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Testing Vegetation Flammability: Examining Seasonal and Local Differences in Six Mediterranean Tree Species

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1. Fundamentals of the combustion process

1.1. Definition of combustion

Before one can start measuring and discussing the fire-related characteristics of a material, a basic understanding of the combustion process is necessary. According to Quintiere (2006), combustion can be defined as an "exothermic chemical reaction that results from a runaway rate caused by temperature or catalytic effects". This extensive definition may be applied to any combination of fuels, oxidisers and physical environments. Nevertheless, in environmental sciences, the main area of interest lies in the combustion of vegetation fuels under physical conditions commonly present on Earth. Due to the complexity of combustion, further explanation will focus only on this situation, and it will be presumed that (i) the fuel of interest predominantly consists of polymeric organic compounds; (ii) atmospheric oxygen is the common oxidiser; and (iii) an external heat source is needed for initiation of the chain reaction of combustion. With these presumptions in mind, combustion can be defined as "the rapid exothermic oxidation of pyrolysate hydrocarbon vapours released from the surface of the fuel and slower oxidation of char" (DeBano *et al.* 1998). Conceptually, perfectly complete and efficient combustion of vegetation fuels can be seen as a reaction opposite to photosynthesis, in which organic compounds are oxidised to carbon dioxide (CO_2) and water (H_2O), with release of energy (Byram 1959). In practical terms, combustion of vegetation fuels is neither perfectly complete nor efficient. Furthermore, vegetation fuels contain elements other than carbon, hydrogen and oxygen. As a result, numerous compounds are formed during combustion (Aurell *et al.* 2015; Faria *et al.* 2015; May *et al.* 2015), and the released amount of energy is always lower than the amount of energy chemically bound in the fuel (Pyne *et al.* 1996; Jenkins *et al.* 1998; Ward 2001). Four elements mentioned in the presumptions (fuel, oxygen, heat, and chain reaction) represent the fundamental fire/combustion tetrahedron. They govern the initiation, behaviour and persistence of combustion, and removal of any of them results in the termination of combustion (Pehrson 2004).

1.2. The course of combustion

Upon exposure of plant materials to an external heat source, preignition has to take place before sustained combustion can be achieved. Preignition begins with preheating of the fuel. As the fuel temperature increases, extractives are gradually volatilised (Pyne *et al.* 1996; DeBano *et al.* 1998). Once 100°C is reached, dehydration is initiated and water is expelled from the fuel. Release of hot gases reduces oxygen concentration in the heated zone, and further increase in temperature leads to pyrolysis of long-chain organic molecules. Pyrolysis of vegetation fuels can follow either of two competing pathways. One pathway predominantly produces volatiles and tars, whereas the other mainly yields char and water. Both pathways compete for the same initial substance, as well as for some of the intermediate products, with higher temperatures promoting production of volatiles.

If the first pyrolysis pathway predominates, ignition—the transition point from preignition to combustion—results in flaming (Pyne *et al.* 1996). Flaming represents combustion of the gas phase of the fuel. For flaming combustion to occur, combustible volatiles must be emitted from the solid surface, mix with surrounding air, and produce a flammable mixture that is ignited either spontaneously once a high enough temperature is reached (auto-ignition), or with the help of an external spark or a flame termed a "pilot" (forced or piloted ignition). Furthermore, for flaming to be sustained, the amount of heat released by the nascent flame must be high enough to overcome convective heat losses and ensure a sufficient and continuous supply of combustible volatiles to the reaction zone (Atreya 1998). High exothermicity of flaming combustion results in a pronounced increase in temperature (from 300 to 500°C at ignition to higher than 1,400°C), acceleration of the pyrolysis, and increased rate of production of combustible gases, resulting in fires that can potentially move with the wind as masses of burning gases.

Once combustible volatiles of a fuel are exhausted and the production rate of flammable gases decreases to a point where it can no longer sustain flaming, smouldering combustion starts. In fuels in which the second pyrolysis pathway predominates and the production rate of the combustible volatiles is insufficient for sustained flaming, smouldering forms the initial phase of combustion. In comparison to flaming, smouldering is much slower (<3 cm/h in ground fuels), energy release rates and temperatures are lower (300°C–600°C), but particulate emissions can be up to 10 times higher than during flaming combustion.

As combustion continues, most of the volatile gases are eventually driven off, and smouldering gives way to glowing combustion. At this point, atmospheric oxygen comes in direct contact with char created during the preceding combustion phases, resulting in highly efficient oxidation with little to no smoke production. Once fuel is reduced to non-combustible ashes, or the amount of generated heat is lower than the amount of heat absorbed by the surroundings, extinction will occur and combustion will be terminated (Pyne *et al.* 1996; DeBano *et al.* 1998).

Even though definitions of individual combustion phases and their sequence differ among authors (*e.g.* Barrows 1951; Pyne *et al.* 1996; DeBano *et al.* 1998; Johnson and Miyanishi 2001), they agree that fuel characteristics and heating rates govern the course of combustion, with smouldering sometimes being essential for the initiation of flaming. Furthermore, they acknowledge the problem of delineating between individual combustion phases and the possibility of their overlapping. Due to the high variability of vegetation fuels as well as of natural heat sources and sinks, highly variable combustion processes with diverse characteristics can be expected in nature.

1.3. Fuel characteristics and combustion

As previously mentioned, the characteristics of the combustion are governed by the characteristics of the fuels and heat sources (Barrows 1951; Pyne *et al.* 1996; DeBano *et al.* 1998; Johnson and Miyanishi 2001). The term “vegetation fuels” covers all live and dead vegetation components, in any stage of decomposition and weathering, that can potentially be combusted. This wide range of materials shows a high variation of characteristics, and as a consequence a highly variable influence on the combustion (Barrows 1951). The characteristics of the vegetation materials that define its performance as a fuel can be divided into intrinsic and extrinsic types.

1.3.1. Intrinsic fuel properties

Intrinsic fuel characteristics can be further subdivided into chemical composition and physical properties. In chemical compounds, the content of water, extractives, ash, cellulose and lignin are considered to significantly affect the course of combustion (Pyne *et al.* 1996).

1.3.1.1. Moisture content

The presence of water, usually expressed as moisture content, is often considered to be the most important parameter governing initiation, propagation and course of combustion (*e.g.* Dimitrakopoulos and Papaioannou 2001; Etlinger and Beall 2004; Fernandes *et al.* 2008). Higher moisture content leads to higher heat capacity of the fuel, dilution of combustible volatiles, and exclusion of oxygen from the reaction zone. As a result, more heat needs to be absorbed by the fuel for sustained combustion to be achieved (Byram 1959; Rothermel 1972; Atreya and Abu-Zaid 1991; Dimitrakopoulos and Papaioannou 2001; White and Zipperer 2010). Work as early as that of Graves (1910) and Gisborne (1928) acknowledged the importance of the moisture content in governing fire behaviour. Since then laboratory experiments (*e.g.* Trabaud 1976; Bernard and Nimour 1993), comparison of fuel moisture content data with wildland fires records (*e.g.* Dennison and Moritz 2009), and prescribed burnings experiments (*e.g.* Anderson and Anderson 2010) have confirmed its highly significant effects. Increase in moisture content was shown to prolong ignition delay (*e.g.* Bunting *et al.* 1983; Bernard and Nimour 1993; Pellizzaro *et al.* 2007a); increase the temperature required for the appearance of flame (Atreya and Abu-Zaid 1991; De Lillis *et al.* 2009); reduce the probability of ignition and fire spread; and decrease the burned area (Dennison and Moritz 2009; Anderson and Anderson 2010) and the amount of fuel consumed by the fire (Garlough and Keyes 2011). Shorter flames (Trabaud 1976), lower heat release rate (Weise *et al.* 2005a), and slower rate of fire spread (Curry and Fons 1938; Kreye *et al.* 2013a) were also associated with higher moisture content of the fuel. Furthermore, higher moisture content reduces combustion efficiency, resulting in increased emission factors for volatile organic compounds and carbon monoxide (CO) (Possell and Bell 2013). The combined effects of moisture content indicate that it promotes smouldering combustion. With increasing fuel moisture content, combustion becomes more difficult to sustain, and at a certain point it can no longer proceed. This threshold moisture content beyond which combustion can no longer be sustained is known as "moisture of extinction" (Rothermel 1983). Moisture of extinction is fuel-specific, and it was reported to range between 40% and 140% of the oven-dry weight for some of the Mediterranean fuels (Dimitrakopoulos and Papaioannou 2001).

1.3.1.2. Extractives

As well as water, extractives were also shown to significantly affect combustion. Extractives represent a broad group of chemical compounds (*e.g.* aliphatic and aromatic hydrocarbons, alcohols, aldehydes, gums, sugars, terpenes, fats, waxes and oils) which, in comparison to other organic components of vegetation fuels, have a higher heat content. Furthermore, they are more readily available for ignition and combustion (Philpot 1969). Most of them are easily vaporised, with temperatures required for their evaporation ranging from those reached on a warm day (Pyne *et al.* 1996) to higher than 300°C (Ward 2001). With their high heat content and easy transition to the gaseous phase, they promote high-intensity flaming. Generally, a higher content of extractives results in shorter ignition delay, lower temperature of flame appearance, higher flames, higher rate of fire spread and heat release rate, and faster and more complete fuel consumption (Philpot 1969; De Lillis *et al.* 2009; Ormeño *et al.* 2009). Nevertheless, as extractives cover a broad range of compounds, differences in both extent (Ormeño *et al.* 2009) and direction (Owens *et al.* 1998) of the effect can be expected between individual compounds.

1.3.1.3. Ash content

Ash acts as a catalyst in the pyrolysis reaction, and is generally considered to reduce the production of volatiles (Raveendran *et al.* 1995), thus dampening flaming combustion. In addition to retarding flaming combustion, increased ash content decreases the heat content of the fuel (Pyne *et al.* 1996). Lower ash content was reported for fuels that exhibit more explosive combustion (Dickinson and Kirkpatrick 1985). However, the influence of ash content was shown to depend on its range (Philpot 1970), the presence of individual minerals (Mutch and Philpot 1970; Philpot 1971) and the accompanying lignin and cellulose content (Raveendran *et al.* 1995). Of all the ash components, silica is considered to be inert and not to affect combustion (Mutch and Philpot 1970); hence in addition to total ash content, information on effective mineral content or silica-free ash is sometimes reported (*e.g.* Gill and Moor 1996; Dimitrakopoulos and Panov 2001).

1.3.1.4. Cellulose and lignin

Cellulose and lignin exhibit different behaviour when exposed to heat. Cellulose tends to undergo rapid pyrolysis yielding mostly volatiles, whereas lignin exhibits higher heat resistance. Even though pyrolysis of lignin starts at relatively low temperatures (160°C), it is much slower, and yields less volatiles and substantially more char. Furthermore, pyrolysis of cellulose is mostly endothermic, and that of lignin exothermic (Yang *et al.* 2007). As a consequence, cellulose promotes fast and intense flaming, whereas lignin postpones ignition and retards flaming. Nevertheless, if ignited, lignin can result in prolonged smouldering and glowing combustion. Furthermore, a higher content of cellulose can increase reactivity of the lignin through increased porosity of the char created upon gasification and combustion of cellulose, thus increasing the reaction surface and allowing for better oxygen diffusion through the remaining material (Gani and Naruse 2007).

1.3.1.5. Physical intrinsic properties

Physical intrinsic properties that influence combustion are particle density, thermal conductivity, and heat of combustion (Pyne *et al.* 1996). These properties influence combustion because vegetation fuels, as with any other material, obey physical laws of heat transfer and conservation of energy. Density and thermal conductivity of the material govern heat transfer (Anderson 1970), whereas heat of combustion determines how much heat can be released per unit mass of a fuel (Rivera *et al.* 2012), and yields important information for modelling fireline intensity and the spread of fire (Byram 1959; Rothermel 1972). Of the physical intrinsic properties, heat of combustion is measured more often than the other two. Comprehensive information on the heat of combustion of vegetation fuels is given by Rivera *et al.* (2012). Experiments attempting to directly link effects of particle density on combustion are relatively scarce, with often contradictory results. Scarff and Westoby (2006) found no significant impact of particle density on combustion of reconstructed oven-dry litter beds, whereas van Altena *et al.* (2012) found it to be one of the most important parameters governing combustion behaviour of air-dried litter beds, with increasing particle density leading to decreased speed of flame spread, and increased duration of combustion. Due to a lack of exact measurements, the thermal conductivity of different vegetation materials is often presumed to be similar to that of wood. Even though the physical intrinsic properties of the fuel present important parameters in physically-based models for predicting fire behaviour, the lack of accurate values is recognised as a major problem (McAllister *et al.* 2012).

1.3.2. Extrinsic fuel properties

Extrinsic fuel properties govern heat transfer between particles, oxygen diffusion through the fuel, and the amount of fuel available for combustion (Rothermel 1972). Of all the extrinsic fuel properties, quantity, compactness, arrangement, shape and size are considered to be the most important characteristics of the fuel that govern combustion (Pyne *et al.* 1996).

1.3.2.1. Quantity

Quantity determines how much of a fuel is present, and consequently the amount of energy that can potentially be released in the case of fire, thus making it one of the essential input variables for fire behaviour models (Scott and Burgan 2005; Cruz *et al.* 2013). Quantity of fuel is often expressed as fuel load (*i.e.* dry mass of the fuel per area) (*e.g.* Santana *et al.* 2011); duff depth (*e.g.* Miyanishi and Johnson 2002); trees/area (*e.g.* Kasischke and Johnstone 2005); and surface load of litter fuels (*e.g.* Boboulos *et al.* 2013). The appropriateness of any measure of fuel quantity is governed by the ecosystem in question and the intended usage of the measured values. The quantity of the vegetation fuel shows high variability across ecosystems, with reported fuel loads ranging from 0.3 tonnes per hectare (t ha^{-1}) for patchy grasslands of the Australian Northern Territory (Johnson 2002), up to 644 t ha^{-1} for Tasmanian eucalypt forest (Van Leeuwen *et al.* 2014). Experiments involving manipulation of fuel load demonstrated a significant increase in flame length, fireline intensity, soil surface temperature, duration of heating (Kreye *et al.* 2013a), soil-profile heating (Wright and Clarke 2008), damage to overstorey trees (Bravo *et al.* 2014), and decreased recovery of vegetation (Drewa 2003), with increased fuel load. Nevertheless, it should be noted that the total quantity of the fuel is hardly ever available for combustion (*e.g.* fuels with moisture content beyond moisture of extinction will not burn), and other properties of the fuels as well as their environments will determine the quantity of fuel that can be combusted at any given moment. For this reason, in addition to total quantity, the readily available quantity of fuel may also be specified (Pyne *et al.* 1996).

1.3.2.2. Compactness

The compactness of a fuel is the measure of spacing between the fuel particles. It is commonly expressed as bulk density (*i.e.* dry mass/volume of fuel) or packing ratio (*i.e.* volume of particles/volume of fuel) (Rothermel 1972; Pyne *et al.* 1996). Sometimes, bulk density itself is not calculated, but instead information on fuel compactness is provided by combined information on fuel load and fuel depth (Albini 1976; Anderson 1982). Contemporary understanding of the influence of compactness on combustion relies on Rothermel's work. Rothermel (1972) hypothesised that for any given fuel there is an optimal compactness at which maximal fire intensity and reaction velocity are reached. Increase in compactness leads to suboptimal aeration and heat penetration into the fuel (*i.e.* oxygen-limited combustion); whereas decrease in fuel compactness reduces fire intensity and reaction velocity by increasing heat transfer losses between particles (*i.e.* fuel-limited combustion). Rothermel furthermore demonstrated that optimal compactness is fuel-specific.

1.3.2.3. Arrangement

The arrangement of the fuel determines the position of individual fuel particles in space, and in relation to each other. Important characteristics of fuel arrangement are orientation of the particle (*e.g.* horizontal or vertical) (Engstrom *et al.* 2004); continuity of the fuel; live to dead ratio; and the way fuel particles are mixed and positioned in relation to each other (Anderson 1982; Pyne *et al.* 1996; Barrows 1951). The arrangement of the fuel will predominantly influence the efficiency of the heat transfer. Furthermore, arrangement plays an important role in preheating and drying of fuels, affecting availability of the fuel for combustion. In a prescribed burning experiment involving manipulation of fuel load and canopy architecture, Schwilk (2003) demonstrated that fire intensity (*i.e.* local fire temperatures and heat release) is influenced by both load and canopy architecture. In addition, the spatial distribution of fuel particles and the proportion of dead fuels were shown to have a significant effect on temperatures and the duration of soil heating (Santana *et al.* 2011). Arrangement strongly influences fire development and spread, as will be seen in Chapter 3.

1.3.2.4. Particle size and shape

Individual fuel particles are constituent elements of fuel layers and the fuel complex as a whole, and thus their size and shape inevitably influence combustion. In addition to measurements of fuel particle dimensions and shape, surface area to volume ratio (SA:V) is an additional measure of size, which is relevant in terms of moisture diffusion (Gill and Moor 1996). Fuel size was shown to be an important factor in governing moisture adsorption and desorption of the dead fuel, and dead round fuels are thus often assigned to size classes determined by the timelag. Timelag represents the time necessary for a fuel particle to reach 1/*e* of the difference between initial moisture content and the fuel moisture when at the equilibrium with its environment, with *e* being the base of the natural logarithm (Byram 1963). Byram (1963) demonstrated that timelag is defined by the dimensions and shape of the fuel. Bradshaw *et al.* (1983) defined the following classes of round fuels based on the timelag principle: 1-hour fuels are those with a diameter lower than 0.25 inch; fuels with a diameter between 1 and 3 inches are classed as 100-hour fuels; and fuels ranging between 3 and 8 inches in diameter are classed as 1,000-hours fuels. With moisture content being one of the most important fuel characteristics governing combustion, and round fuel with higher diameter drying slower, increasing diameter of the fuel can be related to lower availability for combustion. Even though this relationship can be considered valid with regard to increasing diameter of dead round fuels, additional complications arise when attempting to relate leaf particle size and shape to the course and characteristics of combustion.

Experiments performed on oven-dry reconstructed litter beds indicate that longer, wider, curled leaves with larger perimeters tend to create less compact litter beds, which burn faster with higher flames and more complete fuel-bed consumption (Scarff and Westoby 2006; Plucinski and Anderson 2008; de Magalhães and Schwilk 2012; Engber and Varner III 2012; Cornwell *et al.* 2015). As well as relating particle size to fire behaviour of the fuels, these studies indicated a high level of intercorrelation between size, arrangement and compactness of the fuel beds. Furthermore, it was demonstrated that the shape of the leaves has a significant effect on the burning characteristics of leaf litter beds (Kane *et al.* 2008) as well as of individual leaves (Engstrom *et al.* 2004). Testing on individual leaves has shown that increasing leaf size (Murray et al. 2013) and decreasing leaf thickness (Montgomery and Cheo 1971; Engstrom et al. 2004; Kane et al. 2008) are related to faster ignition. The experiments listed tend to show a straightforward relationship between size, shape and combustion behaviour of leaves and leaf litters, with longer and bigger leaves promoting faster ignition and fire spread, and more intense flaming. Nevertheless, by slightly altering test conditions (*e.g.* testing air-dried instead of oven-dry reconstructed litter beds, or testing fresh instead of dry leaves) different relationships between parameters might be obtained (van Altena et al. 2012; Murray et al. 2013). Furthermore, the possibility that a leaf particle of a given size and shape may promote combustion as part of the canopy structure and impede combustion as part of the forest floor cannot be excluded (Scarff and Westoby 2006).

As can be seen from the above, relationships between plant traits and combustion are complex. Furthermore, characteristics of combustion are a result of all the fuel parameters of the whole fuel complex, as well as their interaction with each other and their environment (Fernandes and Cruz 2012).

2. Environmental factors influencing fire

In the previous chapter, basic concepts related to combustion were introduced. In the literature, combustion is commonly related to controlled and optimised technical processes, whereas fire is more often used for uncontrolled burning. Nevertheless, it is essentially the same process, thus in the present work, "fire" and "combustion" will be considered to be interchangeable. With combustion and fire being the same process, spread of fire in the environment is also governed by fuel characteristics and heating rates. Nevertheless, on the landscape level, environmental conditions influence characteristics of the fuel, probability of ignition, and efficiency of heat transfer; and as a result, the fire itself. Thus, on a landscape level, fire is a result of complex interactions between ignition, weather, topography and fuels (Rothermel 1983).

2.1. Ignition

For a fire to start fuel needs to absorb enough energy for the combustion process to be initiated. Even in the case of warm, dry weather and the presence of sufficient amounts of readily available fuels, without an ignition source there will be no fire. Ignition sources can be either natural or anthropogenic, with the importance of individual ignition sources varying across time and space (Scott 2000; Valese *et al.* 2014).

2.1.1. Natural ignition sources

Before humans mastered the ability to start fire at will, all wildland fires were ignited by natural ignition sources (Valese *et al.* 2014). Natural ignition sources include lightning, spontaneous combustion, sparks from falling rocks, volcanic activity, and meteorite impact (Pyne *et al.* 1996; DeBano *et al.* 1998; Scott 2000).

2.1.1.1. Lightning

Lightning presents the most common natural ignition source, and is considered to be responsible for 10% of global biomass burning (Scott 2000). Satellite records show that on average 46 flashes occur every second on Earth, with the highest annual average in central

Africa and the lowest in the polar regions. Flashes are more common over land than over oceans, and during the warm rather than the cold part of the year (Cecil *et al.* 2014). However, only a small proportion of lightning results in the ignition of fires, with lightning efficiency (*i.e.* number of fires per number of flashes) ranging from less than 0.01 for grasslands to 0.05 for Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) stands. Even though lightning often strikes trees in forested areas, these strikes do not necessarily lead to wildland fires. Lightning can cause damage to trees ranging from scarring to blowing up, but even if a tree is blown up and the remaining snag is smouldering from inside out, wildland fire will not spread unless fine ground-fuels are ignited. Smouldering of a snag can last for weeks before conditions for flaming and faster fire spread are achieved. More often, fire is started by a lightning flashing over to the ground at the height of a metre or two. Even though this phenomenon is common, the physical mechanism behind it is still not completely understood (Pyne *et al.* 1996; Latham and Williams 2001). The probability of successful ignition depends on the duration of the continuing current as well as on the characteristics of the fuel. Latham and Schlieter (1989) demonstrated that the relative importance of a fuel's characteristics in governing the probability of ignition by a standardised electric arc discharge changes depending on the fuel type. Whereas fuel-bed depth almost entirely controlled ignition probability in the case of Lodgepole pine (*Pinus contorta* Douglas) and *P. menziesii*, moisture content was the most important parameter in the case of Ponderosa pine (*Pinus ponderosa* Douglas ex C.Lawson) litter. Besides the characteristics of lightning and fuel, low lightning efficiency can be partly related to associated precipitation which, if it occurs, has the potential to extinguish ignited fires as well as to reduce the probability of ignition by increasing fuel moisture content (Latham and Williams 2001). Additionally, there are indications of a positive feedback loop between large fires and lightning. Aerosols produced during large fires have the potential to alter atmospheric polarity. As a consequence, thunderstorms forming in smoke-contaminated air masses show an increase in the percentage of positive cloud-to-ground flashes, as well as an increase in their median peak current (Lyons *et al.* 1998; Murray *et al.* 2000; Fernandes *et al.* 2006), increasing the overall probability of new lightning-ignited fire.

