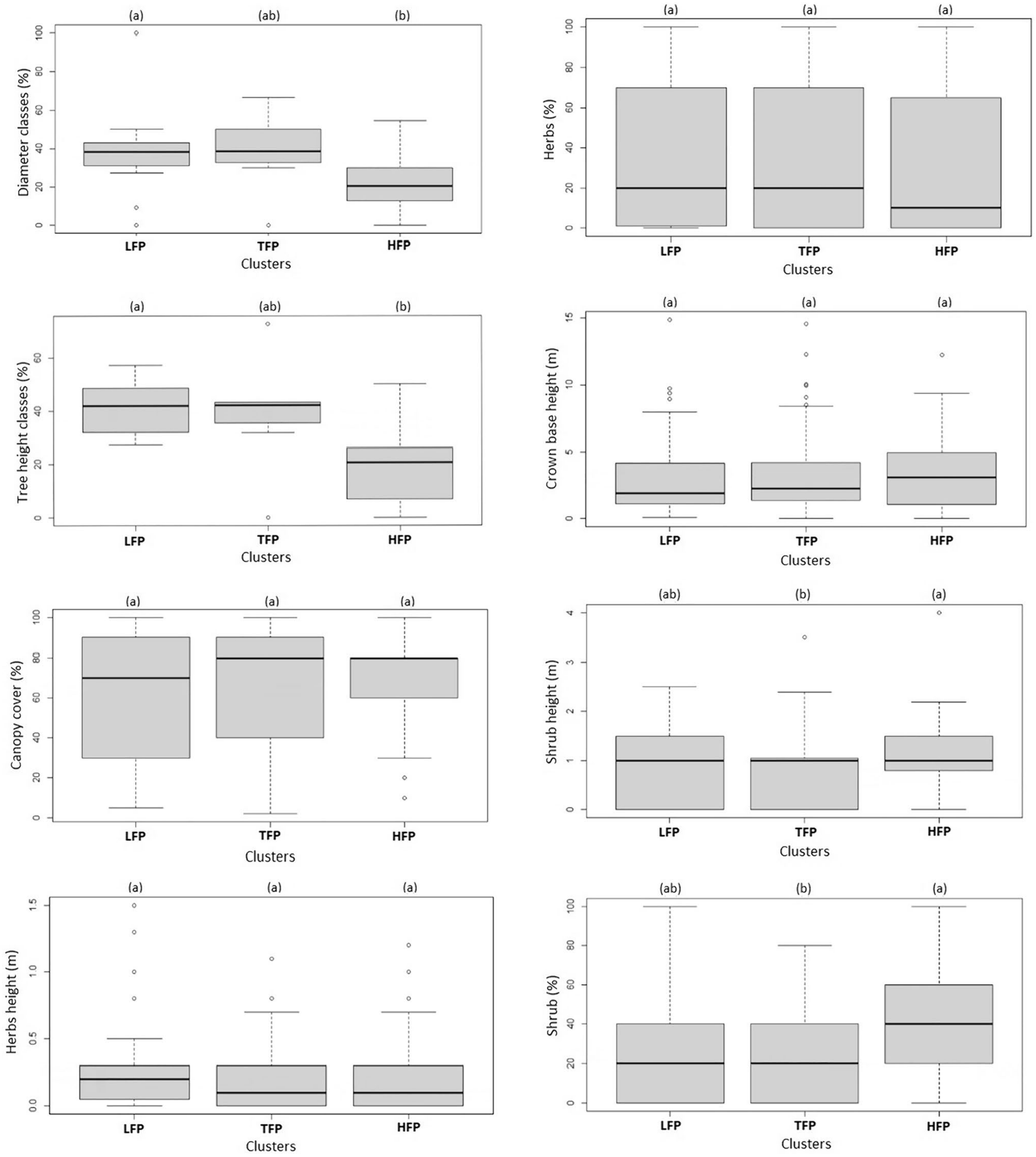

Fig. 5 Box plots showing the distribution of values for each flammability trait. For each plot, a cluster was assigned to a specific group represented by a letter above each box, in accordance with the significance difference of Tukey's HSD test. Clusters with the same letter are not significantly different ($P < 0.05$)

1982; Chazdon and Fetcher 1984; Denslow 1987; Dalling and Hubbell 2002). During their growth from young to mature trees broadleaved species experience abrupt changes in the physical environment: they must overcome the shady conditions under the close canopy of the competing vegetation (i.e., pioneer conifers) and deal with wide changes in the diurnal environment within canopy gaps (Bazzaz and Pickett 1980; Grime 2002).

Following these considerations, our analysis showed that forest stands with greater height and diameter classes are associated with traits with low-flammability propensity. At early successional stages, canopies contribute to fuel loads in the understory and the trees have finer trunks, making them more susceptible to burning along with the resprouting shrubs of the understory (Tiribelli et al. 2018). Furthermore, previous authors have found that interspecific differences in tree structure, due to the diverse allocation of growth to horizontal and vertical extension, have significant consequences for light interception (Horn 1971) and can be associated with predictable forest stand stages (Kohyama 1987; Gamon et al. 2005). This finding is even more evident and important for pioneer species competing for similar light environments during their adult stages when dense canopies mostly try to reach a light intense environment (Goodale et al. 2009). In our study, this is reflected in the canopy depth trait, which is lower in the HFP cluster mostly constituted by conifers. Light intensity increases with decreasing canopy depth, leading to increased solar radiation of the undergrowth. An irradiated undergrowth can lead to dryer fuel increasing potential flammability. These forest ecosystems, belonging to the HFP, where *P. halepensis* and *Cupressus spp.* dominate, showed traits associated to a dense canopy cover, as well as to a huge amount of fuel loads in the litter of finer dead woody fuel classes (Hernandez-Tecles et al. 2015; Saracino et al. 2017; Jafarzade et al. 2022).