2.1.1.2. Spontaneous ignition

Spontaneous combustion of piled vegetation material has been well investigated due to the risk of ignition and significant economic losses in the storing facilities of cellulosic materials (Armstrong 1973), as well as in coal production and handling (Schmal *et al.* 1985; Kuenzer *et al.* 2012). As well as in fuel piles created by human activities, these kinds of ignitions are possible in natural deep fuels such as peat bogs and dry snags. The process itself can be divided into two phases. Initially, the fuel needs to provide optimal conditions for survival of thermophilic bacteria, and sufficient depth to ensure thermal insulation of the centre of the pile. Thermophilic bacteria are responsible for the initial heating and drying of the pile centre, simultaneously increasing temperature and reducing humidity, so creating conditions suboptimal for their survival. At this point, if sufficient heat is produced by the bacterial activity, a physiochemical reaction will be initiated resulting in a continuous rise in temperature until ignition is achieved. In most cases, the pile will start to smoulder in its centre, with disturbance of the smouldering pile possibly resulting in sufficient aeration for the initiation of flaming (Armstrong 1973).

A flammable gas mixture might surround live vegetation, as numerous plant species release volatiles as a response to heat and drought stress. Spontaneous ignition of these gases (DeBano *et al.* 1998), or their ignition with a spark from a falling rock (Pyne *et al.* 1996), are both acknowledged as possible, but are much less probable natural causes of fuel ignition.

2.1.1.3. Volcanic activity and meteorites

Volcanic activity will result in vegetation burning. Nevertheless, little attention is given to wildland fires ignited by volcanic activity, as their relative importance in comparison to other consequences of volcanic activity is often negligible.

The importance of the meteorites as ignition sources is controversial. It is generally accepted that small- to medium-sized meteorites cannot start fires. Nevertheless, some authors claim that even the impacts associated with Cretaceous–Tertiary boundary clays and the Tunguska event were not able to ignite wildland fires (Jones and Lim 2000). Others are confident that impacts of these sizes result in ignition (Svetsov 2002). Even if the latter claim is true, the frequency of impacts that could start a wildland fire is low enough to make meteorites very unlikely ignition sources.

2.1.2. Anthropogenic ignitions

With lightning being responsible for 10% of the burning of the global biomass, and the rest of the natural ignition sources playing only a minor role (Scott 2000), it is safe to presume that anthropogenic ignitions are currently responsible for most of the global biomass burning. The importance and scale of anthropogenic ignitions varies through time and space. Anthropogenic ignitions gained importance with hominins mastering the skill of igniting fire at will, a skill unique to humans and their ancestors. The earliest evidence that connects hominins and fire dates to approximately 1.6 million years ago, with the oldest evidence of the ability to set fire at will (the Gesher Benot Ya'aqov site in Israel) dating to approximately 800,000 years ago, and habitual fire use to around 300,000–400,000 years ago (Roebroeks and Vill 2011). Positively separating anthropogenic and background ignition for this vast time period was shown to be unfeasible (Bowman *et al.* 2011). Generally, anthropogenic ignitions will have the highest influence in areas where natural fires are rare, vegetation is poorly adapted, and a high quantity of continuous biomass is present. In contrast, the lowest influence is expected in areas with high natural fire activity in which vegetation is already adapted to frequent fire disturbance, and the environment is almost saturated with lightning-induced fires (Mcwethy *et al.* 2013).

Throughout history, reasons for setting fire have diversified, with even the earliest forms of fire usage still continuing in the present day, though possibly in a modified form. Early hunters and gatherers used fire to manage habitat and game. With the development of settlements it became a tool for creating arable land, removing harvest residues, preparing fields for cultivation, and improving pastureland quality. In recent history, humans have influenced fire not only through ignitions, but also by fire suppression and exclusion (Bowman *et al.* 2011). Upon realisation that fire cannot be excluded from fire-prone environments, and that attempts to do so result in loss of biodiversity and higher severity of wildland fires once they do occur, prescribed burning (*e.g.* deliberate burning with the purpose of maintaining biodiversity, and reducing the risks and negative consequences of uncontrolled fires) was added to the list of human fire uses (Fernandes and Botelho 2003). As well as using fire as a management tool, anthropogenic ignitions can also be set in order to resolve a conflict of interest, or as a result of pyromania, negligence or accident (Maingi and Henry 2007). The frequency and importance of different anthropogenic ignitions depends on land cover and use, on the location and position of infrastructure (*e.g.* roads, railroads and power lines), and on the socio-economic conditions of a region (Ganteaume *et al.* 2013a).

In Europe, 51% of fires with known cause are caused by intentional anthropogenic ignition, 44% by negligence or accident, and 5% by natural ignition, with high regional differences in both number of fires and causes of ignition (Carty *et al.* 2010). Furthermore, in addition to increasing frequency of ignitions, anthropogenic ignitions result in a prolonged fire season, and possibly altered fire behaviour (Platt *et al.* 2015).

2.2. Climate and weather

Climate and weather play an important role in governing wildland fire occurrence and spread, through controlling the presence of fuel and the conditions favourable for fire spread.

2.2.1. Climate

Analysis of the sedimentary records from the last glacial maxima to the present indicates that, globally, climatic conditions played a crucial role in governing biomass burning, up until the Industrial Revolution. Generally, less burning occurred in an area when it exhibited local cooling (Marlon *et al.* 2008; Power *et al.* 2008). The Industrial Revolution initiated large-scale land-use intensification, and human activities became an increasingly important factor governing global biomass burning (Marlon *et al.* 2008). Anthropogenic influences aside, climate is the most important factor governing primary production and global distribution of major vegetation types (Lieth 1973), thus having a long-term effect on determining distribution and quantity of fuel. As well as long-term effects, climate also governs short-term availability of the fuel, due to temperature dependency of the fuel's moisture content (Marlon *et al.* 2008; Krawchuk *et al.* 2009). On a global scale, fire activity was shown to be highest in areas with intermediate productivity and aridity (*e.g.* tropical grasslands, savannas and tropical dry forests). These areas are characterised by precipitation seasonality, creating optimal conditions for fuel build-up during the wet season and for fuel drying and fire spread during the dry season. With decreasing productivity and increasing aridity, lack of fuel becomes a limiting factor for fire activity (*e.g.* tundra and deserts), whereas shortening of the dry season limits fire activity in more productive and humid ecosystems (*e.g.* equatorial tropical forests) (Meyn *et al.* 2007; Pausas and Bradstock 2007; Van Der Werf *et al.* 2008). Mediterranean-type forests, woodlands and shrublands exhibit intermediate-to-high fire activity when compared to other ecosystems worldwide, ranking sixth out of 13 ecosystems involved in the analysis (Pausas and Ribeiro 2013).

The concept of fuel-limited and drought-limited fire regimes implies a positive relationship between precipitation and fire activity in the arid and unproductive areas, and a negative one in humid and productive environments (Pausas and Ribeiro 2013; Barbero *et al.* 2014), so complicating prediction of future changes in fire activity (Moritz *et al.* 2012). Additionally, explanation of current climate–vegetation–fire relationships, along with prediction of future ones, cannot be undertaken without accounting for the anthropogenic influence (Marlon *et al.* 2008; Van Der Werf *et al.* 2008). Opening of closed forest structures, road construction, logging, and fragmentation of forested areas have all led to increased fire activity of, by their nature, almost fire-free tropical rain forests (Cochrane 2003). At the same time, abandonment of long-managed surfaces in naturally fire-prone areas, together with fire suppression, leads to higher fuel accumulation and more severe fires in the northern part of the Mediterranean Basin, whereas land-use intensification leads to fuel reduction in the southern part of the Mediterranean Basin (Dimitriou *et al.* 2001).

It should also be noted that when scaling down from global trends to landscape level, short-distance variations in productivity and standing biomass are present due to differences in soil characteristics, topography, fire activity, successional stage, age of dominant plants, and floristic history (Lieth 1973). As a result, areas with contrasting vegetation characteristics can coexist within a climatic region.

2.2.2. Weather

At any given point in a landscape, the amount, composition and structure of vegetation fuels is governed by numerous previously mentioned factors. At any given moment, the cumulative effects of past and present local weather conditions determine the water status of the vegetation and the proportion of the fuel readily available for combustion. Furthermore, if ignition occurs, the presence of wind significantly affects the rate and direction of fire spread. Thus, by governing fuel availability, and fire direction and spread, weather conditions are an essential part of fire-risk assessment (Pyne *et al.* 1996).

One of the most important direct effects of weather is in governing the moisture content of dead fuels. The moisture content of dead fuels is governed by the physical processes of adsorption and desorption, with moisture content at any given moment resulting from interaction between fuels and their environment. Weather elements governing the moisture status of dead fuels are precipitation, temperature, air humidity, wind, sunlight, evaporation, vapours pressure, barometric pressure, and winter snowfall. Most of these parameters are correlated, and they are partly governed by vegetation characteristics and the topographic position of the stand itself.

Precipitation is the only weather element that can completely hinder ignition of vegetation fuels and extinguish existing wildland fires. A sufficient amount of precipitation increases the moisture content of the fuels beyond moisture of extinction, and dissipates the energy of already-burning fires (Gisborne 1928).

The influence of air humidity on fuel moisture depends on the difference between the two. Fuels drier than the air will adsorb moisture, and fuels wetter than the air will desorb it. Under conditions of constant temperature and air humidity, the process of adsorption or desorption would continue until equilibrium between air and fuel is reached. Even if air humidity and temperature are held constant, the equilibrium moisture content depends on whether the fuel is adsorbing or desorbing moisture (Gisborne 1928; Catchpole *et al.* 2001; Matthews *et al.* 2012; Schunk *et al.* 2013). In nature, due to constantly changing environmental conditions, equilibrium is never reached, and a fuel's moisture content is in a constant state of flux. Dead fuels will dry remarkably quickly if high temperature co-occurs with low air humidity, sunny weather and high winds (Gisborne 1928). Nevertheless, due to the different response time of varying fuels, dead fuels with different moisture contents can be found within a single stand (Gisborne 1928; Byram 1963). Whereas a few days of warm and dry weather may suffice to dry cured grass to the point when it is readily ignited, a long drought period will be necessary in order to dry deep duff or fallen snags. In the simplest terms, the longer the drought period, the bigger proportion of fuel will be readily available for combustion in case of ignition.

In addition to directly influencing the fuel moisture content of dead fuels, weather conditions affect live vegetation. For vegetation to persist in a specific area it needs to be adapted to general climatic conditions (*e.g.* seasonality of precipitation, temperature, day length), as well as to the possible weather extremes. As Earth shows a high diversity of local conditions and adaptations, which allow plant species to persist under a variety of specific conditions, the issue of vegetation adaptations will be addressed separately, taking into account only the species included in the study presented here.

The importance of weather can be seen when examining the relationship between weather conditions and area burned. Even though fire can be initiated within a broad range of environmental conditions, the area burned in a single fire event increases if the fire is started after a prolonged drought, on a hot, windy day with low relative humidity (*e.g.* Maingi and Henry 2007; Carvalho *et al.* 2008; Barbero *et al.* 2014; Molina-Terrén and Cardil 2015). These conditions (*i.e.* hot, sunny, dry, windy weather after a prolonged drought) are also known as "fire weather". Large fires, which account for the majority of area burned within the region, commonly occur under fire-weather conditions (*e.g.* Moritz 1997; Flannigan and Wotton 2001; Carvalho *et al.* 2008; Koutsias *et al.* 2013; Amraoui *et al.* 2015).

2.3. Topography

Topography has direct and indirect effects on fire behaviour, with the relative importance of slope, aspect and elevation in governing fire severity depending on the spatial scale used for analysis (Wu *et al.* 2014; Birch *et al.* 2015).

Of the topographic characteristics, slope has pronounced direct effects which are the result of its influence on warm-air fluid dynamics and heat transfer (Morandini *et al.* 2014). Increase in slope steepness results in tilting of the flame and increased heat transfer to potential fuel, resulting in longer flames, faster uphill fire spread (Rothermel 1972; Rothermel 1983; Rothermel 1984; Morandini *et al.* 2014), and increasing fire severity (Lecina-Diaz *et al.* 2014). Tilting of the flame may result in attachment of the flame to the slope (no downhill indrift) resulting in lower fire-scarring of trees positioned above the flames, but higher scarring further uphill, once the convection plume breaks away from the slope (Rothermel 1984).

While the direct effect of slope on fire behaviour is fairly straightforward, aspect, elevation, topographic convergence and clear-sky irradiance mostly affect fire behaviour indirectly, by changing local environmental conditions and affecting water balance (Dobrowski *et al.* 2009). Changes in environmental conditions and water balance result in changes in species composition and structure (Kane *et al.* 2015), affecting both fuel composition and moisture status. Additionally, topography influences post-fire erosion and vegetation recovery (*e.g.* Dobre *et al.* 2014; Han *et al.* 2015; Ireland and Petropoulos 2015; Karamesouti *et al.* 2016). North-facing slopes tend to be more humid, have higher fuel moisture content and faster vegetation recovery (Ireland and Petropoulos 2015), and exhibit lower post-fire erodibility (Dobre *et al.* 2014). Increase in altitude is associated with decrease in average and maximal temperature (Dobrowski *et al.* 2009); and increase in mean annual precipitation results in more open stands with less biomass and lower fire severity (Kane *et al.* 2015). Furthermore, dump gullies tend to accumulate more fuel than adjacent exposed slopes (Bassett *et al.* 2015)

Similarly to the influence of fuel characteristics on combustion at the elementary level, climate, weather, fuels, topography and the probability of ignition interact on the landscape level with fire probability and behaviour being governed by the resulting conditions.

3. Development and types of fire

Development and types of fire are commonly defined and explained in relation to the fuel strata involved in the combustion; thus, firstly, the concept of fuel stratification will be introduced.

3.1. Fuel stratification

In his early work Barrows (1951) separated fuel complex into ground fuels and aerial fuels. Ground fuels include all the combustible material positioned in the ground, on the ground, or immediately above it, including tree roots, soil, duff, dead leaves, grass, fine dead wood, downed logs, stumps, limbwood, low brush, and reproduction. Aerial fuels include all combustible materials located in the upper forest canopy, including tree branches and crowns, snags, moss, and high brush. The most important differences between the two fuel classes are their exposure to environmental influences, their drying rates, and their bulk density. Ground fuels are less exposed, dry slower, and usually have higher bulk density. Nevertheless, this classification is not sufficient for differentiating between fuels involved in different types of fire.

Scott and Reinhardt (2001) separated fuels into ground, surface, and canopy fuels. Whereas their definition of canopy fuels corresponds to Barrows' definition of aerial fuels, they divided Barrows' ground-fuel stratum into ground and surface fuels. According to Scott and Reinhardt (2001), ground fuels include duff, roots, rotten buried logs and other buried combustible materials. The surface fuels layer is found on top of the ground fuels, and consists of needles, leaves, grass, dead and down brunch wood, logs, shrubs, low brush, and short trees. This classification would suffice for introducing forest types, but additional layer separation facilitates the explanation of forest-fire development.

Gould *et al.* (2011) provide more detailed stratification of the fuel complex. They divide fuels into the following layers: overstorey tree and canopy, intermediate tree and canopy, elevated fuel, near-surface fuel, and surface fuel.

The overstorey tree and canopy layer is defined as a layer formed by dominant and co-dominant trees of pole size or greater (diameter at breast height greater than 15 cm).

The intermediate tree and canopy layer is formed by immature individuals of the overstorey tree species, or tree species with intermediate structure, with their crowns being either below or extending into the lower part of the forest canopy. This layer has the potential to act as ladder fuel, carrying fire into the overstorey canopy.

The elevated fuels layer includes tall shrubs and understorey plants with no, or very little, suspended material. Elevated fuels are commonly upright-oriented live or dead materials, with regeneration of overstorey trees sometimes being present in this layer.

The near-surface fuel layer is defined by mixed-orientation fuels with a substantial amount of suspended material. The height of this layer can vary from a few centimetres to over a metre above the ground, and it includes grasses, low shrubs, creepers, and collapsed understorey.

The surface fuel layer is predominantly composed of horizontally layered leaves, twigs and bark of overstorey and understorey trees. As this fuel classification was created for dry eucalyptus forests, which neither have a developed duff layer nor are established on peatlands, a ground fuel layer was not defined.

Even though there are numerous other stratifications possible (*e.g.* Parker and Brown 2000; Lopes *et al.* 2014; Roccaforte *et al.* 2015), for the following section on fire development and types of fire, the stratification introduced by Gould *et al.* (2011) with additions of a ground-fuel stratum as defined by Scott and Reinhardt (2001) will be used.

3.2. Development and types of fire

When discussing fire development and spread, it should be noted that fire spreads from the ignition point in all directions. Under a presumption of uniform fuel distributed over level ground and in the absence of wind, fire ignited by a point ignition source would uniformly spread in all directions, maintaining a circular shape (Fendell and Wolff 2001). However, in nature these presumptions are usually not met, and the fire perimeter elongates under the influence of wind, slope, or both. Fire spreads more rapidly in the direction of wind or upslope. This fast-spreading fire front is called the front or the head fire. Opposite to the head fire is positioned a fire front that spreads against the wind or downslope. It has the lowest velocity, and it is known as “back fire”. Intermediate-velocity spreading, side-on fire fronts are known as flanks (Pyne *et al.* 1996). An alternative to point ignitions, which correspond to lightning ignition as well as numerous negligence and accident ignitions, is line ignition. Line ignitions are usually associated with deliberate anthropogenic ignitions, such as prescribed burning (Richards 1993).

In addition to ignition source, weather conditions and topography, the development of fire and the resulting type of fire depend on the ecosystem, amounts, positioning, and moisture status of different fuel components (fine dead fuels, fine live fuels, coarse fuels) (Davies and Legg 2011). Under a presumption of a uniform fuel bed, constant slope and wind, fire initially builds up in intensity (build-up or acceleration phase) until equilibrium or steady state is reached (Richards 1993). Under natural conditions, due to fluctuation of both fuel characteristics and environmental conditions, only short-term quasi-steady states/spread rates are reached. A change in any of the external factors results in change in the fire behaviour pushing it out of equilibrium. Nevertheless, even under natural conditions fire initially needs to accelerate in order to spread. Later on, depending on external factors, its speed and energy release can both increase and decrease (Pyne *et al.* 1996). For as long as fire is accelerating, the proportion of fuels that are available for combustion increases. Commonly, fine dead fuels are initially ignited. If there is sufficient amount and continuity of dry, fine dead fuels to release enough energy to preheat and ignite other fuel components, fire will spread (Pyne *et al.* 1996; DeBano *et al.* 1998).

3.2.1. Fire in grasslands and low-density woodlands

In grasslands, fire is initiated in fine dead fuels in the near-surface fuel layer. Grassland fuels are usually vertically oriented, predominantly fine fuel, well-aerated and cellulose-rich; thus, when cured, they are prone to highly efficient flaming combustion with relatively short residence time. The high combustion efficiency of grassland fires is reflected in its measured combustion completeness. Grassland savanna was shown to have the highest combustion completeness (81% on average) of all the biomes for which sufficient data could be compiled (Van Leeuwen *et al.* 2014). In addition to the percentage of curing, development, spread and intensity of fire in grassland communities is governed by fuel load and continuity. Grasslands with low fuel load and non-continuous fuels burn only in low-intensity, patchy fires. In these ecosystems, fire spreads only if there is sufficient wind to carry flames from one fuel patch to another. As fuel load, continuity and depth of grassland fuels increase, so do fire spread rate and intensity (Johnson 2002).

With the transition from pure grasslands to low-density woodlands, an elevated fuel layer composed of shrubs and tree regeneration as well as sparse mature trees develops. Nevertheless, fire is still predominantly carried by near-surface herbaceous fuels (Savadogo *et al.* 2007). Due to their sparsity, mature trees are rarely damaged, but tree regeneration and shrubs can be burned if herbaceous fuels release enough energy to combust them. Scrubs and tree regeneration, due to their higher moisture and lignin content in comparison to cured grasses, can continue to burn (smoulder, flame and/or glow) upon passage of the flame front. As the fire-driving fuels in both grasslands and low-density woodlands are herbaceous plants, there is an annual fluctuation in the presence of exposed fine dead fuel. There is a low presence of exposed dry fuels during flushing, and a high presence at the end of the growing season, once plants of the near-ground fuel layer have reached full senescence. These ecosystems can be considered fire-dependent, with the exclusion of fire resulting in encroachment of trees (Bond *et al.* 2005). For example, in the Sudanian-savannah woodland, between 25 and 50% of the area burns annually, and early-season prescribed burning is accepted management practice, used in order to prevent higher-intensity late-season fires, improve pasture productivity for wildlife, and maintain species composition and richness (Savadogo *et al.* 2007).

3.2.2. Fire in shrublands

Shrublands, compared to low-density woodlands, have a higher proportion of fuels in the elevated and surface-fuel layer, and lower in both the near-surface and intermediate/elevated canopy layer. In comparison to grasslands, these ecosystems tend to have fuels richer in lignin with a lower percentage of fine fuels. Furthermore, accumulation of larger amounts of dead fuels, even though dependent on stand characteristics and species composition, generally requires a longer time period than in grasslands. Fire danger models presume an increase in standing dead fuel with stand age until a steady state is reached (Gould *et al.* 2011). However, there are indications that in the Mediterranean shrublands, successional species composition change, together with between-species differences in dead biomass retention and accumulation, can result in peak standing dead biomass amounts in the intermediate succession stage (Baeza *et al.* 2011). It is still not clear whether surface moss and litter, or retained elevated dead fuels, are the first fuel to ignite (Davies and Legg 2011), but it was shown that in shrublands with a high proportion of retained elevated dead fuels, fire can spread through the elevated fuel layer independently of surface fuels (Anderson and Anderson 2010). Thus, retention of elevated dead fuels is regarded as a characteristic promoting fire spread and intensity, and the combustion success of live shrubland fuels is often related to the amount and moisture contents of retained elevated dead fuels (Fernandes 2001; De Luis *et al.* 2004; Anderson and Anderson 2010; Davies and Legg 2011; Ganteaume *et al.* 2013c). Due to the high vertical continuity of the shrubland fuel, in most cases, spreading fire is going to involve the whole fuel complex, with prolonged smouldering of ground fuels after passage of flames has been reported (Davies and Legg 2011).

3.2.3. Fire in forests

In comparison to shrublands, in which vertical continuity of the fuel is generally present, forests exhibit high variability in the vertical continuity of the fuel, as well as in the characteristics of different fuel layers. Furthermore, forests generally have a higher fuel load (Anderson 1982), and thus they have the potential to release a higher amount of energy if the whole fuel complex is involved in the conflagration. Depending on the ecosystem, fire in a forest starts either in the surface-litter layer, or in the near-surface fuel layer. The initial spread and development of fire is the same as in grasslands and shrublands, but in the forests there is an overstorey fuel layer allowing for development of crown fires.

All fire types start as surface fires. Surface fires involve surface fuel, near-surface fuel, and elevated fuel, and they can “torch out” an occasional densely crowned mature overstorey/intermediate tree; but they remain surface fires for as long as their spread rate depends on lower fuel strata (Pyne *et al.* 1996; DeBano *et al.* 1998). Whereas lack of overstorey renders crown fires in grasslands, shrublands and low-tree-density woodlands unfeasible, development of crown fires in the high-tree-density woodlands/forests is highly affected by the vertical continuity of the fuel complex. In addition to characteristics of lower fuel strata and resulting surface fire intensity and flame length, the characteristics of the intermediate and overstorey fuel layer have an important role in facilitating crown fires (Rothermel 1991). Increased crown–base height and intercrown distance results in decreased probability of surface fire developing into crown fire, and reduces damage to the overstorey trees. The same holds true for decrease in crown-bulk density, and lower presence of the intermediate fuel layers. In contrast, poor health state, overstorey tree mortality, and accompanying accumulation of standing dead fuel increases the probability and intensity of crowning fires (Jenkins *et al.* 2012). Of all the topographic and weather parameters, steep slope, strong winds, and unstable atmosphere favour development of crown fire.

Before fire can actively burn through live tree crowns it needs to gain energy and reach sufficient size. A fire may spread for a long period of time as a surface fire without interacting with the overstorey. Initially, as surface fire gains energy, flames become longer and they can reach into crowns or climb ladder fuels, occasionally igniting and "torching" one or more crowns. If conditions are unfavourable for sustained crown fire, individual torched trees will quickly burn out. They sometimes produce a shower of firebrands that may create new fires ahead of the main fire line in the process called "spotting". Spotting in forested stands can result in pre-drying of the tree canopies ahead of the fire line. If conditions are favourable for fire development, both torching and spotting are going to result in further increase in fire intensity until sustained crowning is reached. Wildland fire-behaviour research and modelling are mainly interested in ignition of free-burning fire, rate of spread, released heat per unit area, fireline intensity, flame-front dimensions, perimeter, and area growth (Rothermel 1991), while trying to account for phenomena such as torching, crowning, spotting and firewhirls (Alexander and Cruz 2013a). These parameters are extremely important for organising appropriate firefighting responses, as well as ensuring public safety.

Nevertheless, depending on the vertical structure of a stand, flames can potentially spread with different speeds through different fuel strata, adding uncertainty to the predictions (Rothermel 1993). Furthermore, when observing fire from an ecological point of view, smouldering and glowing that continues after passage of the flame front should be taken into consideration as well. These processes can continue for extended periods of time, substantially prolonging duration of heat exposure and overall emissions released from the fire. Additionally, glowing embers, if lifted by the wind, can start new fire once the initial fire line is already extinguished. As combustion is terminated at the moment when energy is no longer released from the fuel (complete extinction), then so if the fire.

Different fire types result in different amounts of unburned material. Low-intensity surface fires spreading through a forest ecosystem will leave large a portion of fuel completely undamaged, but even high-intensity crown fires that result in complete “crown kill” leave a substantial amount of scorched, but unburned, material behind, usually as char or standing tree trunks (Figure 1). Furthermore, in the case of forest fires, with increasing fire size there is increased probability of occurrence of large unburned “islands” within the fire perimeter (Gill and Allan 2008).

Figure 1. Burned young stand of Aleppo pine (*Pinus halepensis* Mill.) with substantial amounts of dead, but not completely combusted, material and a small unburned “island” within the fire perimeter (middle of the photo). Unaffected terraced olive (*Olea europaea* L.) orchard, recovered shrubland and grassland patch, and unaffected older *P. halepensis* patches are also visible in the photo. The photo was taken on 13.10.2010, near Promajne, Makarska. The fire probably burned during the previous year’s fire season.

3.2.4. Ground fires

As crown fires require a developed intermediate and overstorey fuel layer, the principal requirement for ground fires is a well-developed ground-fuel stratum. Ground fuels usually have high bulk density and lignin content, and are thus prone to smouldering combustion (Miyanishi 2001). Passing surface fire can ignite ground fires at places where there is a sufficient amount of dry-enough ground fuel present. From this ignition point, combustion will develop in all directions creating a concentric burn hole. As ground material is combusted, the hole will spread with the produced heat drying and pyrolysing nearby material. Ashes created upon combustion end up settling on top of the reaction zone, simultaneously decreasing oxygen availability and acting as a highly efficient thermal insulator, resulting in prolonged and deep soil heating. Even though these types of fire spread very slowly and have relatively low temperature, they can burn for days to weeks after passage of the fire front. Furthermore, this kind of fire is difficult to notice, control and extinguish, especially in deep-profile peatlands (Pyne *et al.* 1996; DeBano *et al.* 1998). High accumulation of duff underneath old trees can make them very susceptible to smouldering-induced fine-root mortality and cambium injury, potentially leading to tree death. These injuries can cause tree mortality even if the ground fire is a consequence of low-intensity, prescribed, surface fire with no damage to the tree crown (Hood 2010; Garlough and Keyes 2011).

As can be seen from the previous section, information on the fire frequency and area burned does not yield information on the ecological effect of the fire. Ecosystems are adapted to certain fire regimes (*i.e.* frequency, season, type, severity and extent of fire) (Bond and Keeley 2005), with a shift in the fire regime, if it exceeds the ecosystem plasticity, resulting in a shift of the ecosystem. In order to assess the ecological effects of the fire disturbance, the ability of the ecosystem to recover should be taken into consideration as well.

4. Defining and measuring plant flammability/fire behaviour

Flammability as a concept was first introduced in the material sciences where well-defined standardised tests are applied in order to assess whether or not a material fulfils prescribed safety requirements. Tests required are defined by the relevant authority and related to intended use of the material (*e.g.* ASTM E84, DIN 4102, UL 2085). Nevertheless, even in material sciences, where composition and properties of a test sample are replicable, there is no single parameter that can be used to quantify the potential fire risk of a combustible solid. Furthermore, the ranking of materials can change depending on the testing procedure (Thomson and Drysdale 1987). Determining flammability of vegetation material brings additional difficulties, as vegetation does not have an "intended use" for which flammability tests could be adjusted; and properties of the vegetation materials change in space and time, making it impossible to keep characteristics of the test samples constant. Furthermore, wildland fires occur under a wide range of environmental conditions, which additionally alter resulting fire behaviour. As a consequence, standardising testing of vegetation flammability, as well as defining flammability as a concept applicable for vegetation sciences and ecological purposes, was shown to be a challenge.

4.1. Definition of vegetation flammability

Flammability is broadly defined as the propensity to burn (Pérez-Harguindeguy *et al.* 2013). When applied to vegetation, the most often-used definition is the one introduced by Anderson (1970) and further expanded by Martine *et al.* (1994). Anderson (1970) identified three components of vegetation flammability: ignitibility, sustainability, and combustibility.

Ignitibility represents the ease with which fuels ignite, and is commonly expressed as the time necessary for initiation of glowing or flaming combustion upon exposure of the material to a heat source—with more ignitable fuel igniting earlier. Sustainability is the measure of how well fire will continue to burn with or without the heat source. Combustibility is a measure of the speed and intensity with which a fuel is consumed. Martin *et al.* (1994) added consumability as an additional flammability component. This component is related to the proportion of mass or volume consumed by fire. Despite the commonly-used definition, ways of measuring vegetation flammability, interpreting obtained results and relating them to flammability components and/or flammability, show a high diversity of approaches.

4.2. Measuring vegetation flammability/fire behaviour

4.2.1. *In situ* experimental fires

Full-scale properly instrumented experimental fires offer information on fire behaviour that can be easily transferred to wildland fires. Nevertheless, they are limited by operational, safety and cost constraints (Fernandes and Cruz 2012). Safety concerns are one of the predominant reasons for limited field-experimental information on crown fires, as well as a reason for the majority of experimental fires being conducted under marginal burning conditions (Alexander and Cruz 2013a). As well as safety and costs, an additional problem with conducting outdoor experimental fires is ensuring a sufficient level of repeatability. Reduced repeatability is caused by constant fluctuations in environmental factors (Alexander and Cruz 2013b) as well as heterogeneous stand structure (Cruz *et al.* 2013). As a consequence, a high number of *in situ* experimental fires is necessary in order to gain reliable information on factors influencing fire behaviour in a specific stand type (Bilgili and Saglam 2003).

Due to high costs and safety issues, *in situ* experimental fires are usually conducted as a part of development and validation of management decision-making support systems (Cruz *et al.* 2010; Cheney *et al.* 2012; McCaw *et al.* 2012; Stocks *et al.* 2004; Fontaine *et al.* 2012), or for validation of the applied management practices (Fernandes *et al.* 2004; Govender *et al.* 2006; Davies *et al.* 2009; Fernandes 2009; Kreye and Kobziar 2015). Experimental fires are usually not concerned with flammability as previously defined. They strive to examine effects of weather conditions (*e.g.* temperature, relative humidity and wind) and fuel status of a certain stand (*e.g.* age, fuel load, fuel arrangement, moisture content, dead-to-live fuel ratio, *etc*.) on the probability of successful ignition and fire spread (Fernandes *et al.* 2008; Anderson and Anderson 2010), as well as on the resulting fire behaviour (De Luis *et al.* 2004).

In order to fulfil this objective they are usually coupled with detailed fuel characterisation and monitoring of weather conditions, with measured and evaluated fuel characteristics depending on the complexity of the stand in question. In addition to ignition success and success of fire spread, commonly measured/determined fire-behaviour characteristics include flame geometry, rate of spread, fire intensity, residence time, and fuel consumption (Baeza *et al.* 2002; Fernandes *et al.* 2008; Anderson and Anderson 2010; Cruz *et al.* 2010). The size of the experimental plots depends on the research question as well as the stand characteristics. It was reported to vary from 93 ha for aerial suppression experiments conducted in South Australia (Plucinski *et al.* 2010), to an individual shrub in an experiment testing the ignition success of gorse (*Ulex europaeus* L.) in New Zealand (Anderson and Anderson 2010). Less common are *in situ* experiments in which fuel is manipulated (Schwilk 2003; Ellair and Platt 2013), or which focus on small in-stand differences (Wright and Clarke 2008), with these experiments often including information on soil heating.

4.2.2. Stand/fuel recreating experiments

Conducting experiments on reconstructed stands/fuels eliminates the problem of natural *in situ* stand heterogeneity. Experiments on reconstructed stands/fuels are commonly conducted in the laboratory, but they can be performed outdoors (Madrigal *et al.* 2011; Beutling *et al.* 2012; Kreye *et al.* 2013a). Outdoor experiments allow for manipulation and standardisation of fuel characteristics, whereas laboratory experiments additionally allow for manipulation of environmental conditions such as slope and wind velocity. Even though reconstructed fuels are criticised as being a poor representation of the arrangement of natural fuels (Ganteaume *et al.* 2014), these experiments enable researchers to test the influence of the chosen factor across a wide range of values, while holding fuel parameters constant. This is especially important when it comes to slope and wind. These two parameters are known as the most important environmental factors altering the behaviour of a spreading fire (Rothermel 1972), but conduction of *in situ* experimental fires under high winds and/or slope is unadvisable due to safety reasons. Even if such conduction of *in situ* experimental fires under high wind and/or slope were feasible, capturing the full range of both wind velocities and slope angles, as well as all possible combinations, would be impossible.

4.2.2.1. Wind tunnel tests

Similarly to *in situ* experimental fires, wind tunnel experiments are not concerned with determining flammability of the material tested. They are usually conducted in order to provide information for modelling of fire development, predominantly focusing on the influence of wind, with some systems having a possibility of tilting the testing surface, enabling simultaneous manipulation of both wind and slope (Morandini *et al.* 2001; Mendes-Lopes *et al.* 2003). Reconstructed litter beds are commonly tested fuels, but tests with suspended material simulating canopy (Tachajapong *et al.* 2014) and reconstructed shrubland stands (Marino *et al.* 2008; Madrigal *et al.* 2012) have been conducted as well.

In this testing procedure, the desired fuel is reconstructed on the square surface within a wind tunnel and linear ignition is achieved, usually by applying a small amount of alcohol on one of the sides facing the fan. The fan induces air movement of the desired velocity, simulating wind. Thermocouples are positioned within the wind tunnel and measure the temperature profile of the burning experiment, with the number and position of thermocouples differing between experimental setups. Experiments are often recorded to allow for later analysis of the flame geometry. In addition to flame geometry (*e.g.* height, angle) commonly measured parameters include rate of spread and residual mass fractions (mass remained after burning in comparison to initial mass). A recorded temperature profile can be presented as it is (Mendes-Lopes *et al.* 2003), or can be used to calculate the heat-release rate and peak heat-release rate (Madrigal *et al.* 2011). In the latter case, wind-tunnel experiments are coupled with mass-loss calorimetry in order to evaluate the accuracy of the heat-release rate curves. The authors followed the premise that "Heat release rate of a fuel is one of the most important properties for understanding the combustion process, fire characteristics, and fire propagation rates." In order to accurately assess the influence of wind on the movement of the fire line, recreated fuels have a minimal length of 2 m. Besides the above-mentioned wind-tunnel experiments, a similar approach was applied by Delabraze and Valette (1974, 1982), Weise *et al*. (2005b), Marino *et al.* (2012, 2014), Nelson *et al.* (2012) and Sullivan *et al*. (2013).

4.2.2.2. Large-Scale Heat Release (LSHR) apparatus

LSHR is a system used by the research group at the University of Corsica (Santoni *et al.* 2010; Santoni *et al.* 2011; Morandini *et al.* 2013; Santoni *et al.* 2015; Tihay *et al.* 2015). It applies the oxygen consumption calorimetry principle to determine fire-line intensity/heat release rate. This principle states that released heat is proportional to oxygen consumed for complete combustion of most organic compounds, and thus it can be approximated by measuring the oxygen deficit in the exhaust gas flow of burning materials. In its basic state the device consists of a hood with 3 m x 3 m area and a 2 m x 2 m combustion bench fixed on a load cell. The size of the fuel beds tested varied from 0.9 m x 1.1 m to 1 m x 2 m. The load cell measures mass loss during the experimental burn. Released gases are analysed for composition, temperature, optical obscuration and flow speed with a bidirectional probe positioned in the exhaust duct. Linear ignition is achieved by a small amount of alcohol and a flame torch. Heat-release rate, net heat of combustion, and fire-line intensity are calculated from recorded values (Santoni *et al.* 2010, 2011). By equipping the system with a camera, total heat gauges and radiation heat gauges, additional information on flame geometry, total and radiation heat fluxes can be obtained (Morandini *et al.* 2013). Additionally, tilting of the combustion bench allows for testing of the effect of slope (Tihay *et al.* 2015). The purpose of these experiments is the same as that of the previously mentioned experimental setups. Additionally, some of the experiments were concerned with the influence of fuel load (Morandini *et al.* 2013; Tihay *et al.* 2015) and experiment scale (Santoni *et al.* 2015) on the fire behaviour metrics.

White *et al.* (1997) used the same principle to determine flammability of whole Christmas trees. Stephens *et al.* (1994) applied it to Tam juniper (*Juniperus sabina* L. *var. tamariscifolia*). Etlinger and Beall (2004) and Weise *et al.* (2005a) used it to test the fire performance of whole landscaping plants. Later experiments were followed by exhaustive analysis of intrinsic and extrinsic fuel characteristics.

4.2.2.3. Burning tables

Similarly to previous methods, burning-table experiments can be used to improve fire behaviour models without being concerned with differences in flammability (Tachajapong *et al.* 2009). Nevertheless, the examples presented here were interested in flammability as previously defined. Ormeño *et al.* (2009) and de Magalhães and Schwilk (2012) conducted experiments on recreated litter beds that were ignited along their shorter side with a pilot flame. Both research groups were interested in examining differences between single species of litter beds and their mixtures, as well as in determining traits responsible for observed fire behaviour. Ormeño *et al.* (2009) focused on the influence of terpene content and fuel depth, whereas de Magalhães and Schwilk (2012) were mostly interested in the effects of particle size and bulk density on flammability. Despite the difference in burning table dimensions (2 m x 1 m *vs* 0.15 m x 1.5 m) and fuel load (1 kgm^{-2} *vs* 2 kgm^{-2}), parameters measured and the basic principle of the experiments were comparable. Both experiments measured combustion time (duration for which flame was visible) as a sustainability measure; spread rate and maximal flame height as a measure of combustibility; and mass loss (calculated as a difference between initial mass and remaining mass after testing) as measure of consumability. In both cases thermocouple measurements were made. Ormeño *et al.* (2009) reported maximal, minimal and mean temperature recorded during combustion, whereas de Magalhães and Schwilk (2012) reported a time period with temperatures higher than 100°C.

Additionally, de Magalhães and Schwilk (2012) measured the time between exposing the shorter side of the litter bed to a propane torch and observing flames in the litter bed (*i.e.* ignition delay) as a measure of ignitibility. Both methods succeeded in demonstrating significant differences between tested litter beds, as well as significant relationships between the examined parameters. A similar approach was used by Viegas *et al.* (2013).

4.2.3. Small-scale experiments (disturbed samples)

All of the previously introduced flammability tests required substantial amounts of fuels to be gathered, potentially limiting the number of replications. Furthermore, the combustion of large amounts of fuel generates substantial amounts of heat and smoke, increasing the safety requirements of the testing facilities. By reducing the amount of the material necessary for a single test, more replications can be conducted with the same amount of gathered material, and less heat and smoke are generated per individual test, making safety requirements less strict.

The methods introduced in this chapter test samples that are not in their original state and position. Their composition and orientation do not represent the "in-stand" situation: *i.e.* these samples are "disturbed".

4.2.3.1. Experiment employing the burning table principle

In experiments employing the burning-table principle, fuel (usually a litter bed) is reconstructed and ignited, and fire behaviour characteristics are observed. Parameters recorded and their interpretation are comparable to those of the full-scale litter beds, but depending on the individual approaches some parameters are omitted and others are added. This type of experiment accounts for a large proportion of overall flammability experiments.

In one of the approaches, fuel is ignited with a xylene-soaked string grid positioned either on top of (Mutch 1970) or below the reconstructed litter bed (Mutch 1970; Taylor and Fonda 1990; Fonda *et al.* 1998; Kane *et al.* 2008; Engber and Varner III 2012). The strings are ignited with a lighter. The duration of flaming and smouldering (sustainability measure), maximum flame height (combustibility measure), and the amount of unburned material (consumability measure), are recorded. Mutch (1970) also recorded weight loss during the experiment.

As an alternative to this method, fuel can be reconstructed in a round mash frame positioned on a solid, fire-resistant surface and ignited at the centre with a point ignition source (Philpot 1969; Plucinski and Anderson 2008; van Altena *et al.* 2012; Bianchi and Defosse 2014; Ganteaume *et al.* 2014; Santana and Marrs 2014; Blauw *et al.* 2015; Cornwell *et al.* 2015). The standardised point ignition source varies between authors (*e.g*. a match, a cotton ball soaked in fire accelerator, a direct injection of the fire accelerator into the centre of the recreated litter, a glowing piece of wood), and mass loss is not monitored in all experimental setups. Nevertheless, except for Bianchi and Defosse (2014), who were interested only in the ignition probability, all the other above-mentioned experiments monitored the same parameters as full-scale burning tables, including temperature records. Additionally, Santana and Marrs (2014) used mass-loss records to derive additional parameters. Besides the previously mentioned ignition sources, ignition can be achieved by a stream of hot convected air from a Bunsen burner (Scarff and Westoby 2006), or radiant energy flux (Grishin *et al.* 2002), with the latter experiments recording a lower number of parameters.

In addition to examining between-species differences, all of these experiments were interested in relating observed fire-behaviour differences to measured intrinsic and extrinsic characteristics of the tested fuels. Additionally, van Altena *et al.* (2012) and Blauw *et al.* (2015) were interested in the behaviour of the fuel mixture in comparison to monospecific samples.

4.2.3.2. Small-scale wind tunnel

The small-scale wind tunnel was first introduced by McAllister *et al.* (2012) in a study that strove to compare measured to predicted values. The small-scale wind tunnel is not commonly used, and so it will only be briefly introduced here. The sample is placed in the sample holder in such a way that it creates a single layer covering as much as possible of the area without overlapping of individual particles. A prepared sample is put on a stand, positioned inside a small wind tunnel (9 cm tall, 25 cm wide and 60 cm long), and connected to a high-precision balance. An IR heater, which creates uniform heat flux in the range of 0–50 KWm^{-2}, is positioned above the sample, and a coiled wire igniter acts like a pilot. Wind velocity and heat flux can be controlled. Additionally, a LI-COR CO_2/H_2O analyser can be used in order to measure the release of water vapours.

4.2.3.3. Measurements based on oxygen consumption calorimetry

Apart from for testing smaller amounts of material, and using IR heaters and pilots as ignition sources, these systems apply the same principle as LSHR (Section 4.2.2.2.). IR heaters provide uniform and constant radiation heat flux, with most instruments having the possibility of generating heat flux in the range of 10–100 kWm^{-2}. The pilot ignites the flammable gas mixture released upon pyrolysis of the sample. The sample is positioned in a sample holder connected to a load cell. The mass-loss rate and heat-release rate (determined on the basis of the exhaust gas analysis) are recorded throughout the experiment. These testing systems are directly transferred from polymer testing, and their working principle is highly comparable. In addition to recording all the same parameters as LSHR, these systems also allow for measurements of ignition delay and flaming duration.

Fire Propagation Apparatus (FPA) (Figure 2) is used as a part of the ASTM E2058-03 (ASTM International 2003) testing standard. Next to mass-loss and heat-release rate, FPA is also equipped with a CCD camera, which records the experiment. Fuentes and Consalvi (2013) added a second CCD camera that allowed for measurement of flame height. Experiments conducted with FPA were mostly interested in the influence of external factors (*e.g.* openness of the sample holder, air flow, and external heat flux) on the combustion process, with limited interest in the effects of fuel load, packing ration, and surface-to-volume ratio. Dead needles/leaves with their natural moisture content are the only vegetation fuels tested so far in FRA, with mass of the test sample ranging between 4.1 g and 20 g (Schemel *et al.* 2008; Bartoli *et al.* 2009; Consalvi *et al.* 2011; Mindykowski *et al.* 2011; Fuentes and Consalvi 2013).

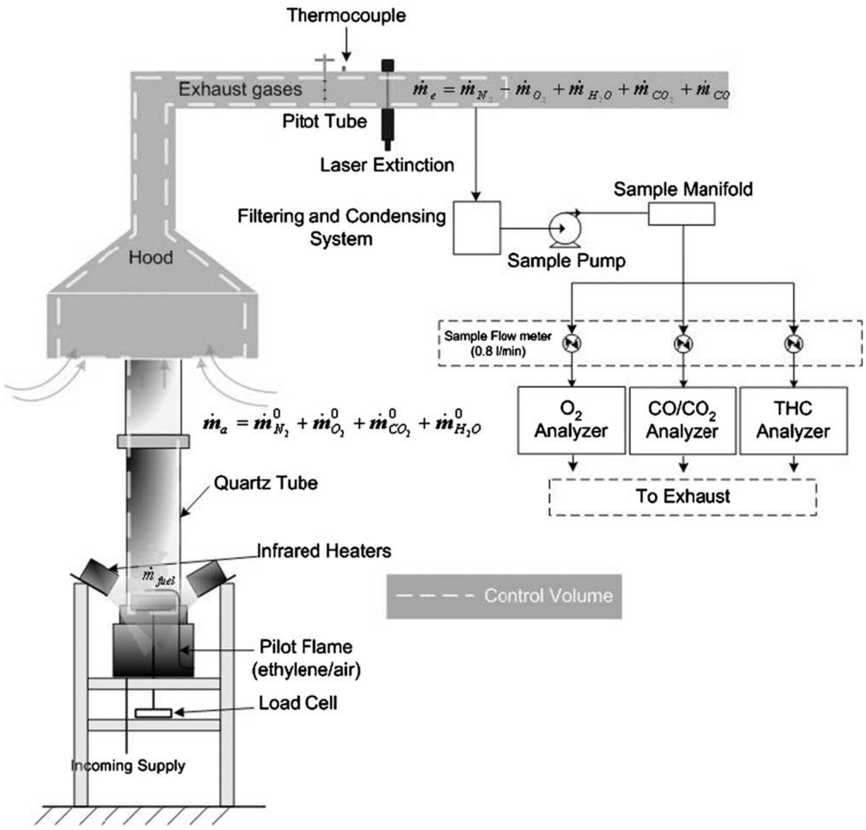

Figure 2. Overview of the Fire Propagation Apparatus (Bartoli *et al.* 2011)

A cone calorimeter is used as part of the ISO 5660-Part 1 (International Organisation for Standardization 2002) and ASTM E1354 (ASTM International 2002) testing standards (White *et al.* 1996; Weise *et al.* 2005a; Dibble *et al.* 2007; Liu *et al.* 2013). Whereas mass is usually held constant in the FPA tests, a single layer of foliage is commonly tested in the cone calorimeter. If an amount of material is manipulated, a single foliage layer is taken as a measure of the amount of the test material. For example, Dibble *et al.* (2007) tested single and “double” foliage layers. Exceptionally, Liu *et al.* (2013) held the testing mass constant (10 g). These experiments were mostly conducted in order to compare species performance (White *et al.* 1996; Weise *et al.* 2005a; Dibble *et al.* 2007; Liu *et al.* 2013) and they were often paired with detailed measurements of intrinsic and extrinsic fuel characteristics. In addition, Weise *et al.* (2005a) investigated seasonal variations in species performance.