Litter traits play a fundamental role in forest flammability (Scarff and Westoby 2006; Parsons et al. 2015), and vary among clusters according to their positive or negative relationship with flammability components. In general, variations in litter traits between forest categories were mostly explained by leaf thickness and volume and to a lesser degree by leaf area and the litter S/V ratio.

For example, the *P. halepensis* and *Cupressus spp.* litter traits are similar; their needles and twigs are relatively thin and small with a higher litter RA S/V than oak litter traits of the TFP and LFP clusters. The litter RA S/V was found to be one of the most important flammability traits among the structural and morphologic parameters of fuel complexes. This trait defines the particle geometry and relative dimensions of fuel-complex elements (Fernandes and Rego 1998) and has a significant influence on flammability propensity (Grootemaat et al. 2017). Its higher values are associated with higher rates of energy and mass exchange, resulting in shorter ignition delays and faster fire spread (Simeoni et al. 2012; Popović et al. 2021). These litter traits are explained by different life history strategies such as shade-tolerance, browse-tolerance, carbon allocation, growth strategies, and drought tolerance of parent trees (Valladares and Niinemets 2008). For instance, conifer pioneer species use needle foliage (thick leaves) as a mechanism to withstand high temperatures and perform evaporative cooling on warm, dry sites (Abrams and Kubiske 1990). In contrast, more shade-tolerant species, like oaks, tend to have thinner leaves with increased leaf area which helps increase light capture efficiency and maximize carbon gain in shady environments (Jackson 1967; Evans and Poorter 2001).

It is also worth highlighting the importance of shrubs in differentiating the clusters. In HFP, the abundance of shrubs was about 20% more than in the other two clusters denoting their strong influence in contributing to increased fuel loads and thus litter and fuel bed traits. Tiribelli et al (2018) found that the fuel amount quickly increases during early forest successional stages, when shrubs dominate the community, and decreases to a relatively constant value when tall trees dominate in later successional stages of the forest community. The decrease in shrub fuels prevents the potential surface to crown fire transition. The presence of later successional communities (broadleaved species such as *Quercus spp.*, *F. sylvatica*) alters light environments, reduces thermal excursion, and augments the relative humidity of the understory, increasing the difference in flammability propensity among young and old stands (Paritsis et al. 2015; Tepley et al. 2016; Blackhall et al. 2017). Therefore, these changes in flammability traits were largely related to shifts in horizontal and vertical structural features of forest stands, which in turn were controlled by the dominant growth strategies and life forms.

Taken together these results lead us to suppose that high-flammability propensity traits are associated with typical pioneer successional stages. Baeza et al. (2011) found that early successional species, such as *P. halepensis*, have a higher percentage of standing dead biomass at earlier stages in the succession than species typical of later successional stages (e.g., *Q. spp.)*. These findings support the notion that flammability is not necessarily proportional to increasing stand maturity in Mediterranean forests, since it has been demonstrated that the turnover of early species by later species with fewer amounts of accumulated fuel loads could reduce flammability in the more progressive stages of succession (Bond and Midgley 1995; Bond and van Wilgen 1996).

Despite the interesting results found in the forested landscape of the Apulia region, we recognized that there is room for improvement in our study. Our investigation was developed at a wide scale, i.e., a scale that includes several forest ecosystems from an ecological, geomorphological, and pedological point of view. Research carried out at a lower scale (e.g., catchment area, single-forested landscape), where biophysical characteristics are similar, would allow to obtain a more precise analysis of successional dynamics and the relative influence on flammability traits.

Conclusions

Our study suggests that forest stands of the Mediterranean landscape of Southern Europe manifest a set of fuel traits that promote a gradient from flammable to less flammable. These traits may become pronounced according to their potential ecological successional stage. On the one hand, we found forest stands with greater height and diameter classes, large leaf area, elevated canopy depth and litter compactness, and reduced-S/V ratios, often characterized by late-successional species, such as broadleaved. These traits configure stands with a reduced flammability propensity because of the major presence of humidity and moist litter in their understory. On the other hand, we found pioneer forest stands, mostly characterized by conifer species and a high presence of shrub coverage. These forest stands denoted traits associated with high-flammability propensity, given their decreased canopy depth and high values of litter RA S/V. We further found plant communities in dynamic transition between early and late-successional forest stages, with traits associated with decreasing flammability propensity.

However, forest successions in the Mediterranean landscapes of Southern Europe are still complex ecological processes that need to be fully understood as they are dynamic and strongly subject to climate change and anthropic influence. Climate change, human pressure and their effects on fire regime can affect the succession of forest stands and the associated flammability traits as well as create conditions that promote secondary successions or conversions to shrub or grass landscapes. Furthermore, fire regimes are foreseen to vary across the Mediterranean Basin (Pausas 2022), generating potential mesophication processes with hotter and drier conditions that promote pyrophytic plant communities (oaks and conifers) and more severe fires (Nowacki and Abrams 2015). Understanding the mechanisms of plant communities that contribute to reducing flammability and benefit forest resistance and resilience could lead to more effective fire implementation and management interventions.

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Author contributions Analyzed data, editing and reviewing was performed by Onofrio Cappelluti; Study design, research development and first draft of the manuscript was carried on by Mario Elia; Editing and reviewing, supervision was performed by Giovanni Sanesi. All authors read and approved the final manuscript.

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Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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