These methods generate a continuous record of the mass loss, heat-release rate, exhaust-gas composition, and (if the system is equipped with a camera) flame characteristics. Additional parameters can be derived from this information. Commonly determined parameters include time of ignition, peak of heat release rate, time to peak release rate, total heat released, effective heat of combustion (heat released per unit mass), effective heat of combustion *vs* time, and mass-loss rate (White *et al.* 1996; Weise *et al.* 2005a; Dibble *et al.* 2007). Liu *et al.* (2013) also determined total smoke release, specific extinction area (a measure of the instantaneous amount of smoke being produced per unit mass), rate of smoke release, yield of CO, and yield of CO_2. Due to the remarkably high number of parameters, Liu *et al.* (2013) resorted to principal component analysis and clustering when interpreting their data.

As well as cone calorimetry, mass-loss calorimetry can also be used in order to gain a continuous record of mass loss and heat-release rate (Madrigal *et al.* 2009, 2012, 2013; Possell and Bell 2013; Dehane *et al.* 2015), but this method does not provide the information on the exhaust-gas composition. Instead, it uses a calibrated thermopile positioned in the exhaust duct in order to calculate the energy release rate.

Authors differ in their willingness to interpret data obtained by FPA, cone calorimetry and mass-loss calorimetry in relation to flammability as defined by Anderson (1970) and Martin *et al.* (1994). Whereas White *et al.* (1996) called for further experimentation before relating cone calorimeter results to flammability, Madrigal *et al.* (2012) readily attributed measured parameters to flammability component. According to Madrigal *et al.* (2012), time to ignition is a measure of ignitibility, rate of temperature increase, heat-release rate, peak heat-release rate and time of the peak heat release rate are measures of combustibility; duration of visual flaming, total heat release, and average effective heat of combustion are measures of sustainability; while mass-loss rate and residual mass fraction are measures of consumability.

4.2.3.4. Epiradiator-based tests

These tests employ an epiradiator as a heat source. The position of the device in relation to the sample, the sample amount and the temperatures utilised differ between authors. In the most common assemblage (Figure 3), the epiradiator is positioned horizontally, with the heating surface facing upwards, and the sample is placed directly on the epiradiator surface. A pilot flame is positioned 4 cm above the surface. The pilot ignites a flammable gas mixture, once it is created, without participating in the pyrolysis of the fuel. Determined parameters include ignition delay (time between placing the sample on the epiradiator surface and appearance of flame); flaming duration (time between placing the sample on the epiradiator surface and extinction of the flame, minus ignition delay); and ignition frequency (number of tests in which flame was observed divided by total number of tests performed). Additionally, flaming intensity can be estimated and temperature of the sample can be recorded. The method was initially applied by a French working group (Doat and Valette 1980; Delabraze and Valette 1982; Valette 1990; Alexandrian and Rigolot 1992; Moro 2004). They tested 1 g samples on a 500 W epiradiator with a nominal heat flux of 7 Wcm^{-2} and a surface temperature of 420°C. Individual tests were repeated either 100 or 50 times, and parameters determined were ignition frequency, ignition delay, flaming duration, and intensity. Based on ignition delay and ignition frequency, overall flammability score (*note d'inflammabilité*) was attributed to the material. This note can take a value ranging from 0 (very low flammability) to 5 (extremely flammable), with shorter ignition delay and higher ignition frequency resulting in higher overall flammability note.

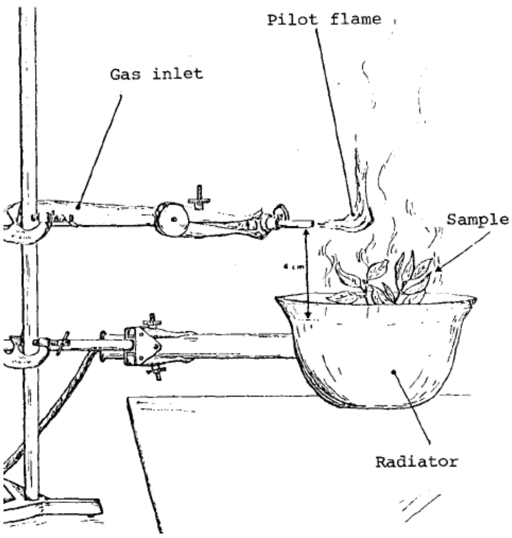

Figure 3. The most common assemblage of the epiradiator-based flammability test (Delabraze and Valette 1982).

As well as being used as a sole method for determining flammability of the material, the same methodology was employed in combination with other methods to provide more complete information on the fire behaviour of the tested samples (*e.g.* Viegas and Viegas 1997; Ormeño *et al.* 2009; Ganteaume *et al.* 2013c; Della Rocca *et al.* 2015). Furthermore, it was used to determine seasonal variation of the measured flammability parameters (Pellizzaro *et al.* 2006b; Pellizzaro *et al.* 2007c).

Besides testing 1 g samples, 10 g samples are also commonly utilised. These samples are often positioned on a wire mesh either directly in contact with the epiradiator surface (Trabaud 1976), or 4 cm above it (Massari and Leopaldi 1998; Alessio *et al.* 2008a; Alessio *et al.* 2008b; De Lillis *et al.* 2009). Furthermore, they employ a higher epiradiator surface temperature (either 620°C or 800°C), and the onset of combustion phases other than flaming is monitored (*i.e.* appearance of smoke, incandescence of the leaves) as well. In addition to time, temperature can also be recorded, providing information on the temperature reached before the onset of the combustion phase of interest. Three to five replications are usually performed when testing 10 g samples.

There are also tests that utilise a lower epiradiator temperature (250°C) with the sample positioned directly on the epiradiator surface (Petriccione *et al.* 2006), or on the wire mesh above it (Della Rocca *et al.* 2015). The epiradiator can also be turned 180° around its horizontal axis and the sample heated from above (Bernard and Nimour 1993).

Whereas most of the previously mentioned studies held the test mass constant, Pausas *et al.* (2012) performed epiradiator-based tests on branch tips while maintaining the length of the branch at between 4.5 and 6 cm. This was also the only study in which information gathered with this testing procedure was used to calculate heat release and mass-loss rate.

Frejaville *et al.* (2013), Della Rocca *et al.* (2015) and Dehane *et al.* (2015) used an epiradiator as a heat source in more innovative experimental setups.

4.2.4. Single-leaf testing

Besides allowing for flammability comparisons between different samples, testing of individual leaves enables researchers to make detailed observations of the combustion process, and to relate observed behaviour to characteristics of the individual leaf, while excluding possible interactions between particles. There are two predominant approaches to testing individual leaf samples: holding a leaf above a known heat source, and exposing a leaf in the open muffle furnace.

4.2.4.1. Exposing leaves above a known heat source

Even though flammability measurement methods using a single leaf held above a known heat source have been employed at least since the late 80s (Bowman and Wilson 1988), the most commonly used method was introduced by Engstrom *et al.* (2004), and further refined by Fletcher *et al.* (2007) and Pickett *et al.* (2009; 2010), and utilised by Shen and Fletcher (2013). These experiments were conducted in order to determine the influence of individual leaf characteristics (thickness, moisture content, perimeter, surface area) and orientation on the observed fire behaviour, as well as to compare species based on their flammability. Furthermore, Pickett *et al.* (2009) employed the same methodology in order to evaluate interactions between two leaves exposed to the same heat source.

Experimental apparatus was designed to closely resemble the conditions of an incoming fire flame front. Samples are attached to a stationary horizontal rod connected to a mass balance. A flat-flame burner (FFB) with 3 cm x 7.5 cm dimensions is placed on a movable platform underneath the sample. FFB provides a stable flame creating a convective heat source to the fuel. Leaf samples are held 5 cm above the burner, where the temperature is 987°C ± 12°C (mean ± standard deviation) and heat flux 80–140 KWm^{-2}. Thermocouples attached to the leaf measure leaf temperature. The whole experiment is recorded with a camera operating in the visual range and an additional IR camera. Records of the temperature profile, visual data and IR data are time-stamped to allow for cross-referencing of information. In addition to determining ignition temperature and ignition delay, flaming duration and maximal flame height, these experiments allow for detailed qualitative observations of leaf behaviour upon exposure to heat sources (*e.g.* bubbling, bursting, fire-brand production). Furthermore, the influence of the leaf shape and orientation on the position and characteristics of the flame can be determined (Engstrom *et al.* 2004; Fletcher *et al.* 2007; Shen and Fletcher 2013). Mass-release rate was first determined in the work of Pickett *et al.* (2010) as they resolved previous problems with low-balance sensitivity. In the same work, Pickett *et al.* (2010) compared species based on their flammability. They used a slope of the regression between the mass released before ignition and the initial mass of moisture as a measure of flammability, with the more flammable species having a lower slope (*i.e.,* at the same initial mass of moisture, more flammable species lose less mass before igniting).

Experiments were also conducted in which a freshly cut small branch was held on top of the known heat sources (Bunting *et al.* 1983; Dickinson and Kirkpatrick 1985), with Dickinson and Kirkpatrick (1985) striving to hold a branch in its natural position and providing both qualitative and quantitative information on the fire behaviour.

4.2.4.2. Muffle furnace tests

In the experiments in which an individual leaf is exposed to the heat of a muffle furnace, fewer details on the combustion process can be gathered in comparison to holding a leaf above a known heat source. In this experimental setup, individual leaves are immersed into the muffle furnace, and ignition delay is monitored. Ignition can be either spontaneous (Montgomery and Cheo 1971) or aided by a spark pilot (Gill and Moor 1996; Grootemaat *et al.* 2015). Furthermore, ignition was considered to occur either at the beginning of pyrolysis (incandescence) (Murray *et al.* 2013) or flaming (Montgomery and Cheo 1971; Gill and Moor 1996). Montgomery and Cheo (1971) did not report the temperature of the open furnace during tests, but stated that furnace was preheated to 750°C; whereas Murray *et al.* (2013) reported that the temperature inside the furnace was 500°C. Gill and Moor (1996) and Grootemaat *et al.* (2015) reported a 400°C muffle furnace temperature during testing.

These experiments were conducted in order to examine the relationship between leaf traits (length, width, thickness, mass, specific leaf area, surface-to-volume ration, moisture content) and leaf flammability. In all cases, ignition delay was taken as a measure of flammability. Gill and Moore (1996) and Murray *et al.* (2013) also compared fresh and oven-dry samples.

4.2.5. Testing ground samples

Testing of ground samples removes any influence of the natural fuel structure on the combustion process. Any observed differences are thus the result of the chemical composition of the samples, with samples usually tested in the form of standardised pellets. Most of the methods that test grounded/pelleted samples are adopted from the field of chemistry. Due to the high number of methods used and their general similarity, only a few of the most commonly used will be briefly presented.

4.2.5.1. Gross heat of combustion measurements

Heat content is an intrinsic physical characteristic of the fuel, and its importance was discussed earlier. Heat content is usually determined with an oxygen bomb calorimeter, and used in combination with other parameters when determining fire behaviour/flammability of the sample (Dimitrakopoulos and Panov 2001; Liodakis *et al.* 2002; Behm *et al.* 2004; Pellizzaro *et al.* 2007b; Ganteaume *et al.* 2011a; Madrigal *et al.* 2012; Ganteaume *et al.* 2013c; Cóbar-Carranza *et al.* 2014; Della Rocca *et al.* 2015). Oxygen bomb calorimetry measures the total amount of energy released by complete combustion of a fuel, a value know as gross heat of combustion, gross calorific value, or higher heating value (Rivera *et al.* 2012).

4.2.5.2. Thermogravimetry (TGA) and differential thermogravimetry (DTG)

TGA/DTG measurements are performed in a specialised device, which enables control over heating rate of the sample and gas flow, while measuring sample mass loss. Vegetation samples are usually tested with a linear heating rate of 10°C/minute, with air acting as a carrier gas, and the air flow being varied (Dimitrakopoulos 2001b; Liodakis *et al.* 2008; Zhang *et al.* 2011). Elder *et al.* (2011) conducted experiments with vegetation fuels using both air and nitrogen as the carrier gas. Depending on the experimental setting, DTG curves of vegetation materials exhibit up to three peaks. The first peak, which is very small, occurs around 100°C and corresponds to dehydration and volatilisation of the sample. The second and third peaks correspond to gas-phase and solid-phase combustion respectively. Their exact position and extent are material-dependent, but for most of the vegetation fuels the peak indicating gas-phase combustion occurs at around 300°C, and the one indicating solid-phase combustion at 400–450°C. In addition to TGA/DTG curves *per se*, Liodakis *et al.* (2008) suggested temperature of the onset of gas-phase combustion as the relative spontaneous ignition temperature and measure of ignitibility; DTG peak heights (for gas-phase and soil-phase peaks) as a measure related to combustion rate; and endset minus onset of DTG peak as a measure defining combustion duration. Liodakis *et al.* (2008) argued that the relative spontaneous ignition temperature is inversely related to the piloted one. They argued that fuels with high spontaneous ignition temperatures have low pilot ignition temperatures, and that they are, as a consequence, highly ignitible. Upon detailed examination of the works to which Liodakis *et al.* (2008) referred when making this statement (Lewis 1990; Liodakis *et al.* 2005; European Commission 1984), no justification for this conclusion could be found. Dimitrakopoulos (2001b) suggested a different interpretation of TGA data. He chose mean volatisation rate (the average percentage of weight loss of the sample); maximum weight-loss rate; onset and end temperature at which a rate of weight loss of 0.002 mgs^{-1} is achieved; and total weight loss at 700°C as parameters. In this work, plant species were grouped on the basis of the mean volatisation rate, with higher mean volatisation rate being attributed to higher ignitibility and combustibility.

4.2.5.3. Relative limiting oxygen index (RLOI)

This method was developed for standardised testing of plastics (ASTM D2863-00) (ASTM International 2000) and it was applied to pellets of vegetation material (Liodakis *et al.* 2008). The test is performed using a Limited Oxygen Index Chamber. The device consists of a 95 mm glass quartz column in which a sample holder is positioned. The gas composition and flow of the oxidative medium passing through the quartz column can be controlled.

Commonly, the amount of oxygen in the oxidative medium is increased until full flaming combustion of the pellet positioned on the sample holder can be observed. This parameter is known as RLOI, and is expressed as volumetric % of the oxygen in the oxidative medium. Liodakis *et al.* (2008) related lower RLOI to higher ignitibility.

Besides the relatively standardised methods, Liodakis *et al.* also developed two methods which are not broadly applied. One deals with testing of pellets (Liodakis *et al.* 2002), and the other with testing of leaf samples in a cage suspended within the furnace (Liodakis *et al.* 2005). As these methods are not commonly used they will not be presented in detail here.

4.2.6. Testing undisturbed samples

Testing recreated fuels allows for standardisation of the fuel parameters. Nevertheless, natural fuels are not homogenous, and litter beds are not composed solely of freshly fallen material, as usually tested in the previously mentioned methods. Testing of undisturbed samples allows for testing of fuels in their natural arrangement under laboratory conditions, thus including influences of the natural variability of the fuel while excluding fluctuations of the environmental factors. Testing of undisturbed samples can be undertaken with emphasis on either flaming or smouldering combustion.

4.2.6.1. Flaming combustion of undisturbed litter beds

This approach is often used and promoted by the working group at Irstea (*Institut national de recherche en sciences et technologies pour l'environnement et l'agriculture*) (Curt *et al.* 2011; Ganteaume *et al.* 2011b, 2013a, 2014). Even though the surface area of a sample, as well as the material, of a fire bench may vary, the basic principle of all the methods employed is the same. A litter sample is collected in a pure stand, or under an individual tree. The sample represents the full depth of the litter profile (down to mineral soil) and it is carefully transported into the laboratory without disturbing its structure. A subsample of predetermined area is placed on the fire bench, positioned on top of the balance, allowing for weight-loss measurements during combustion. Ignition is achieved with a standardised point-ignition source, and only flaming combustion is taken into account. Rulers are used to determine maximal flame height, and thermocouples record the temperature profile of the combustion process. Similarly to previously introduced methods, ignition delay and ignition frequency are taken as ignitibility-related parameters; flaming duration is measured to assess sustainability; flame spread (the number of opposite sides reached by the flame), rate of spread, mean flame temperature and maximum flame height assess combustibility; and the percentage of fuel consumed determines consumability. The Irstea working group commonly uses a domestic fan in order to create a constant wind of 9.8 ± 0.1 kmh^{-1}. As the fuel is heterogeneous, these experiments are coupled with fuel-sorting studies in which subsamples from the same stand are sorted according to their fuel components. Furthermore, as fuels are not standardised, fuel load and bulk density of test samples are determined. Samples are usually oven-dried before testing.

Initially this testing procedure was used to assess differences between stands in relation to stand composition and time since the last fire (Curt *et al.* 2011; Ganteaume *et al.* 2011b), with the time since the last fire accounting for the stand age. Ganteaume *et al.* (2013b) used the same method to compare surface fuels beneath ornamental vegetation, but in this case possible differences in stand age and effects of the age on the fuel characteristics were not accounted for.

4.2.6.2. Smouldering combustion of undisturbed duff samples

As duff usually burns with smouldering combustion, a method that takes into account only flaming would be inappropriate. Thus, when conducting their experiment on the effects of moisture content, mineral content and bulk density on combustion of Ponderosa pine (*Pinus ponderosa* C. Lawson) duff mounds, Garlough and Keyes (2011) used the method developed by Frandsen (1987). In this study, samples were placed into an open-topped burning box of 10 cm x 10 cm x 10 cm inner dimensions, constructed of 2.5 cm thick heat-resistant ceramic board. Dry sphagnum peat moss of the same depth and bulk density as a test sample acted as the ignition transfer medium, and it was in contact with one of the lateral sides of the sample. A glowing resistance coil ignited the peat moss, and the electricity was disconnected once the peat moss supported sustained smouldering. Once the smouldering in the peat moss reached the duff material, it was observed whether or not it continued to spread through the sample. The sample response was recorded binomially as either unburned (≤60% consumption of volume) or burned (>60% consumption).[1] In addition to the binomial response, the percentage consumption was recorded as a continuous variable.

4.2.7. Determining flammability by combining results of different measurements

As flammability is a complex issue, researchers have looked for an approach that would allow them to compare different samples based on the combined effects of all the measured parameters, and so determine their overall flammability. In these endeavours, flammability

[1] In the article by Garlough and Keyes (2011) it is written that "Sample response was recorded as either burned (≤60% consumption by volume) or unburned (>60% consumption)." The obvious mistake in positioning of ≤ and > symbol is corrected in here presented text.

was explained based on measurements of intrinsic and extrinsic properties, direct measurement of flammability, or a combination of both.

Studies that deal with flammability solely on the basis of intrinsic and extrinsic fuel properties include Dimitrakopoulos (2001a), Behm *et al.* (2004), and Cóbar-Carranza *et al.* (2014).

Behm *et al.* (2004) compared pine flatwoods and hardwood hammocks of Florida by measuring extrinsic and intrinsic characteristics of the most abundant understorey plant species. As well as comparing ecosystems, they made a comparison at the species level. They presumed ignitibility to be associated with litter depth, height of the lowest branch, and foliar moisture content; sustainability with fuel-bed bulk density; combustibility with energy content; and consumability with fine-fuel biomass and volatile content.

Cóbar-Carranza *et al.* (2014) applied a similar approach, assessing the effects of *P. contorta* encroachment into Chilean pine (*Araucaria araucana* (Molina) K. Koch) and Antarctic Beech (*Nothofagus antarctica* (Forster) Oerst.) communities. As in the work of Behm *et al.* (2004), foliar moisture content was found to be associated with ignitibility, bulk density with sustainability, and energy content with combustibility. In this work, volatile content was associated with combustibility, and proportion of fine fuel to consumability.

Dimitrakopoulos and Panov (2001) assessed the flammability of different species, taking into account surface-to-volume ratio, heat content, particle density, and total and silica-free ash data of leaves and branches. They named these properties “pyric properties”, and applied hierarchical cluster analysis and canonical discrimination analysis to the data, separating samples into four flammability groups.

In “A handbook of protocols for standardised and easy measurement of plant functional traits worldwide”, Cornelissen *et al.* (2003) also suggested a flammability classification based solely on intrinsic and extrinsic fuel characteristics. Further options were later added in the revised “New handbook for standardised measurement of plant functional traits worldwide” (Pérez-Harguindeguy *et al.* 2013).

Ganteaume *et al*. (2013b; 2013c) also applied hierarchical cluster analysis to determine flammability groups of ornamental vegetation, but in this case parameters included were the result of direct flammability testing, or undisturbed litter samples (Ganteaume *et al.* 2013b) or epiradiator testing of foliage (Ganteaume *et al.* 2013c). Hierarchical cluster analysis was also applied by Liu *et al.* (2013). They included 12 parameters directly measured or calculated from cone calorimeter data to separate 26 species into flammability clusters.

Liodakis *et al.* (2008) based his fuel classification on TGA and LOI results without any further measurements, but he did state that these results are only relative and for comparative use, with further work being necessary in order to assess the importance of the gathered data.

5. Anthropogenic influence and fire in the Mediterranean Basin

According to Pyne (2001), the global fire regime can be divided into three epochs. The first epoch is characterised by a natural fire regime, and ends with humans mastering the ability to set fire. The second epoch is characterised by anthropogenic influence on the fire regime, and lasts until the Industrial Revolution. The last fire epoch is characterised by an industrial fire regime, where fire is not only set, but also supressed. In comparison to other fire-prone areas worldwide (*e.g.* Australia, and areas of North America), the Mediterranean Basin exhibited a higher diversity of human influences during the epoch of the anthropogenic fire regime (Mooney *et al.* 2011; Walsh *et al.* 2010). The history of the Mediterranean Basin makes it impossible to discuss current landscape structure and species composition without taking into account millennia of profound anthropogenic influences. Since the first evidence of domestication and plant cultivation in the Levant (Asouti and Fuller 2012) up until the present day, the Mediterranean Basin witnessed the rise and fall of numerous cultures, kingdoms and empires. As a consequence, unsynchronised periods of high and low anthropogenic pressure on natural resources can be seen throughout the region. Furthermore, historical colonialisation, expansion and trade led to the introduction and naturalisation of plant species in new areas. Species expansion, variations in anthropogenic land use, and pressure on natural resources are well recorded in lake sediments across the region, from the Neolithic influences to the recent introduction of *Eucalyptus* species into the area (*e.g.* Tinner *et al.* 2009; Carrión *et al.* 2010a; Vanniére *et al.* 2011; López-Blanco *et al.* 2012; Morales-Molino *et al.* 2013; Quintana Krupinski *et al.* 2013). In the Mediterranean Basin people influenced landscapes not only through burning, but also through cutting and grazing on non-arable land, clearing, terracing, cultivating, and later on the abandonment and neglect of arable portions (Naveh 1975) (Figure 4).

Although paleobotanic studies conducted in the Mediterranean biogeographical region of Croatia are relatively sparse, those conducted on the islands of Cres (Schmidt et al. 2000) and Mljet (Sadori et al. 2011) reveal a high anthropogenic influence on vegetation composition, with the main features of the current vegetation structure on the island of Cres being a direct consequence of Illyrian and Roman influences.

Figure 4. Abandoned (left) and managed (right) olive (*Olea europaea* L.) orchard. Both photos were taken in the Zadar area. In the left photo, recognisable *O. europaea* trees are indicated, and the remains of a dry wall can be seen at the bottom of the photo.

Following millennia of varying anthropogenic influences, the last couple of decades with their large-scale socio-economic change, introduction of complete fire suppression, and climate change have led to a pronounced shift in fire regimes in the region. Castellnou and Miralles (2009), using the example of Catalonia, identified five successive generations of large fires from the1950s onwards. The first generation (1950–1960) of fires was driven by a decrease in rural populations that led to the abandonment of land. Under conditions of total fire suppression, abandoned farmlands were soon converted into continuous low shrub vegetation. Agricultural land no longer acted as a fuel break, and the fire perimeter was increased. The second generation (1970–1980) of fire was a result of further fuel accumulation on the previously low fuel-load areas, resulting in further perimeter and intensity increase. Since the 1990s, the third generation of fires has emerged. At this point, accumulation of fuel was sufficient to allow for continuous crowning. An increase in fuel load together with increase in heat-wave intensity created conditions that resulted in further growth in fire intensity and perimeter, with decreasing efficiency of fire-suppression activities. The fourth and fifth generation are both encountered from the 2000s onward. The fourth generation is driven by encroachment of urban areas into newly expanded continuous wildlands, creating substantial areas that could be defined as wildland-urban interfaces (WUI). As a consequence, residential and industrial areas are increasingly involved in wildland fires. The fifth generation presents a situation in which, under extreme weather conditions, simultaneous large fires co-occur, overwhelming any fire-suppression organisation (Castellnou and Miralles 2009). A similar change in the fire environment was observed in other areas of the European Mediterranean (Pausas and Fernández-Muñoz 2012;

Viedma *et al.* 2015) and central Europe (Valese *et al.* 2014). This scenario, with slight modifications, could be applied to the study area as well. In the study area, similar to other regions of the Mediterranean Basin, conversion from landscapes with high patchiness of habitats to landscapes with large, uninterrupted forested areas was largely facilitated by afforestation and reforestation efforts. At the end of the 19^{th} century, upon realisation of the potential negative consequences of deforestation, intensive reforestation and afforestation efforts started in the European Mediterranean. Pioneer pine species, such as Aleppo pine (*Pinus halepensis* Mill.) and maritime pine (*Pinus pinaster* Aiton), were promoted under the presumption that they were going to facilitate re-establishment of late-succession hardwoods (Pausas *et al.* 2004; Tekić *et al.* 2014). Their ability to spread naturally outside the established plantations facilitated the establishment of large continuous areas covered in pine forests. Nevertheless, there is no field evidence of *P. halepensis* stands remaining unaffected by fire for long enough to be replaced by late-succession species (Tekić *et al.* 2014).

As in the whole of the Mediterranean Basin, the species composition of the study area is highly affected by human influences. As such, when giving the description of main characteristics and adaptation strategies of the studied species, origin and spread of allochthonous species will be addressed as well. Furthermore, as species composition is largely influenced by anthropogenic promotion of individual species, screening of species for their influence on probability of fire initiation and spread, and further promotion of species that reduce this probability, represent a sensible management option in the study area.

6. Species of interest and their adaptations to coping with drought

In Section 1.3, fuel characteristics that influence fire behaviour/flammability of vegetation fuels were introduced. While influencing fire behaviour, some of these characteristics are considered to be the result of adaptation to other environmental stress factors. As frequent fires often co-occur with seasonal lack of precipitation, high insolation and high temperatures, it is impossible to assess the relative importance of these factors as selective forces. This problem prompted a certain amount of debate in the scientific community, as traits that are considered to be fire-adaptive by fire ecologists are often considered to be an adaptation to other stress factors by scientists who attribute less value to fire as a selective force (*e.g.* Bradshaw *et al.* 2011a; Bradshaw *et al.* 2011b; Keeley *et al.* 2011; Anonymous 2011). In this work, no attempt will be made to determine which selective force is responsible for the existence and persistence of any given trait or adaptation. In the following section, the characteristics of the species of interest and their adaptations to cope with drought as a prevailing environmental stress factor will be introduced. Additionally, for underutilised and neglected species, more information on their potential uses will be provided. As relationships between fuel characteristics and fire behaviour have been previously addressed (Section1.3), in the following section no attempt will be made to associate species characteristics and adaptation mechanisms to fire behaviour.

6.1. Strawberry tree (*Arbutus unedo* L.)

A. unedo is a circum-Mediterranean species, its natural area of distribution reaching out of the Mediterranean zone to the north of the Iberian Peninsula, going along the west coast of France, occurring in Brittany and reaching its septentrional limit in the northwest of Ireland (Sealy 1949). It is an evergreen, slow-growing species, which grows in bush form in drylands, but can reach up to 9 metres in height in less arid areas (Sulusoglu *et al.* 2011). Seeds germinate well, but small and slow-growing seedlings are sensitive to shading, drought and waterlogging, resulting in relatively low seedling recruitment (Sealy 1949; Gugliuzza *et al.* 2013). Early in the plant's development, lignotubers are formed, allowing for vigorous resprouting after disturbance (Mesléard and Lepart 1989; Rosas *et al.* 2013). Furthermore, *A. unedo* was reported to form a dimorphic root system, enabling it to use different water resources depending on their availability (Filella and Peñuelas 2003; Barbeta *et al.* 2015).

A. unedo is characterised by a long reproductive cycle lasting approximately 12 months, with flashy barriers and inflorescences, arranged as corymbose panicles with 15–25 flowers, co-occurring on the plant between October and December. The long reproductive cycle and relatively wide distribution range make it a good species for studying the influence of climate and distance from the sea on the production and development of fruit and seeds (Chiarucci *et al.* 1993). Furthermore, flowers and fruits of *A. unedo* represent a valuable food source for insects and frugivores, and thus the presence of this species was shown to increase the conservation value of a habitat (Gurel *et al.* 2008; Sarmento *et al.* 2010; Virgós *et al.* 2010). The fruits are also used in human nutrition. Although sometimes consumed fresh (Redzic 2006; Menendez-Baceta *et al.* 2012), they are usually processed into jams, jellies, marmalades and alcoholic beverages (Soufleros *et al.* 2005; Cavaco *et al.* 2007; González *et al.* 2011). In addition to the fruits being used as a food source, all of the plant's parts are reported to be used in traditional medicine for treating a wide variety of disorders (Ballero *et al.* 2001; Loi *et al.* 2004; González-Tejero *et al.* 2008), with contemporary research demonstrating its medicinal potential (Afkir *et al.* 2008; Bnouham *et al.* 2010; Mendes *et al.* 2011; Pavlović *et al.* 2011).

Based on the leaf morphology *A. unedo* exhibits only a low degree of sclerophylly (Gratani and Ghia 2002b). Even though leaves of *A. unedo* have well-developed palisade parenchyma, and their thickness is similar to that of other evergreen sclerophyllous species, they are short-lived, and bigger, with a lower leaf mass per area (higher specific leaf area). *A. unedo* exhibits a higher level of control of leaf angle and orientation in comparison to other evergreen sclerophyllous species. As such it can be considered to be on the borderline between drought semi-deciduous and sclerophyllous species (Gratani and Bombelli 1999; Gratani and Bombelli 2001; Gratani and Ghia 2002a). Leaves of *A. unedo* contain epicuticular waxes and oils on their surface (Koukos *et al*. 2015).

When discussing leaf morphology it should be noted that a high variability in leaf sizes is reported in the literature (Lopes *et al.* 2012), as well as being found in the study area. In the study presented here, the average leaf size of an *A. unedo* sample containing only mature leaves ranged from 5.81 cm^2 to 21.16 cm^2 (Figure 5).

In *A. unedo,* drought induces a strong stomatal response, with only a limited variation in leaf water potential, a response typical for total or partial-isohydric species (Raschke and Resemann 1986; Rhizopoulou and Mitrakos 1990; Ripullone *et al.* 2009; Raimondo *et al.* 2015). Besides the short-term responses, prolonged exposure to drought can result in long-term down-regulation of stomatal conductance (*i.e.* lack of recovery despite increased water availability) and allometric adjustments to the plant structure resulting in a decreased leaf-area index (Ripullone *et al.* 2009). Furthermore, *A. unedo* was shown to exhibit an intermediate decrease in photosynthetic activity during colder than usual winter conditions (Varone and Gratani 2007).

Figure 5. Strawberry tree (*Arbutus unedo* L.) Branches (left) and leaves (right), collected within the same stand in Istria. Photos present the terminal branch of a young (uppermost), intermediate (middle) and mature (lowermost) individual. Leaves in a row belong to the same terminal branch on their left. Similar trends of decreasing leaf size and change in branching pattern with increasing plant age were observed within the other sampling sites as well.

In the study area, *A. unedo* was found in various communities and fuel layers. It was found as a codominant overstorey species in recently burned forest, understorey shrub in mature oak–pine forest, a dominant species in dense shrubland, coexisting with other species in low-density shrublands, and as individual shrubs on steep slopes and ridges.

6.2. Carob (*Ceratonia siliqua* L.)

Unlike *A. unedo*, which is considered to be native to the study area, *C. siliqua* was brought there, presumably as a crop tree. With the earliest pollen findings in Israel dating to the Würm period, it is thought that *C. siliqua* originated in the eastern Mediterranean/Arabian Peninsula (Talhouk *et al.* 2005) and was further spread through the Mediterranean Basin by Greeks and Arabs (Batlle and Tous 1997). It is mentioned in Talmud, as well as by Theophrastus (370–287 B.C.) and Columella (4 B.C.–A.D. 65). In Croatia, early evidence of *C. siliqua's* presence is found in the lake sediment of the Malo Jezero (island of Mljet), which can be roughly dated to the period between 1,300 B.C. and 0 A.D. (Jahns and Van Den Bogaard 1998).

In the southern part of the study area, distribution of *C. siliqua* is dependent on whether or not it was locally introduced. Once introduced, volunteer individuals and naturalised populations can often be found. Absence of *C. siliqua* in the northern part of the study area can be attributed to its sensitivity to cold, which is reported in the literature (Christodoulakis 1992; Shepperd 2008), as well as confirmed by local landscape managers. In addition to its frost sensitivity, the species is also very sensitive to waterlogging and excess water during early seedling development (Batlle and Tous 1997; Orwa *et al.* 2009). Furthermore, as it is very sensitive to shading, it can be found either as an overstorey tree or as individual trees/shrubs in open areas. In the study area, trees of considerable size were found on very shallow soil profiles.

C. siliqua is small evergreen tree, belonging to the legume family (*Fabaceae*), usually reaching 8–15 metres, but can grow up to 20 metres under ideal climatic conditions. Like *A. unedo*, it is capable of resprouting after disturbance. It is a polygamo-trioecious species which exhibits high plasticity in inflorescence and flower characteristics (Figure 6). Nearly all cultivated varieties are dioecious, but trees with both sexes on the same plant as well as completely hermaphroditic flowers can be found in nature (Shepperd 2008). Individual flowers, arranged spirally along the raceme axis, are reddish-green with no corolla, and with a disc-shaped calyx tube with nectar. Its reproductive cycle is similar to that of *A. unedo*, but slightly shorter. Flowering occurs in mid-September to mid-November, and 10–11 months are required for complete fruit development (von Hasalberg 2000). 10–20 centimetre-long composite pinnate leaves usually have 4–10 leaflets. Leaflets are 3–7 centimetres long, ovate to elliptic. *C. siliqua* leaves have a characteristic dark green adaxial leaf surface, whereas the abaxial leaf surface is pale (Batlle and Tous 1997). Leaves are usually retained up to 2 years (Lo Gullo *et al.* 1986).

Figure 6. Carob (*Ceratonia siliqua* L.) inflorescences: hermaphrodite (left), male (middle), and female (right). Inflorescences with a mixture of both male and female flowers can also be found in the nature, but they are less common.

C. siliqua fruits are large (10–30 cm long, 1.5–3.5 cm wide, and about 1 cm thick), indehiscent pods with pulp accounting for around 90% of the dry pod weight, and seeds for 10%. *C. siliqua* pulp is rich in sugars (48–56%), tannins (18–20%) (Batlle and Tous 1997) and proteins (5.03–6.8%) (Coit 1951; El-Shatnawi and Ereifej 2001). Due to its high nutritional value, *C. siliqua* is commonly used as a food and fodder crop, with local cultural differences in the extent of its usage and the final products being consumed. In addition to the pulp, the seeds are also a highly valuable food source, with the germ meal containing 50% protein, and seed endosperm being a source of the galactomannan carob bean gum (CBG). CBG is a commonly used additive in food production, with its usage ranging from an adhesion agent in juices to a thickening agent in jams. It also has various industrial uses. The seed coat can be utilised as a leather tanning agent. *C. siliqua* timber was traditionally used for making utensils, as it is hard and close-grained, as well as for the production of slow-burning charcoal. Furthermore, the species is valued as a shading ornamental in dry climates, and in the wild it provides shelter and food for browsing animals (Batlle and Tous 1997). Despite its broad spectrum of potential uses, *C. siliqua* is rarely utilised in the study area.

C. siliqua develops an extensive root system, enabling it to access deep-soil water resources. Drought conditions further stimulate vertical root growth (Batlle and Tous 1997). Before Missbah El Idrissi *et al.* (1996) isolated nodulating bacteria in a Moroccan population of *C. siliqua*, it was thought that it did not form a symbiosis with nitrogen-fixating bacteria.

In contrast to *A. unedo,* which initially responds to drought by stomatal closure, *C. siliqua* predominantly responds to drought by decreasing plant water potential (fast turgor pressure change) and compensates for water loss by more efficient water extraction from the soil. *C. siliqua* could be characterised as a predominantly anisohydric species, coping with drought through drought avoidance by employing a water-spending strategy. As such, leaves of *C. siliqua* maintain relatively high conductance, show pronounced recovery of pre-dawn leaf-water potential, and retain a relatively high water content through the growing season, despite exposure to drought (Lo Gullo *et al.* 1986; Salleo and Lo Gullo 1989; Lo Gullo *et al.* 2003). Nevertheless, stomatal response will be triggered in the event of prolonged and severe drought (Ramalho *et al.* 2000). Despite its pronounced response to severe drought, *C. siliqua* is very well adapted to coping with the weather extremes of the Mediterranean Basin (*e.g.* Lo Gullo *et al.* 2003; Ouzounidou *et al.* 2012).

Even though rigid, leaves of *C. siliqua* do not possess all the anatomical characteristics of xeromorphic leaves. Besides the leaves of *C. siliqua* being unusually big for the communities in which they are encountered, they also have a much thinner cuticle (1/2 to 2/3 thinner), and their spongy parenchyma has large intercellular spaces and few fibres surrounding vascular bundles; thus according to Lo Gullo *et al.* (1986) they can be considered anatomically as mesophytes. Nevertheless, leaves of *C. siliqua* do exhibit some morphological adaptations to drought such as epicuticular wax on both sides of the leaves, and leaf rolling under severe drought (Kolyva *et al.* 2012). Furthermore, lipid droplets may be localised in leaves of *C. siliqua*, but in smaller amounts than in *O. europaea* (Christodoulakis 1992).

In comparison to all the other species involved in the study, *C. siligua* has by far the biggest leaves. Nevertheless, in the study presented here, leaflets and stalk parts were treated as individual particles. The reason for doing so lies in the fact that individual leaves are separated into leaflets and stalk upon abscission (the reason for considering a leaflet as a constructing particle in the case of leaf litter). Furthermore, individual leaflets are separated in space, allowing for heat and air flow between then, so justifying usage of the leaflet as a constructing particle in the case of fresh leaves.

6.3. Olive (*Olea europaea* L.)

Whereas the origin of *C. siliqua* is currently not in question, there are divided opinions on the origin of *O. europaea*. The classical point of view (Figure 7) states that *O. europaea* was first cultivated in the Middle East, and spread through the Mediterranean Basin as a cultivated tree (Loussert and Brousse 1978; Diez *et al.* 2015).

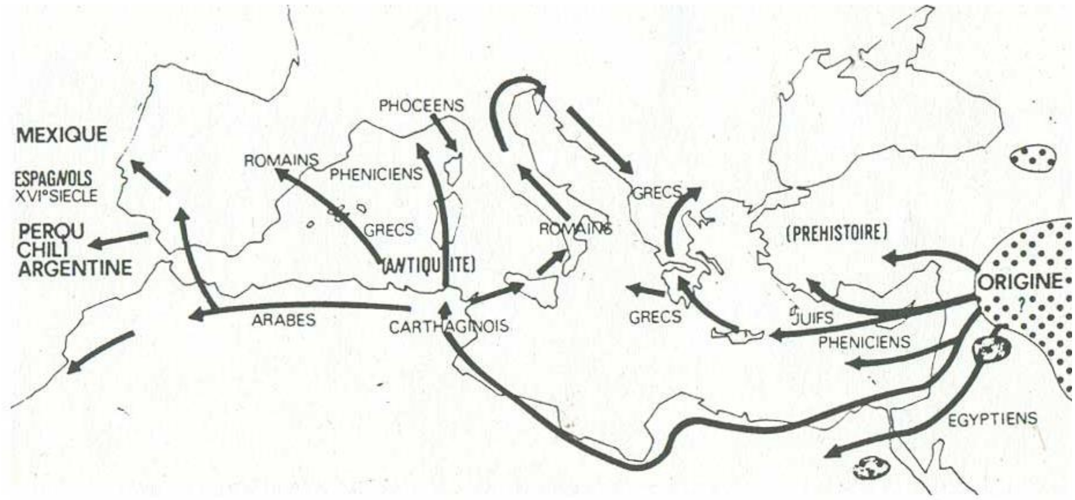

Figure 7. Origin and expansion of olive (*Olea europaea* L.) Adapted from Loussert and Brousse (1978)

During the last few decades this point of view has been challenged, and questions of the number of domestication events, their time and place, and their relative importance remain unanswered (Besnard and Bervillé 2000; Breton *et al.* 2009; Besnard *et al.* 2013; Diez *et al.* 2015). Present populations of *O. europaea* in the Mediterranean Basin are a mixture of wild type, cultivated varieties and secondary feral forms (Carrión *et al.* 2010b) with indications of their additional crossing (Besnard and Bervillé 2000). Notwithstanding the debate on the origin of *O. europaea,* when the whole Mediterranean Basin is taken into consideration, there is currently no doubt that *O. europaea* was introduced into the study area as a cultivated tree (Besnard and Bervillé 2000; Carrión *et al.* 2010b). Furthermore, the current distribution range, presence and genetic profile of *O. europea* have been strongly affected by millennia of cultivation, anthropogenic promotion and spread. Cultivation and selection enabled *O. europaea* to be grown on higher altitudes and latitudes, with the current area of distribution remotely indicating that of the wild variety (Carrión *et al.* 2010b). Due to the high promotion of *O. europaea* by humans, the increase of *O. europaea* pollen concentration in sediments is used, when cross-referenced with other historical information, as an indicator of higher anthropogenic presence (Morales-Molino *et al.* 2013). In the Mediterranean Basin it is often related to Hellenic and Roman influences (Quintana Krupinski *et al.* 2013), with the Romans strongly encouraging cultivation of *O. europaea* (Jiménez-Moreno *et al.* 2013). In the study area, evidence of the extensive cultivation of *O. europaea* date back to the Bronze Age (Jahns and Van Den Bogaard 1998). Despite millennia of cultivation, secondary volunteer populations (*i.e.* populations which are the result of seed dispersal out of orchards and successful seedling recruitment) are relatively sparse in the study area, especially in the northern part. Most of the unmanaged *O. europaea* trees can be related to abandoned olive groves. It should, however, be noted that in other parts of the world (*e.g.* Australia) *O. europaea* is considered to be an invasive species (Besnard *et al.* 2007).

O. europaea is an evergreen plant with wild types that usually grow as shrubs and tree-like cultivated forms (Carrión *et al.* 2010b). It is known for its longevity, and trees older than 1,000 years are not uncommon. Old trees, if their height is not controlled by pruning, can reach up to 20 metres. Similarly to *A. unedo, O. europaea* builds lignotubers and readily resprouts after disturbance (Loussert and Brousse 1978). *O. europaea* trees have an extensive root system which adapts to soil properties and water availability, expending up to several metres deep with a large proportion of the root system also spreading horizontally to the ground-exploring topsoil layer. The root system is sensitive to waterlogging and hypoxia. Flowers are small, hermaphroditic or functionally staminate. Up to 40 flowers are arranged on a paniculate inflorescence positioned in the leaf axis of the previous year's shoot (Fernández 2014). They are usually pollinated by wind (Hashmi *et al.* 2015). The time required from pollination to fruit ripening is much shorter than for the two species previously introduced. Flowering usually occurs in April, and harvesting of fruits for oil production starts at the beginning of November. Flowering and fruiting are highly sensitive to temperature, requiring a short period of vernalisation for undisturbed flower development. Even though a certain amount of fruit is set in the area where the chilling period is shorter than in the Mediterranean Basin (*e.g.* some parts of Argentina), the shorter chilling period results in a reduced yield. Due to the temperature dependency of its reproductive cycle, it is reasonable to presume that climate change will influence future yields (Fernández 2014).

O. europaea is one of the most important fruit-tree crops of the Mediterranean Basin. EU–Mediterranean together with Turkey accounted for 70% of the worldwide production of olive oil in 2011 (FAO 2014). Olive oil is the most important product derived from *O. europaea,* with as much as 90% of annual production being used for oil extraction (Hashmi *et al.* 2015). Only a small percentage of the fruit is grown for direct fruit consumption. Besides being valuable in human nutrition, olive oil was historically important as lamp fuel, as it burned with little to no smoke. Furthermore, olive oil, along with other parts of the plant, played an important part in cultural/religious ceremonies. *O. europaea* was an important feed source, and its wood was a valued fuel, as it can burn when fairly wet due to the substantial amounts of oil it contains (Breton *et al.* 2009). Moreover, all parts of *O. europaea*, including the seed oil and bark, were widely used in traditional medicine, and they contain numerous secondary metabolites, which are currently being investigated for their potential medicinal uses (Hashmi *et al.* 2015).

Leaves, which are retained on the tree for up to 3 years (Fernández 2014), are small and thick, shiny green on the adaxial leaf surface, and pale and hairy on the abaxial leaf surface (Christodoulakis 1992). They have waxy cuticles and contain high amounts of lipids (Fernández 2014). The palisade parenchyma is well developed, with two to three layers of densely packed elongated cells underneath the upper epidermis, with some cultivars having a single short cell layer of palisade parenchyma next to the lower epidermis. Leaf morphology is strongly affected by environmental conditions, with leaves developed under drought conditions having higher thickness, cell and tissue density (Bosabalidis and Kofidis 2002; Fernández 2014). According to results obtained by Christodoulakis and Mitrakos (1987) *O. europaea* is one of the species with the smallest and thickest leaves among the evergreen broadleaved phanerophytes of Greece. Nevertheless, it should be noted that leaves of the varieties commonly grown in the study area tend to be substantially bigger than that reported by Christodoulakis and Mitrakos (1987). In the study presented here, the average leaf size of the samples gathered that originated from unmanaged trees was 4.01 cm^2, and values higher than these were measured for autochthonous Croatian varieties (Kauf 2008).

Leaves of *O. europaea* also roll and adjust their position in order to reduce the amount of intercepted radiation. Leaf ageing reduces their ability to control not only their position, but also their stomatal closure (Fernández and Moreno 1999).

Unlike *C. siliqua* and similarly to *A. unedo*, in times of drought *O. europaea* resorts to early stomatal closure, thus reducing water loss. It initially acts as an isohydric species that adopts a water-saving strategy in order to cope with drought. Under non-extreme drought conditions, stomatal closure suffices for maintaining plant hydration. However, as drought intensifies, osmotic adjustments will follow (Fernández *et al.* 1997; Lo Gullo *et al.* 2003; Torres-Ruiz *et al.* 2013). Unlike *A. unedo*, *O. europaea* is known to be able to reach very low leaf-water potential values, as well as a remarkably low moisture content without excessive damage to the tissues (Lo Gullo and Salleo 1988; Lo Gullo *et al.* 2003). Furthermore, restoration of leaf conductivity, water potential and photosynthetic capacity upon termination of drought conditions is very fast (Torres-Ruiz *et al.* 2013).

6.4. Aleppo pine (*Pinus halepensis* Mill.)

The origin of *P. halepensis* is as unclear as that of *O. europaea*. Whereas some authors think that *P. halepensis* was brought to the Balkan by Roman settlers (Jahns and Van Den Bogaard 1998), others claim that it is native to the southern part of the study area (*i.e.* on the mainland south of the city of Split, and on all the islands south of the island of Krapanj) (Tekić *et al.* 2014). Even if the latter claim is true, *P. halepensis* would present as part of the natural vegetation only on the southernmost study site. The current distribution of *P. halepensis* in the study area is largely influenced by its utilisation for afforestation and reforestation since the late 19th century. Its ability to produce large amounts of light seeds and spread outside the initial area of established plantations, together with the production of large amounts of dead needles, were considered positive characteristics (Prgin 2005). However, there are indications that their ability to spread outside the initially intended area might make them invasive (Lavi *et al.* 2005; Ganatsas and Thanasis 2010; Osem *et al.* 2011); that the large production of needles increases the fine dead fuel load, potentially increasing fire danger; (Španjol *et al.* 2011) and that allelopathic compounds it contains might delay secondary succession (Fernandez *et al.* 2006).

Within the study area, depending on the ability of *P. halepensis* to spontaneously spread, three regions are defined: (i) the northernmost part in which *P. halepensis* successfully grows in plantations and it is not able to naturally spread; (ii) the area of northern and middle Dalmatia where *P. halapensis* is spreading outside the plantations, and (iii) the area where it is considered to be naturally present. A case study conducted in the wider area of Šibenik (belonging to the second group based on the potential of *P. halepensis* to spread) indicated that introduction of *P. halepensis* to the islands of Zlarin and Žirja, followed by its invasive spread, led to suppression of the native vegetation, with currently 74% and 66% of the area of the two islands respectively being covered by a vegetation type completely dominated by *P. halepensis* (Tekić *et al.* 2014).

The *P. halepensis* tree can reach up to 32 metres in height (Mahmood and Athar 1997). It is the only obligate seeder and gymnosperm included in the study. *P. halepensis* has serotinous cones, and its post-fire regeneration depends completely on the canopy-stored seed bank. Next to serotinous cones, it also produces cones that open regularly in warm weather, allowing for spread into new areas in the absence of fire. It is a relatively short-lived tree (up to 125 years) with almost no recruitment under the forest canopy, and thus fire plays an important role in the stand rejuvenation (Ne'eman *et al.* 2004). *P. halepensis* is monoecious when adult, a wind-pollinated species that flowers in late winter to early spring, depending on the climatic conditions and genotype (Weinstein 1989; Ne'eman *et al.* 2004). There are also indications of additional autumn flowering (Pardos *et al.* 2003). Cone maturation can last up to 28 months after pollination (Goubitz *et al.* 2002). Needles usually appear in pairs, with a semi-circular cross-section and morphological characteristics, including epicuticular waxes, similar to other pine species (Soda *et al.* 2000; Matas *et al.* 2003; Kivimäenpää *et al.* 2010). It stores significant amounts of terpenes in the needle resin ducts, which presumably play an important role in sealing leaf wounds and act like a pest barrier (Pasqua *et al.* 2001; Blanch *et al.* 2009). In comparison to stone pine (*Pinus pinea* L.), the resin ducts of *P. halepensis* are more numerous (5–7 in comparison 0–2), and always present (Pasqua *et al.* 2001). Despite being a terpene-storing species, *P. halepensis* also emits a substantial amounts of terpenes, thus influencing formation of tropospheric ozone and aerosols (Blanch *et al.* 2007). In addition to terpenes, the needles contain significant amounts of phenolic compounds, with the composition and concentration of secondary metabolites depending on environmental conditions, season and provenience, as well as the age of the individual in question (Kaundun *et al.* 1998; Pasqualini *et al.* 2003; Llusià *et al.* 2006; Blanch *et al.* 2009; Fernandez *et al.* 2009; Djerrad *et al.* 2015).

Resins, which comprise the most important non-timber product of *P. halepensis* (Ghanmi *et al.* 2007), are tapped from tree trunks. Production of resins has substantially decreased due to socio-economical change since the 1960s, with Greek production (Greece being the biggest producer of *P. halepensis* resin in Europe) at the beginning of the 21st century being around one third of that in 1965 (Spanos *et al.* 2010). *P. halepensis* resin had various uses in traditional medicine (Boulâacheb 2010) and confirmed antimicrobial effects (Ghanmi *et al.* 2007). In addition to its traditional uses, *P. halepensis* resins recently regained attention as a renewable source of chemical compounds for industry (Favvas *et al.* 2015), ranging from petrochemical (Tsanaktsidis *et al.* 2013) to cosmetic (Djerrad *et al.* 2015). Furthermore, *P. halepensis* is used as a food source by common crossbills (*Loxia curvirostra* L.) and European red squirrels (*Sciurus vulgaris* L.) (Mezquida and Benkman 2005). In the study area, despite numerous potential uses, *P. halepensis* stands are not commercially exploited, and substantial areas lack management. Despite its potential invasiveness, it is generally accepted that *P. halepensis* can add recreational value to an area (Tekić 2013).

P. halepensis is deep-rooting, pioneer, shade-intolerant, drought-avoiding species which can be considered predominantly isohydric, as it responds to drought conditions by closing stomata, and retains a relatively high water potential despite increasing drought (Baquedano and Castillo 2007; Klein *et al.* 2011). Even though *P. halepensis* exhibits high photoinhibition during summer drought, it recovers quickly and completely within a short period of time. Furthermore, it has been shown to retain high photochemical efficiency during winter, despite the low temperatures (Baquedano and Castillo 2007). Additionally, in comparison to Holm oak (*Quercus ilex* L.) it maintains higher water content during the whole growing season (Alessio *et al.* 2008a).

6.5. Pomegranate (*Punica granatum* L.)

Today's Iran is generally accepted as the origin of *P. granatum*. Nevertheless, there are differences is opinion regarding the size and position of the initial, natural distribution area. *P. granatum* has been cultivated for millennia, with evidence of its cultivation being found in Uruk, Mesopotamia, dated to the 4th millennium B.C. Spread of *P. granatum* out of Mesopotomia can be considered to be similar to that of *O. europaea* according to the classical point of view (Figure 7), with additional spread towards China (Ward 2003; Stover and Mercure 2007). The current area of pronounced presence of naturalised populations extends through the southern Caspian belt and north-eastern Turkey, extending along the Mediterranean coast as far as Montenegro in the east (Xhuveli 2012), and the western Himalayan region of Indian to the west (Narzary *et al.* 2010). *P. granatum* is cultivated in Iran, Afghanistan, India and countries of the Mediterranean Basin, and to a lower extent in the USA, China, Japan and Russia (Narzary *et al.* 2010). It was neglected for a long period of time, but due to its confirmed positive effects on human health there is rising interest in this tree crop. It is estimated that worldwide 1.5 million tons of *P. granatum* fruits are produced annually (Ajal *et al.* 2015), with fruit production being especially important in Iran, Tunisia, Morocco, Turkey and Spain (Stover and Mercure 2007; Mansour *et al.* 2011; Ajal *et al.* 2015). Studies from the island of Mljet indicate that *P. granatum* was introduced into southern parts of Croatia later than any other species included in the study (Jahns and Van Den Bogaard 1998).

P. granatum is the only deciduous species included in the study. It grows as a shrub or a small tree, not exceeding 7 metres in height. Unmanaged plants develop numerous trunks, produce numerous suckers, and resprout after disturbance. Orchard trees are usually trained to a single trunk (Stover and Mercure 2007). Red to red-orange flashy flowers are up to 4 cm wide, appearing in clusters of up to five from April to November, depending on the climatic conditions. They can be both self-pollinating and cross-pollinated, with most cultivars being self-pollinating. Pollination can be aided by insects and hummingbirds. Its fruit, a very large fleshy berry, contains many arils (seeds surrounded by pulp) (Ward 2003; Stover and Mercure 2007; Narzary *et al.* 2010). In the study area, flowering usually occurs from late May to the end of July, and fruits are usually harvested in October and November.

P. granatum leaves are small and narrow with a short stem, usually oblong, obovate or elliptic-lanceolate, with apical foliar nectary on the leaf tip (Turner and Lersten 1983; Narzary *et al.* 2010). They are very thin, and dorsiventral with a simplified leaf structure (Keating 1984) typical of mesophytes. Underneath the adaxial epidermis a single layer of palisade cells is present, followed by two layers of spongy mesophyll and the lower epidermis. Within the leaves, crystalline structures can be found (Lersten and Horner 2005). Even though the adaxial surface of the leaves is quite shiny, no information could be found on the presence or absence of epicuticular lipids or waxes. Furthermore, there are no indications of *P. granatum* leaves storing or emitting any of the compounds that might directly alter their fire behaviour. It should, however, be taken into consideration that, in comparison to other species included in this study, much less information is available on the physiological and morphological characteristics of *P. granatum*. *P. granatum* invests little resources in its leaves, and we observed that a substantial proportion of the leaves are readily abscised under severe drought conditions.

Similarly to most of the species previously introduced, *P. grantum* initially responds to drought by adjusting stomatal opening and decreasing leaf conductivity (isohydric response). Prolonged drought triggers osmotic adjustments resulting in decreased leaf water potential, with both leaf conductance and water potential recovering quickly upon ending of drought (Intrigliolo *et al.* 2011; Rodríguez *et al.* 2012). In comparison to *O. europaea*, a species that exhibits similar behaviours, *P. granatum* does not reach such a low leaf water potential or level of leaf dehydration (*e.g.* Fernández *et al.* 1997; Torres-Ruiz *et al.* 2013).

P. granatum is almost exclusively grown for its fruits, which are mostly consumed fresh or used for juice production. The fruits are valued for their taste as well as for their chemical composition, as they contain numerous compounds that exhibit positive effects on human health (Viuda-Martos *et al.* 2010). Besides consumption of fresh arils or extraction of juice, fruit peel and oil extracted from the seeds were shown to have potential pharmaceutical uses (Schubert *et al.* 1999; Syed *et al.* 2007; Joseph *et al.* 2012). Flowers were also shown to relieve some medical problems (Goshtasebi *et al.* 2015). Due to its antimicrobial properties, the fruit peel and seed oil have been considered as potential food additives, or as part of the treatment of bacterial infections caused by antibiotic-resistant bacteria (Al Laham and Al Fadel 2013; Mahajan *et al.* 2015). Alternative uses of *P. granatum* include ornamental use, leather tanning, textile dying (Stover and Mercure 2007) and usage in cosmetics (Aslam *et al.* 2006). Detailed information on the potential uses of *P. granatum* can be found in a review by Teixeira da Silva *et al.* (2013).

In Croatia, *P. granatum* is mostly present as a minor fruit in traditional plantations, with fruits being sold in a nearby local market for fresh consumption (Gadže *et al.* 2012). It was traditionally planted in home gardens and/or mixed orchards. Similarly to *O. europaea*, most of the unmanaged plants can be attributed to abandoned groves with limited naturalised populations, mostly in the southernmost part of Croatia in sun-exposed, dry areas.

Figure 8. Typical damage found on pomegranate (*Punica granatum* L.) fruits in the southernmost part of the study area. Fruits were occasionally completely hollow.

In the northernmost part of the study area, *P. granatum* is grown exclusively as an ornamental. The duration of the vegetation period in this region suffices for physiological ripening of the seeds (*i.e.* seeds are capable of germinating), but suboptimal climatic conditions result in fruits that are small and taste unpleasant. Furthermore, although little information is present on *P. granatum* as a wildlife food, due to damage seen on the fruits it can be presumed that it is consumed by birds as well as mammalian frugivores (Figure 8).

6.6. Holm oak (*Quercus ilex* L.)

Q. ilex is a circum-Mediterranean species present in the area at least since the Miocene epoch. Throughout time, its dominance and area of distribution have varied in relation to local climatic conditions and anthropogenic influences (Barbero *et al.* 1992). Its current natural distribution range includes the larger part of the Mediterranean Basin and the inland Iberian Peninsula (Figure 9). It is distributed through the coastal area of Croatia, where it comprises an important element of the potential natural vegetation (Nikolić 2015).

Q. ilex is a long-lived evergreen tree that can be found in shrub form under unfavourable conditions, and in early succession stages (Barbero et al. 1992). Similarly to A. unedo, it has a dimorphic root system (Barbeta et al. 2015) and exhibits a high variability in leaf traits. Niinemets (2015) examined leaf characteristics of 79 *Q. ilex* populations across the current species distribution range, and found trait variations of around twofold for most of the traits, to almost an order of magnitude for the leaf area. *Q. ilex* exhibits high plasticity not only of morphological, but also of anatomical and physiological leaf traits, explaining its wide ecological distribution (Gratani *et al.* 2006).

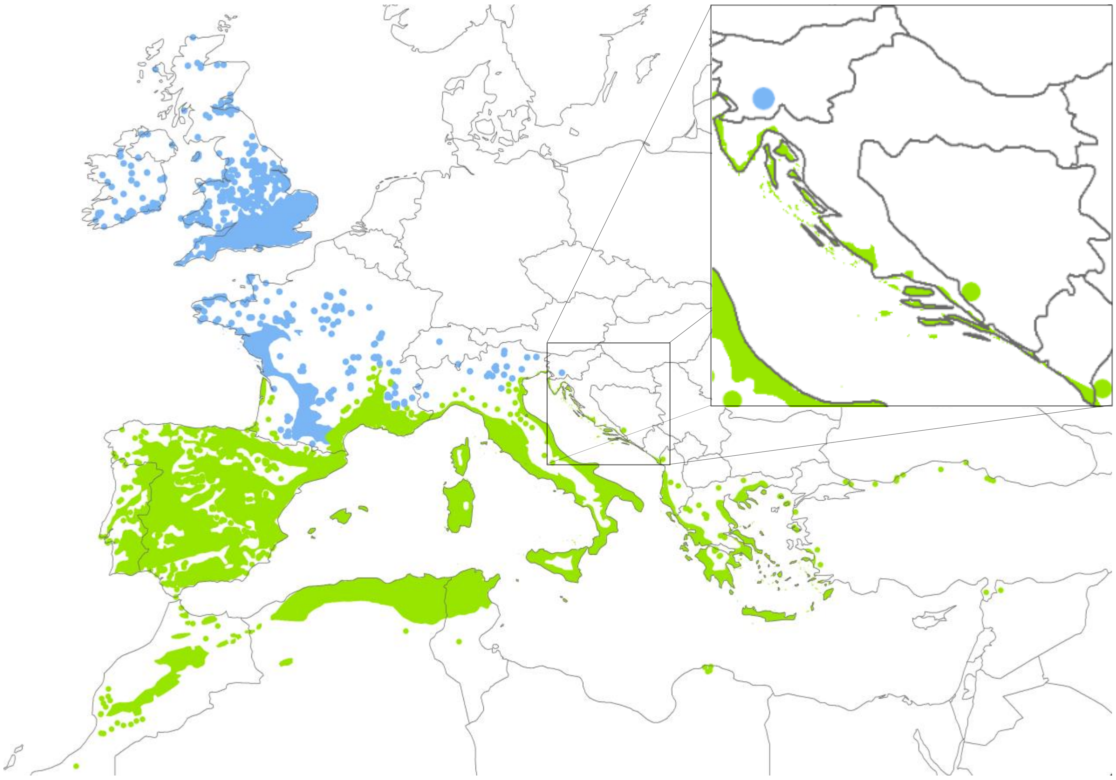

Figure 9. Distribution map of Holm oak (*Quercus ilex* L.). Green – natural range; blue – synantropic range. Data compiled, mapped, and provided by Erik Welk, AG Chorology & Macroecology of Vascular Plants, Institute of Biology, Martin-Luther-University, Halle-Wittenberg.

Increasing drought results in increased leaf thickness, density, and dry mass per area, as well as thickness of cuticle and decrease of leaf area. Of the leaf tissues, there is significantly higher investment in the upper epidermis and palisade parenchyma under drought conditions (Bussotti *et al.* 2002). Furthermore, Ogaya and Peñuelas (2007) demonstrated that an increase in leaf dry mass per area can be observed not only as a response to drought, but also as a response to cold. Additionally, photosynthetic activity of *Q. ilex* is less limited by cold conditions in comparison to other Mediterranean evergreen species (Gratani *et al.* 2013). In contrast to *A. unedo*, *Q. ilex* exhibits low control over leaf angle, constantly maintaining a relatively steep leaf angle (Gratani and Bombelli 1999). Leaves of *Q. ilex* are remarkably long-lived and can be remain on the tree from 2 up to 6 years, resulting in a substantial proportion of the canopy being formed by leaves from the previous years (Gratani and Bombelli 1999; Niinemets *et al.* 2005). As in many other evergreen Mediterranean species, increase in leaf age leads to increase in leaf dry mass per unit area, and reduction in photosynthetic activity and stomatal control (Niinemets *et al.* 2005). Despite high morphological and anatomical plasticity, leaves of *Q. ilex* can be generally considered sclerophyllous due to their high leaf dry mass per area, high leaf-tissue density, two layers of relatively long and densely arranged palisade parenchyma cells (Gratani and Bombelli 1999;

Gratani and Bonito 2009), well developed epicuticular wax, and hairs on the abaxial surface of mature leaves (Fernández *et al.* 2014).

Q. ilex responds to drought similarly to *O. europaea*. It initially closes its stomata, thus reducing leaf conductivity and transpiration. Under prolonged drought it can reach very low values of leaf water potential and low water content without permanent damage to the tissues, and with fast recovery of photosynthetic activity upon cessation of drought (Bussotti *et al.* 2002; Gratani and Bonito 2009; Gratani *et al.* 2013). Unlike *O. europaea*, *Q. ilex* is not reported to store substantial amounts of lipids in its leaves. *Q. ilex*, similarly to *P. halepnsis*, emits substantial amounts of terpenes into the atmosphere, with potential consequences for the atmospheric chemistry and ozone formation (Niinemets *et al.* 2002). In contrast to *P. halepensis*, *Q. ilex* does not store terpenes, but emits them upon their synthesis, with the result that *Q. ilex* terpene emissions are directly related to environmental conditions (predominantly light, temperature and CO_2 concentration) (Kesselmeier *et al.* 1998; Loreto *et al.* 2001; Pasqua *et al.* 2001). There are indications that these emissions may help plants cope with heat stress (Loreto *et al.* 1998).

Q. ilex is a resprouting, wind-pollinated, monoecious species, which flowers in spring and whose acorns mature in November and December. Male flowers are grouped on catkins and carry around 20 flowers. Female flowers occur in groups of up to three in the axils of the leaves (Yacine and Bouras 1997). Acorns readily germinate under moist conditions and exhibit only slight epicotyl dormancy, which is commonly broken during the Mediterranean winter (Ghasemi and Khosh-Khui 2007). Young seedlings are relatively sensitive to harsh weather and susceptible to desiccation (Smit *et al.* 2008). As the acorns are recalcitrant they do not form an extensive soil seed bank. *Q. ilex* acorns represent an important food source for the wildlife, and feed for livestock (García-Mozo *et al.* 2007). In addition to being a source of wood and acorns, *Q. ilex* can be used as a tannin source for dye production. Even though *Q. ilex* has an important economic value in other Mediterranean countries (*e.g.* Spain) (García-Mozo et al. 2007), it is generally unutilised in the study area. In the study area, *Q. ilex* and *A. unedo* were the only species included in this study that were able to grow in the understorey. Furthermore, these two species were found in a higher diversity of stands and fuel layers in comparison to all the other studied species.

7. Overview of the study

The study presented here was conducted in order to assess the adaptability and flammability of six Mediterranean tree species in response to expected climate change. Since the initiation of this study, a substantial amount of work has been published on the topic of vegetation flammability, as well as effects of climate and change in land use on the Mediterranean ecosystems. Furthermore, the research proposal was written with limited access to literature. In order to present the original objective of this work in an appropriate light, this overview will present only the information that was available at the time of the study initiation. More recent information has been abundantly included in the previous chapters, and will be referred to at the end of the study overview.

It has been hypothesised that climate change might have the greatest effect on the Mediterranean regions due to the transitional nature of the ecosystems present there. These ecosystems are exposed to prolonged drought periods, and a further decrease in annual precipitation could shift them to low-cover desert shrublands (Lavorel *et al.* 1998). For Croatia, none of the IPCC scenarios (Christensen *et al.* 2007) predict a positive difference between precipitation and evaporation, so it can be presumed that drought is set to remain the major factor affecting natural and agricultural systems. Furthermore, in the Mediterranean, fire is the predominant natural disturbance, and with a predicted increase in extreme weather conditions it can be expected that the importance of fire will further increase (Vázquez and Moreno 1995). Nevertheless, the presence of fire is not only related to weather conditions, but it is also influenced by the vegetation, with some of the species exhibiting higher flammability than others (Massari and Leopaldi 1998; Petriccione *et al.* 2006; Alessio *et al.* 2008b). Establishment of fast-growing pines or eucalypts in dense monospecific plantations has been shown to result in a positive feedback loop for fire occurrence, and thus a need has been identified to shift the focus towards favouring species assemblages with high resilience to disturbance and drought (Naveh 1995).

Objectives of the study presented here were to examine to what extent morphological characteristics, physiological activity and flammability of different species are governed by environmental conditions, with a special interest in drought as the most important limiting factor of the Mediterranean ecosystems. In addition, we aimed to examine interactions between morphology, physiology and flammability of the studied species. We intended the following: a comparison between flammability parameters and morphological and physiological characteristics of the species; an exploration of the relationship between these parameters; and a determination of whether differences in measured flammability parameters could be explained by adaptation strategies employed by the different species.

With regard to variations in the flammability of the material, our general hypothesis was that in drier and warmer conditions, regardless of whether they are influenced by local climate or seasonal weather fluctuations, vegetation is more prone to burn.

Species were selected based on their abundancy, importance, potential uses, or presence of unique leaf characteristics. *Q. ilex* and *P. halepensis* were chosen as the most important forest species, and *O. europaea* as the most important agricultural tree crop of the region. These three species were chosen due to their abundancy, and compared to another three species which are generally present, but neglected in both forestry and agriculture. *A. unedo* was chosen as a forest species with numerous potential agricultural uses, and *C. siliqua* as a neglected agricultural crop with relatively abundant volunteer populations and potential forestry uses. As a neglected agricultural crop with numerous potential uses, *P. granatum* was included as the only deciduous species. It was chosen due to its remarkably thin leaves. Comparing commonly used species with neglected ones was done in order to assess whether promotion of neglected species could potentially decrease fire danger.

In order to meet its objectives, the study was divided into three parts: (i) a field study, (ii) a study of seed manipulation and germination, and (iii) a watering experiment. As detailed analysis of the first part of the study (field study) provided sufficient information for the writing of three articles and the meeting of the official requirements of a PhD thesis, the work presented here will deal only with this part of the study.

7.1. Field study

The field study was conducted in order to assess the *in situ* response of the chosen species to environmental conditions, with special interest in the effects of weather and climate. During this part of the study, direct measurements of flammability, physiological activity and morphological characteristics were conducted on the chosen trees, in three different locations over a six-month period. In the study area, a distinct climatic gradient can be found. From northwest to southeast there is an increase in all temperature indices (average, maximum and minimum), the yearly sum of sunshine hours, precipitation amounts outside of the drought period, duration of the frost-free period, and severity and duration of drought. Three main sampling sites, which represent a transect of these conditions, were selected. It was considered important to have three sampling sites in order to adequately assess the influence of climate. Sampling sites were chosen by combining long-term climate information provided by the Croatian Meteorological and Hydrological Service, species distribution maps provided by the Flora Croatica Database, and information gathered in direct contacts with forestry offices located in the areas that were considered promising based on the first two information sources. Due to difficulties in finding an area in which sampling was allowed, and where mature unmanaged or minimally managed trees of all the species were present, two auxiliary sampling sites were chosen. Auxiliary sampling sites had similar climatic conditions to the corresponding main sampling site, and were used for sampling of only one species. The choice of individuals for permanent sampling is explained in the third submitted paper (Section 8.3), and it was a compromise between the need for standardised sampling trees that represent behaviour of the species under given climatic conditions, and the low level of logistical support during the field study.

Originally, monthly measurements on fresh leaves were planned for the time period from April to October, 2010. Planned measurements included flammability measurements, determination of moisture content and dry matter content, leaf-area measurements, chlorophyll content (SPAD) measurements, measurements of pre-dawn leaf water potential (pressure chamber), and gas exchange measurements. Of the planned measurements, monthly gas exchange measurements were not performed, as the measuring system was not available on-site, and funding constraints did not allow for its acquisition.The monthly measurements started one monthe later than planed (*i.e.* in May 2010).

In addition to monthly measurements performed on fresh leaves, a series of measurements were to be undertaken on the leaf litter, and fresh and dead twigs, on three separate occasions during the study: at the beginning of study period, immediately after leaf abscission, and at the end of the study period. These measurements included determination of moisture content and dry matter content, and flammability. In the case of leaf litter, measurements of the particle area were conducted as well. On these occasions, gathering of samples for gas chromatography was planned, but was not conducted due to lack of funding. The same is the case for detailed chemical analyses of the gathered materials.

Twig drying time, degree of ramification, standing fine litter in the driest season, and assessment of the presence or absence of volatile oils, waxes and resins were the items of information collected only once. This information was gathered as Cornelissen *et al.* (2003) suggested flammability as a categorical variable that could be determined based on previously mentioned values with the addition of twig dry-matter content (determined three times in the study period), leaf dry-matter content, and leaf size (both of which parameters were determined on a monthly basis). It was planned to test the flammability of fresh leaves according to Alessio *et al.* (2008b), and of leaf litter according to Petriccione *et al.* (2006), with adjustments of these methods for testing of fresh and dead twigs. Pretesting of the methods led to method modification, and the protocols suggested by Alessio *et al.* (2008b) and Petriccione *et al.* (2006) were not followed. Some of the pretesting results are presented in the first published paper (Kauf *et al.* 2014).

8. Articles

8.1. Testing Vegetation Flammability: The Problem of Extremely Low Ignition Frequency and Overall Flammability Score

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Research Article

Testing Vegetation Flammability: The Problem of Extremely Low Ignition Frequency and Overall Flammability Score

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In the recent decades changes in fire regimes led to higher vulnerability of fire prone ecosystems, with vegetation being the only component influencing fire regime which can be managed in order to reduce probability of extreme fire events. For these management practices to be effective reliable information on the vegetation flammability is being crucial. Epiradiator based testing methods are one of the methods commonly used to investigate vegetation flammability and decrease in ignition frequency is always interpreted as a decrease in flammability. Furthermore, gathered information is often combined into a single flammability score. Here we present results of leaf litter testing which, together with previously conducted research on similar materials, show that material with very low ignition frequency under certain testing conditions can be extremely flammable if testing conditions are slightly changed. Additionally, our results indicate that combining measured information into one single flammability score, even though sometimes useful, is not always meaningful and should be performed with caution.

1. Introduction

In recent decades land use coupled with climate change led to changes in the fire regime making fire prone ecosystems more vulnerable to wildfires [1, 2], with further shift towards more devastating fire regimes being predicted in the future [3, 4]. Fire regime is the result of complex interactions between ignitions, weather, topography, and vegetation acting as fuel [5–7]. Even though vegetation is rarely the most influential factor, it is the only one that can be managed in order to reduce the probability of occurrence of extreme wildfires [8]. To achieve this goal correct and reliable information on vegetation flammability is being crucial, becoming one of the essential components of fire risk assessment and management planning [9, 10]. Even though there are numerous lists of species based on their flammability [11–13], the complexity of vegetation flammability makes such a ranking challenging and resulting lists unreliable and possibly misleading [10].

Flammability is comprised of (i) ignitibility—the fuel ignition delay once exposed to heat, (ii) sustainability—the measure of how well a fire will continue to burn with or without the heat source, (iii) combustibility—the reflection of the rapidity with which a fire burns [14], and (iv) consumability—the proportion of mass or volume consumed by fire (Martin et al. 1994). There is currently no validated method of integrating all flammability components into one single index of plant flammability [15]. Furthermore, vegetation fuels are highly variable; their flammability changes with genotype, age, season, location, and material tested [8, 16].

Due to rising importance of reliable vegetation flammability information numerous researchers worked on quantifying it with studies ranging from field burning experiments [17, 18] and burning tables/benches [19–22] to individual leaf testing [16, 23]. In this effort a high number of testing procedures and measured parameters were associated with vegetation flammability. Nevertheless, results of laboratory scale testing as well as vegetation flammability as a concept were challenged due to the discrepancy between laboratory testing results, field testing, and modelling outputs [24]. Simultaneously, they were defended as an opportunity to better understand the influence of fire as a selective evolutionary force [25] and being a useful tool for providing basic information for assessing fire risk despite the inability to directly transfer testing results to a bigger scale [26].

Epiradiator based methods are often criticized for their low reproducibility [27] and low heat flux used [24]. Nevertheless, due to low technical demands and presumably straight-forward interpretation they were often used [20, 28–35]. Up to now they are providing valuable information and are contributing to our better understanding of vegetation flammability [26, 36, 37].

Most of the authors refer to Valette's [38] work as to the reference epiradiator based vegetation flammability testing method. This method attributes flammability score ranging from 0 (the lowest flammability) to 5 (extreme flammability) based on combined information on average ignition delay (average time elapsed between placing a sample on the epiradiator surface and appearance of flame) and ignition frequency (percentage of tests in which flame occurred). Decrease in ignition delay leads to increase in flammability score, whereas decrease in ignition frequency leads to its decrease. If ignition frequency is lower than 50%, material can be assigned only 0 and 1 flammability score regardless of ignition delay. Even when alternative interpretation of data is given [26, 32] or alternative testing method is used [39], its final intention is to give a single flammability score.

Comparing our results to those previously published, we tried to answer two questions.

(i) Does low ignition frequency guarantee low flammability?

(ii) Is it always meaningful to combine gathered information into one single flammability score?

2. Materials and Methods

2.1. Samples Gathering and Storing. Sampling was performed in the coastal region of Croatia. Leaf litter was gathered on May 15, 2010, in the Trstenik area (42°54′N, 17°23′E) on the southwest coast of the Pelješac peninsula, where samples of *Arbutus unedo* L. (strawberry tree), *Ceratonia siliqua* L. (carob), *Laurus nobilis* L. (laurel), *Olea europaea* L. (olive), *Pinus halepensis* Mill. (aleppo pine), *Pistacia lentiscus* L. (mastic), *Pittosporum tobira* Thunb. (Japanese mock orange), and *Quercus ilex* L. (holm oak) were collected.

Samples of *P. tobira* and *P. lentiscus* originated from two and four individual plants, respectively. All the other samples were gathered randomly across the sampling sites and were composed of material originated from more than ten individuals. Only whole leaves and bigger leaf fragments which could be ambiguously identified as belonging to species of interest were gathered; thus only the upper leaf litter layer was sampled. Material was stored in open paper bags, on a storage table, at room temperature and humidity until further processing. Position of samples was occasionally changed.

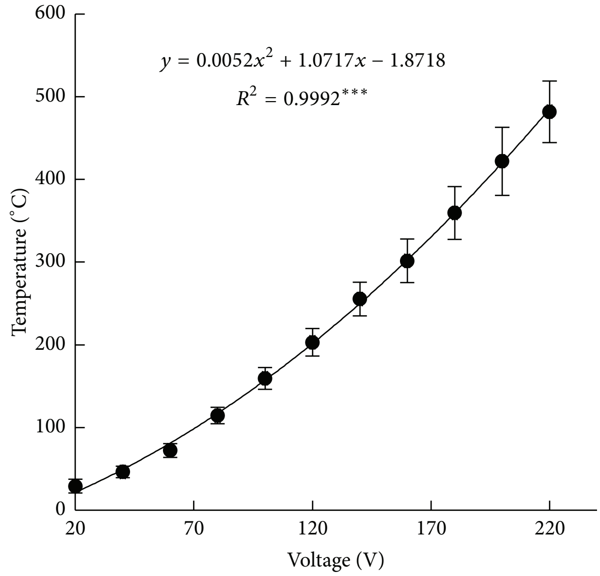


Figure 1: Relationship between input voltage and epiradiator surface temperature. Mean and standard deviation of 10 measurements per voltage input.

2.2. Flammability Testing. For flammability testing, a 500 W epiradiator with 10 cm diameter radiant disc and nominal surface temperature of 420°C was used as a heat source. It was connected to a variable voltage transformer allowing us to reduce and control surface temperature. While determining the voltage-temperature curve, it was observed that the actual temperature was higher than nominal temperature and varied substantially across the epiradiator surface (Figure 1). This was confirmed on three separated epiradiators, one being completely new. Thus, in order to ensure uniform start temperature, the same epiradiator (type 534 Rc2, Quartz Saint-Gobain) was used for all tests with its surface temperature being constantly measured and monitored at fixed point using a K-type temperature probe (GES 900, Greisinger) connected to a digital thermometer (GMH 3210, Greisinger). Additionally, during the process of determining the appropriate surface temperature-material amount combination, it was demonstrated that if the surface temperature rise during the test is substantial, the temperature does not drop back to the initial start temperature, regardless of the waiting time. To give an example for this effect: when testing 5 grams of leaf litter material at a start surface temperature of 500°C and waiting time between two consecutive tests sufficiently long for surface temperature to stabilise, after three successive tests the surface temperature stabilised at 590°C. Under these conditions, the ignition delay dropped from 5.65 seconds for the first test to 1.05 seconds for the third test, indicating that monitoring and stabilising the surface temperature is crucial for reducing systematic errors.

In order to capture the ignitability component of leaf litter flammability we aimed to achieve a higher ignition frequency than Petriccione et al. [34] and a longer ignition delay than Ormeño et al. [20]. Preliminary testing demonstrated that an increase in both epiradiator surface temperature and amount of material tested leads to an increase in ignition frequency; higher temperature results in shorter ignition delay and bigger amount of material tested in longer ignition delay.

After extensive pretesting we chose to test 3.0 ± 0.1 gram sample material at 400 ± 5°C epiradiator surface temperature, respectively. This combination led to 100% ignition frequency with relatively long ignition delay.

The chosen amount of test material formed a layer on the epiradiator surface for all the tested samples ensuring similar heat exposure despite varying surface temperature. After placement on the epiradiator surface samples surrounded the temperature probe, allowing us to use the same probe for measuring initial temperature of the epiradiator surface and temperature at the lower side of the leaf litter during a test. Samples were not additionally oven dried before flammability testing as final moisture content was attributed to intrinsic characteristics of materials governing their ability to retain moisture [40, 41].

The horizontal pilot flame was positioned 4.5 cm above the epiradiator surface. Four parameters were measured: (i) ignition delay (ID)—the time elapsed between placing a sample on the epiradiator surface and appearance of a flame, (ii) flame extinguish time (FET)—time elapsed between placing a sample on the epiradiator surface and end of the flaming combustion, (iii) ignition temperature (IT)—temperature measured at the moment of ignition, and (iv) max temperature (MT)—maximal temperature reached during the test. Flame residence time (FRT) was calculated as the difference between FET and ID, representing the duration of flaming combustion. ID is considered to be a measure of ignitability and FRT a measure of sustainability component of flammability [20, 36, 42]. FET is taken as an additional sustainability measure. IT was interpreted in relation to ID; MT, as it was measured at the bottom of the sample, could not be interpreted in light of flammability components, but provided limited information on heat transfer to the soil during wildfires. Flame intensity was not determined. Time variables were measured using a stopwatch.

Flammability testing was performed on September 5 and 6, 2010, with each sample being tested five times, once in every replication. Samples were tested in random order. Testing was performed in a closed room under a simple chamber, minimizing disturbance due to external air movement. The chamber was opened at the top to allow natural air convection and partially at one side to allow for sample manipulation.

2.3. Physical Measurements. Moisture content (MC), specific leas area (SLA), average area (AA), and average mass (AM) of the single particle are the physical parameters measured and reported. During flammability testing one or two subsamples per species, equal in size to the test samples, were taken. Their dry mass was determined by reweighting them after drying for 24 hours at 85°C and MC was expressed on dry weight basis [43]. After drying fragile leaf litter was soaked in warm tap water and flattened with cloths flatiron before its area was measured with a portable area meter. SLA was calculated by dividing leaf litter area by the corresponding dry mass; AM and AA were calculated dividing dry mass and area of the sample by the corresponding number of particles. An exception was made for *P. halepensis*, as needles were fragmented and the number of particles was difficult to count and it was estimated based on an even smaller subsample and set at 250.

2.4. Statistical Analysis. IBM SPSS Statistics 21 software was used for statistical analysis of gathered data. As all flammability parameters were normally distributed and had homogeneous variances on the species level one-way ANOVA was performed, followed by Duncan post hoc test in order to determine differences between species based on single parameters.

Regression analysis was performed to determine if any of the physical parameters influenced flammability and to what extent different flammability parameters were related. Overall significance of the regression analysis was checked by ANOVA; regression coefficients were tested with t-test against null hypothesis. A relationship between flammability parameters was considered important in order to give appropriate interpretation to collected data, whereas relationships between physical parameters and flammability were reported but are not discussed in detail here.

In order to account for combined influence of all measured parameters on fire behaviour hierarchical cluster analysis was performed using squared Euclidean distances of standardised values (0-1) of measured flammability characteristics (ID, IT, FET, and MT) to determine within-group linkage and try to attribute an overall flammability score to leaf litters of different species.

3. Results and Discussion

When choosing sample mass-temperature combination for our testing procedure we were aware of the argument that masses larger than 1 gram should not be tested with epiradiator based methods as properties such as fuel height could influence the results [20] as well as criticism directed towards the laboratory flammability tests and their use of low heat fluxes [24]. Nevertheless, we consider our testing combination to be acceptable as Anderson [14] stated that there is a clear relationship between sample height and ignition when holding sample density and specific heat constant. If mass is held constant, difference in heights and densities will be present between materials, with both influencing flammability, but also being governed by particle geometry—an inherent characteristic of the material. Furthermore, Fernandes [24] stated that heat fluxes measured during wildland fires are several orders of magnitude higher than that used in laboratory studies, yet still ignition sources do not need to have big heat fluxes. If ignition source has low heat flux (e.g., cigarette butt, sparks, firebrands, not completely extinguished grilling amber, etc.), flammability together with other material properties can have a relevant role in determining whether or not ignition occurs and how fast initial combustion process proceeds, as shown in research made by Ganteaume et al. on reconstructed [22] and undisturbed [39] leaf litters tested with standardised firebrand.

3.1. Means, ANOVA, and Regression Analysis. All five flammability parameters showed statistically significant differences between tested species (Table 1), with the highest level of significance obtained for ignition related parameters: ID and IT. *P. lentiscus* and *P. halepensis* had the shortest ID and were considered the most ignitable of the tested species, whereas *C. siliqua* had by far the longest average ID and was the least ignitable species in this study. *C. siliqua* was followed by *Q. ilex*, *O. europaea*, and *A. unedo*, which formed a group of species with intermediate ignitability as all of the members were significantly different from *P. halepensis*. *L. nobilis* and *P. tobira* were designated as fairly ignitable species as they did not show any significant difference in comparison to *P. halepensis* but had significantly longer ID when compared to *P. lentiscus*. ID and IT grouping results were similar, as could be expected for two parameters measuring the same flammability component and had significant positive linear regression (Figure 2(a)). Nevertheless, the two species *L. nobilis* and *O. europaea* showed substantial difference in their ordering when comparing ID and IT (Table 1). Furthermore, same species showed a deviation from ID-IT regression line with *L. nobilis* having higher and *O. europaea* lower IT in comparison with species with similar ID (Figure 2(a)). These results suggest that in the same time period *L. nobilis* releases more energy and *O. europaea* less energy in comparison with other species involved in this study.

When comparing our ignitability results to those previously published it was observed that *P. lentiscus*, the species with the shortest ID and the highest ignitability in our study, had no positive flammability tests and was identified as species with "null flammability" (ignition frequency = 0) when 1 gram of leaf litter was tested at the epiradiator temperature of 250°C [34]. These contrary results together with the fact that in the research performed by Petriccione et al. [34] leaf litter of four out of fourteen species was considered to have "null flammability" challenge data interpretation with respect to the correlation between low ignition frequency and low flammability.

When taken into consideration that leaf litter is among the most flammable vegetation fraction [44], it is unreasonable for such a big number of species as reported by Petriccione et al. [34] to be "nonflammable"; as small, disturbed samples especially were tested and thus oxygen limitation due to dense packing of the material is highly unlikely.

Vegetation combustion does not start with the appearance of a flame; rather, materials undergo thermal degradation before the start of flaming combustion [45, 46] and complete combustion is possible without flames ever appearing [44, 47]. Therefore, interpretation of negative tests should be reconsidered and testing combinations which do not yield sufficient number of positive tests should be regarded as inconclusive as they do not guarantee low fire hazard. Lack of ignition tells us that critical mass flux of fuel vapours for piloted ignition was not reached, but it does not tell us the reason. A very small amount of highly ignitable material tested at low heat flux can lead to a lack of ignition as release of fuel vapours starts at low temperature and low release rates shortly upon positioning of the sample on the heater surface. As pyrolysis proceeds, mass flux of fuel vapours will increase, but the possibility of complete combustion before a critical mass flux of fuel vapours is reached cannot be excluded. In the same time heat resistant material tested under similar conditions can be completely combusted before a critical mass flux of fuel vapours is reached. In this case due to very slow pyrolysis and slow increase in fuel vapour mass flux. We suggest that tests with extremely low ignition frequency to be repeated under different testing conditions (e.g., higher fuel load and/or heater temperature/external heat flux) or characteristics other than the appearance of a flame are monitored as well [46, 48]. Depending on the purpose of the research and the material tested, different combinations might be appropriate with extra caution being necessary when interpreting and comparing results derived from different testing procedures.

When discussing appropriate fuel load-heater temperature (external heat flux) it should be noted that at low heat fluxes glowing combustion precedes ignition and is necessary for augmenting the radiation heating and enabling ignition [49]. Furthermore, with decreasing heat flux a bigger amount of material needs to be combusted in order for ignition to occur [50]. Thus, to avoid complete preignition combustion of a sample an increased amount of material should be considered at low heat fluxes. Epiradiator testing of leaf litter samples bigger than 1 gram is justified as leaf litter naturally occurs in layers, presenting more or less continuous fuel patches, which even in very fragmented state have mass bigger than 1 gram and a fuel load higher than that corresponding to testing 1 gram at epiradiator with 10-centimetre diameter [18, 22, 51, 52].

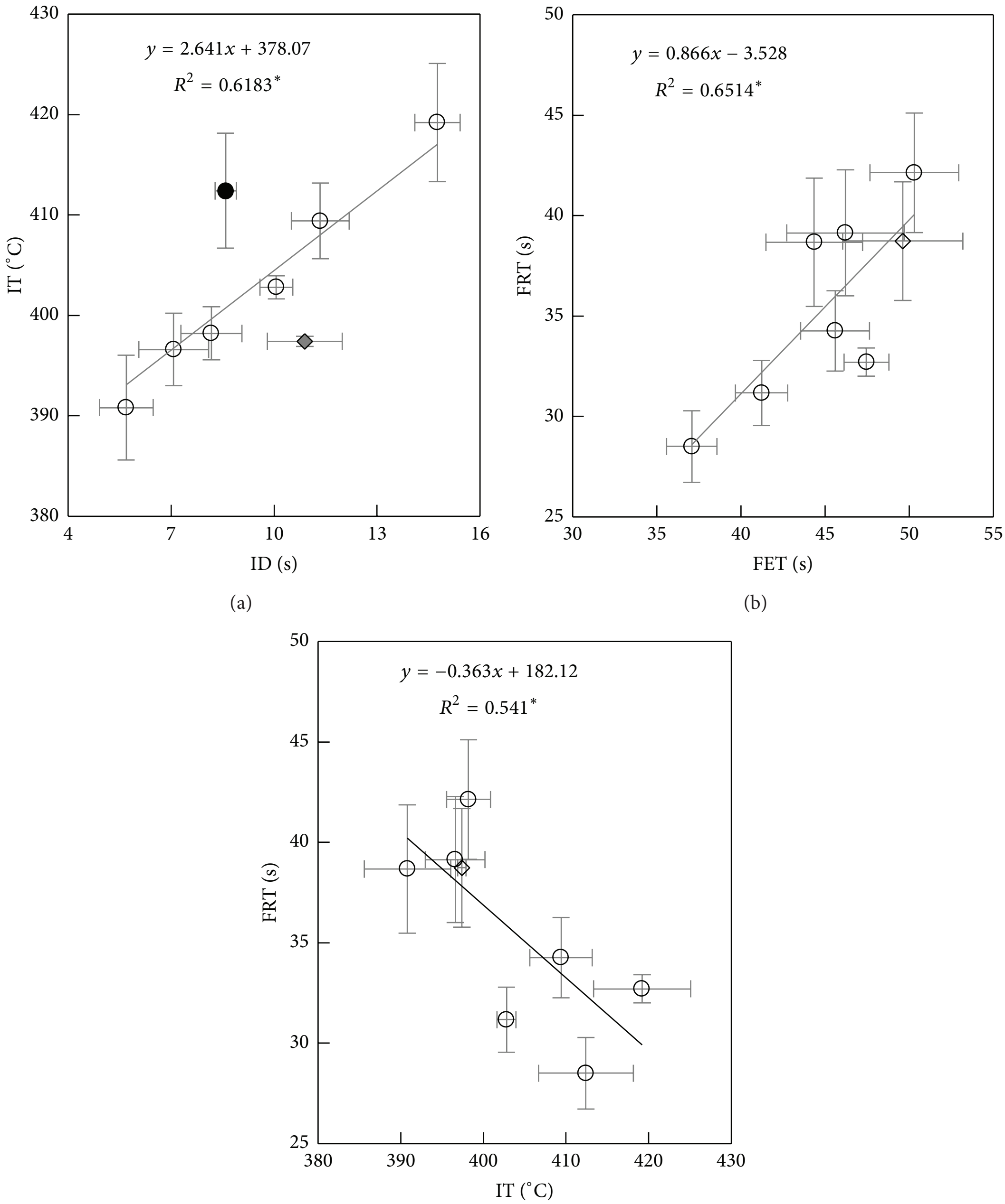
Fewer differences with lower level of significance ($P > 0.001$) were found between species when examining sustainability related parameters. Regardless of the parameter used *L. nobilis* and *A. unedo* were shown to be the species with the lowest sustainability, whereas *P. tobira*, *O. europaea*, and *P. halepensis* were those species with the highest sustainability. Both parameters placed *P. lentiscus* and *Q. ilex* in-between these groups, but in case of FRT *P. lentiscus* was significantly different from the species with the lowest sustainability, whereas that was the case for *Q. ilex* with regard to flame extinguish time. Low sustainability of *L. nobilis* and high sustainability of *O. europaea* confirm that the former has fast energy release rate and the latter has slow energy release rate, as previously indicated by ID-IT results.

C. siliqua was the species that changed its order the most when comparing FRT and FET results. It was among the species with the lowest sustainability regarding FRT (ranking third) and among the species with the highest sustainability (ranking sixth) based on FET.

While similarities in grouping of species based on two different sustainability factors can be explained through their positive linear regression (Figure 2(b)), we were also interested in finding an explanation for differences in species ranking. When taking into consideration that a longer heating process results in an increase of ignition mass loss and ignition delay [53] it can be expected that larger differences in ignition delay will result in larger differences in masses still available for combustion at the moment of ignition. Thus, in cases where ID is relatively long and significantly different

Table 1: Mean values, standard deviations, results of ANOVA, and Duncan post hoc test for measured flammability parameters. Different letters indicating statistically significant differences at $P < 0.05$ level of probability.

	ID (s)			IT (°C)			FET (s)			FRT (s)			MT (°C)		
	Mean	St. dev.		Mean	St. dev.		Mean	St. dev.		Mean	St. dev.		Mean	St. dev.	
A. unedo	10.064	1.076	cde	402.8	2.59	abc	41.232	3.445	ab	31.168	3.637	ab	548.6	18.34	a
C. siliqua	14.758	1.481	f	419.2	13.14	d	47.458	2.977	bc	32.700	1.568	abc	556.2	15.45	a
L. nobilis	8.584	0.694	bcd	412.4	12.80	cd	37.084	3.359	ab	28.500	3.971	a	588.2	22.95	b
O. europaea	10.894	2.438	de	397.4	1.14	ab	49.622	7.970	c	38.728	6.616	bcd	557.4	20.38	a
P. halepensis	7.072	2.268	ab	396.6	8.08	ab	46.210	7.803	bc	39.138	7.018	cd	550.0	15.73	a
P. lentiscus	5.688	1.748	a	390.8	11.69	a	44.358	6.431	abc	38.670	7.134	bcd	545.2	9.76	a
P. tobira	8.172	1.997	bcd	398.2	5.93	ab	50.304	5.901	c	42.132	6.649	d	571.6	19.81	ab
Q. ilex	11.344	1.892	e	409.4	8.41	bcd	45.600	4.591	bc	34.256	4.469	abc	561.0	20.54	a
F		12.597			5.561			3.023			3.689			2.993	
P		<0.001			<0.001			0.015			0.005			0.016	



(c)

Figure 2: Significant liner regressions between flammability parameters. Points indicate mean values and error bars represent standard error. (a) Linear regression between ignitability related parameters ignition delay (ID) and ignition temperature (IT), with black data point indicating position of *L. nobilis* and grey data point indicating position of *O. europaea*. (b) Linear regression between sustainability related parameters flame extinguish time (FET) and flame residence time (FRT). (c) Liner regression between ignitability parameter ignition temperature (IT) and sustainability parameter flame residence time (FRT).

FRT might be distorted as a measure of sustainability and capture a portion of ignitability as well. This explanation is further reinforced by the significant negative linear regression between IT and FRT (Figure 2(c)), as mass needs to be combusted in order for temperature to increase. In our study the average ID of the species with the highest value was more than 2.5 times longer than that of the species with the shortest ID; thus differences in masses still available for combustion at the moment of ignition are very likely even when possible variations in energy release rate are taken into consideration. Nevertheless, in studies where ignition delays were short and there were no significant differences between them [20] the duration of flaming combustion might still be an appropriate measure of sustainability. In order to fully understand the influence of prolonged ID on FRT it might be useful to consider performing two series of epiradiator

Table 2: Physical parameters of tested leaf litter.

	SLA (cm^2/g)	AM (g)	AA (cm^2)	MC (%)
A. unedo	64.89	0.171	11.07	11.72
C. siliqua	72.19	0.232	16.75	13.03
L. nobilis	95.37	0.237	22.60	10.83
O. europaea	50.78	0.087	4.40	10.16
P. halepensis	33.43	0.011	0.36	11.47
P. lentiscus	61.15	0.023	1.43	9.55
P. tobira	74.51	0.095	7.05	9.77
Q. ilex	60.75	0.176	10.73	10.22

Table 3: Significant linear regressions between physical and flammability parameters.

Linear regression models $y = a + bx$					
y	a	b	x	r^2	P
SLA	522.121	0.587	MT	0.564	0.032
AM	41.387	−44.403	FRT	0.693	0.010
AA	40.479	−0.518	FRT	0.709	0.009
AA	393.198	1.092	IT	0.766	0.004

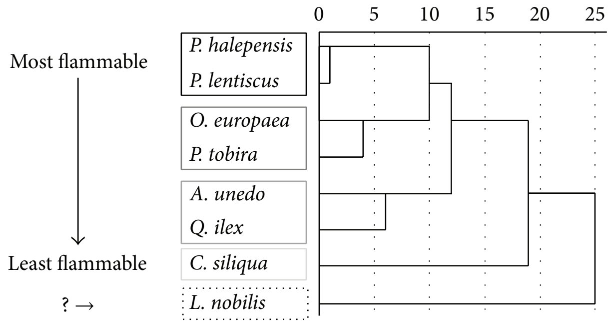


Figure 3: Hierarchical cluster analysis based on standardized measured flammability parameters: ignition delay (ID), ignition temperature (IT), flame extinguish time (FET), and maximal temperature (MT). Distances presented in the dendrogram are automatically rescaled by the SPSS software and thus the presented scale does not show the calculated distances.

tests for each material: one with prolonged ignition delay in order to capture the ignitability portion of flammability and another with extremely short ignition delay in order to capture sustainability while reducing the influence of differences in masses at the moment of ignition.

Out of the measured flammability parameters MT was the one that showed the least differences between species. It identified *L. nobilis* as the species that reached the highest maximal temperature. *P. tobira* did not significantly differ from any other species regarding maximal temperature reached. All the other species had significantly lower maximal temperature than *L. nobilis*, but no significant differences were found among them.

MC was the only physical parameter measured that had no significant influence on any of the flammability parameters (Table 2.). This can be attributed to the relatively small range of values with the minimum achieved for *P. lentiscus* being 9.55% and the maximum for *C. siliqua* being 13.03%. SLA showed a positive linear regression with MT (Table 3), whereas both AM and AA showed a negative relationship with FRT. AA also influenced IT, with an increase in single particle area leading to a higher ignition temperature.

3.2. Hierarchical Cluster Analysis. Based on hierarchical cluster analysis performed on four measured flammability parameters (ID, IT, FET, and MT) five separate clusters could be distinguished (Figure 3). *P. halepensis* and *P. lentiscus* formed the first cluster. On the single parameter bases they had the highest ignitability and intermediate to high sustainability in comparison to the other species tested (Table 1). A second cluster was formed by *O. europaea* and *P. tobira*, two species with the longest FET, which followed species from the first flammability group based on their IT and had a short to intermediate ID, indicating high sustainability and intermediate to high ignitability. *A. unedo* and *Q. ilex*, species from the third cluster, had intermediate to low both ignitability and sustainability. *C. siliqua* formed a fourth cluster with its relatively high sustainability when assessed by FET, the highest IT, and by far the longest ID—indicating species with remarkably low ignitability. All aforementioned species showed similar behaviour and it was possible to compare their flammability based on combined information and, if considered appropriately, attribute an overall flammability score with decreasing flammability from the first to the fourth cluster. Nevertheless, *L. nobilis* results were difficult to compare to the rest of the species. The most pronounced difference between *L. nobilis* and other species included in this study was its comparably faster energy release, which was shown through the shortest FET and FRT, highest MT, and higher IT in comparison to species with similar ID (Figure 2(a)). Combining this data we could conclude that *L. nobilis* was the least sustainable and intermediate to high ignitable species; but where does this information put *L. nobilis* in comparison to other species included in this research? Figure 3 shows that *L. nobilis* differs from any other species, but it does not tell us why and how this difference influences *L. nobilis* overall flammability score. This example raises a further question: can one single score describe the flammability of a material?

In our study we measured four flammability parameters, which could be attributed to two out of four components of vegetation flammability on small standardised samples of eight different leaf litters and were able to meaningfully compare seven species based on combined information. Ganteaume et al. [26], while performing epiradiator based testing of live vegetation, tested eight different materials and were able to attribute meaningful flammability scores to all the materials based on hierarchical cluster analysis that took into account ignition frequency, ignition delay, and flame residence time. Although the results of their analysis were meaningful and useful for the given situation, the included parameters did not account for all the flammability components.

In a different study which tested flammability of undisturbed leaf litters Ganteaumne et al. [39] also performed hierarchical cluster analysis based on four parameters (ignition frequency: IF, time to ignite: TTI, flaming duration: FD, and number of sides reached by the flame/flame spread: S). Even though we acknowledge the remarkable quality of the gathered data we disagree with its interpretation. In our opinion the clusters showed different relationship between flammability parameters which could not be transferred into single and comparable flammability score, similar to our own observations. For instance, in the mentioned work, the cluster containing *Prunus laurocerasus* L. was considered to be more flammable than that containing *Cupressus sempervirens* L. Nevertheless, when comparing values of the measured flammability parameters, only one out of four suggested this relationship between the species in question.

Hierarchical cluster analysis groups elements based on similarity of the measured parameters, maximising within group similarities and between group dissimilarities. Thus it can be expected that species in the same cluster will have similar fire behaviour and that the distance between clusters corresponds to differences in fire behaviour. Nevertheless, it does not tell us anything about the overall flammability score. Thus, attributing an overall flammability score depends strongly on the conclusions of the respective researcher and can only be done by taking into consideration the values of the input parameters on which the analysis is based.

If clustering or any other ranking based on combined information of different measured parameters is made, input parameters, limitations of the used method, and components of flammability taken into consideration should always be kept in mind when assessing output results. Furthermore, it can be expected that with every additional parameter and/or element (material, species, etc.) included into the analysis a meaningful interpretation of the combined results will be more difficult and more of the original information on the fire behaviour of material will be lost. Therefore, even though flammability assessment based on combined information can sometimes be useful, it should be performed with caution and should not be insisted upon.

4. Conclusions

The results presented here suggest that epiradiator testing with extremely low ignition frequency can occur in extremely flammable fuels if an inappropriate fuel load-heater temperature (external heat flux) combination is applied. The importance of these findings lies in the fact that wrongly identifying extremely flammable fuels as having low flammability can lead to misapprehension of vegetation characteristics influencing flammability and management practices with potentially adverse effects on the environment. It is our suggestion to treat tests with extremely low ignition frequency as inconclusive and retest materials yielding these results under different testing conditions or monitor characteristics other than the appearance of flame as well.

Performed clustering analysis showed that, even though sometimes useful, combining all the gathered vegetation flammability information into one single flammability score is not always meaningful. It should be performed with extra caution and should not always be insisted upon. In our study combining information of four measured parameters, which describe two out of four flammability components, allowed us to attribute comparable flammability scores to seven out of eight species included in this study. Nevertheless, in the case of *L. nobilis* we were unable to do so. As such, in this study, we preferred an explanatory comparison of species. Taking into consideration all the parameters in their original state allowed us to compare species based on their ignitability, sustainability, and energy release rates.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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8.2. Seasonal and Local Differences in Leaf Litter Flammability of Six Mediterranean Tree Speceis

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Seasonal and Local Differences in Leaf Litter Flammability of Six Mediterranean Tree Species

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Abstract One of the suggested management options for reducing fire danger is the selection of less flammable plant species. Nevertheless, vegetation flammability is both complex and dynamic, making identification of such species challenging. While large efforts have been made to connect plant traits to fire behavior, seasonal changes and within species variability of traits are often neglected. Currently, even the most sophisticated fire danger systems presume that intrinsic characteristics of leaf litter stay unchanged, and plant species flammability lists are often transferred from one area to another. In order to assess if these practices can be improved, we performed a study examining the relationship between morphological characteristics and flammability parameters of leaf litter, thereby taking into account seasonal and local variability. Litter from six Mediterranean tree species was sampled throughout the fire season from three different locations along a climate gradient. Samples were subjected to flammability testing involving an epiradiator operated at 400 °C surface temperature with 3 g sample weight. Specific leaf area, fuel moisture content, average area, and average mass of a single particle had significant influences on flammability parameters. Effects of sampling time and location were significant as well. Due to the standardized testing conditions, these effects could be attributed to changes in intrinsic characteristics of the material. As the aforementioned effects were inconsistent and species specific, these results may potentially limit the generalization of species flammability rankings. Further research is necessary in order to evaluate the importance of our findings for fire danger modeling.

Keywords Leaf litter · Flammability · Ranking · Epiradiator testing · Sampling time effects · Climate gradient

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Introduction

Fire is an important factor controlling vegetation structure. This is especially true for fire-prone ecosystems, which cover approximately 40 % of the world's land surface and owe their distribution and ecological properties to the fire regime (Bond et al. 2005). In recent decades, land use coupled with climate change led to changes in fire regimes making them more destructive and resulting in higher ecosystem vulnerability to wildfires (Benndorf et al. 2007; Pausas and Keeley 2009). Additionally, high urban pressure presents an increasing risk in terms of fire ignition caused by human activities and burned area threatening inhabited areas (Lampin-Maillet et al. 2010; Simeoni et al. 2012; White and Zipperer 2010). Thus, the need for management practices, which strive to minimize negative socio-economic impacts and maximize environmental benefits of fire, is widely recognized (Fernandes 2013; Loepfe et al. 2012).

Fire regime is the result of complex interactions between ignitions, weather, topography, and vegetation acting as fuel (Fernandes 2013; Moreira et al. 2011; Rothermel 1983). Even though the influence of vegetation varies regionally and sub-regionally (Pausas and Paula 2012), it remains the only component that can be directly managed in order to reduce negative consequences of wildland fires (Fogarty 2001; Moreira et al. 2011; Ortega et al. 2012). For this goal to be reached reliable information on vegetation flammability is required, making it one of the essential components of fire risk assessment and management planning (Dimitrakopoulos and Papaioannou 2001; White and Zipperer 2010).

One of the management options often suggested for the wildland–urban interface (WUI) is the recommendation and promotion of less flammable species (Behm et al. 2004; Ganteaume et al. 2013a, b; Liodakis and Kakardakis 2008; Weise et al. 2005; White and Zipperer 2010). Even though there are numerous lists of species based on their flammability (Barkley et al. 2010; Doran et al. 2010; Fitzgerald and Waldo 2001; Lippi and Kuypers 1998; Lorenson and Callahan 2010; Moore-Gough et al. 2010), the complexity of vegetation flammability makes such a ranking challenging and the resulting lists possibly misleading (Fogarty 2001; White and Zipperer 2010).

Flammability is comprised of: (i) ignitability—the fuel ignition delay once exposed to heat, (ii) sustainability—the measure of how well a fire will continue to burn with or without the heat source, (iii) combustibility—the reflection of the rapidity with which a fire burns (Anderson 1970), and (iv) consumability—the proportion of mass or volume consumed by fire (Martin et al. 1994). There is currently no validated method of integrating all these components into one single index of plant flammability (Behm et al. 2011) and recent work has shown that such single indices might be questionable (Kauf et al. 2014). Furthermore, vegetation fuels are highly variable; their flammability changes with genotype, age, season, location, and material tested (Fogarty 2001; Gill and Moor 1996).

Most of the laboratory research on flammability and its relationship to vegetation properties were made on selected types of vegetation fuel such as leaf litter, branch tips, fresh leaves, or fire brands (Bartoli et al. 2011; Curt et al. 2011; Delabraze and Valette 1974; Dibble et al. 2007; Dimitrakopoulos and Papaioannou 2001; Liodakis et al. 2008; Petriccione et al. 2006; Valette 1990). Some studies manipulated moisture content (Bernard and Nimour 1993; Sun et al. 2006) or fuel load (Mindykowski et al. 2011) in order to investigate the relationship between physical (Engstrom et al. 2004; Plucinski and Anderson 2008; Simeoni et al. 2012), chemical (Alessio et al. 2008a; De Lillis et al. 2009; Liodakis and Kakardakis 2008; Ormeño et al. 2009), and/or morphological characteristics (de Magalhães and Schwilk 2012; Doat and Valette 1980; Engber and Varner 2012; Gill and Moor 1996; Scarff and Westoby 2006) of the vegetation fuel and its flammability. Only early work, e.g., Trabaud (1976), and very recent work (Ganteaume et al. 2013a, b) simultaneously tested fresh leaves and corresponding litter, while the influence of season (Alessio et al. 2008b; McAllister et al. 2012; Pellizzaro et al. 2006; Weise et al. 2005) and location (Blackhall et al. 2012; Massari and Leopaldi 1998; Pausas et al. 2012) remained investigated only on fresh vegetation fuels.

The efforts made in laboratory vegetation flammability testing and in establishing vegetation flammability as a concept was recently challenged due to discrepancies between laboratory testing results, field testing, and modeling results (Fernandes and Cruz 2012). Simultaneously, studies that tried to connect flammability to plant traits were defended as an opportunity to better understand the influence of fire as a selective evolutionary force (Pausas and Moreira 2012). Those approaches were shown to be successful in differentiating between species based on their fire regime and fire life history (Engber and Varner 2012; Fonda et al. 1998; Kane et al. 2008). They are also considered relevant as potentially allowing upscaling from laboratory research to the field community level, thus providing practical information for environmental management (Schwilk and Caprio 2011). Even though laboratory experiments cannot be used for predicting or describing flammability of fuels under natural conditions, they can help to improve our knowledge of the effects of fresh and dead fuel properties on flammability and represent basic information for assessing fire risk (Ganteaume et al. 2013b).

The results of fire risk assessments govern management activities in fire prone areas. Thus, misleading or incorrect information can result in adverse actions and increased fire damage. The relationship between weather, dead fuel moisture, and fire behavior has been explored previously (e.g., Aguado et al. 2007; Anderson and Anderson 2009; Catchpole et al. 2001; Fernandes et al. 2008; Plucinski and Anderson 2008; Sow et al. 2013) and taken into consideration in various fire danger systems (Carlson and Burgan 2003; Cruz et al. 2013; Dimitrakopoulos et al. 2011; Vasilakos et al. 2007; Viegas et al. 2000). Nevertheless, characteristics of dead fuels are assumed to be constant even in the most sophisticated warning systems (Carlson and Burgan 2003). Furthermore, flammability lists are often transferred from one area to another (e.g., DeGomez et al. 2012), not taking into account potential spatial differences.

In this study, we investigated seasonal and local variability of morphology traits, moisture content, and flammability related parameters with the aim to check if current practices of: (i) relating plant traits to vegetation flammability, (ii) transferring flammability lists from one area to another, and (iii) presuming unchanged intrinsic characteristics of dead fine fuel could be improved. Here we present the results for leaf litter, the fuel in which most of wildland fires start (DeBano et al. 1998).

Materials and Methods

Study Area and Selection of Species

The present study was conducted in the Mediterranean biogeographic region of Croatia where forest fires present an important issue for environmental management (JRC 2013). Along the coastline, three main sampling sites were chosen, which represent a transect of the climatic conditions in the region (Fig. 1). From northwest to southeast, a distinct climatic gradient can be observed with an increase in: all temperature indices (average, max and min), yearly sum of sunshine hours, precipitation amounts outside of the drought period, duration of the frost free period, and severity and duration of drought (Fig. 2.).

The northernmost main sampling site (45°6′N, 13°36′E) was located on the west coast of Istria, in the vicinity of the city of Rovinj, with an altitude between 1–25 m and S-SW aspect (Fig. 1). As all the pomegranate (*Punica granatum* L.) trees in the vicinity of Rovinj were intensively managed an auxiliary sampling site was established in Frančeskija (45°28′N, 13°31′E), where a cluster of three adult *P. granatum* individuals under minimal management was sampled. The sites Rovinj and Frančeskija had comparable climatic conditions and topography, thus they were regarded as one site during data analysis and are referred to as "Istria."

The second main sampling site (44°10′N, 15°11′E) was located in Northern Dalmatia in the vicinity of Kožino, near the city of Zadar, with an altitude between 50–60 m and varying aspect. As only individual carob (*Ceratonia siliqua* L.) trees were present in the vicinity of Kožino, an auxiliary site for *C. siliqua* sampling was chosen in Marina (43°30′N, 16°6′E), where the northernmost mainland

Fig. 1 Relief map of Croatia overlapped with map of biogeographic regions. Indicated are locations of: the largest cities, main and auxiliary sampling cites. Individual map elements were obtained from the Flora Croatica Database (http://hirc.botanic.hr/fcd)

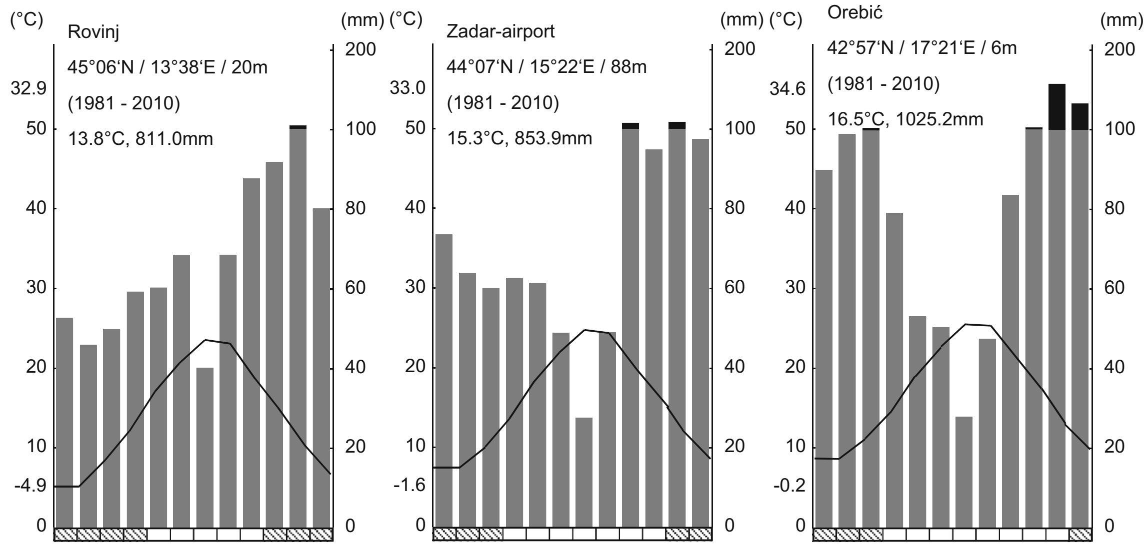

Fig. 2 Walter–Lieth climate diagram for the meteorological stations Rovinj, Zadar-airport, and Orebić closest to the main sampling sites Rovinj, Kožino, and Trstenik, respectively. Data were obtained from the Meteorological and Hydrological Service, Croatia

population of this species was found. Information gathered at these two sites was referred to as "Zadar" due to similar climatic conditions.

The southernmost sampling site, referred to as "Trstenik" (42°54′N, 17°23′E) was located in the Trstenik area, on the southwest coast of the Pelješac peninsula, with an altitude between 5 and 200 m, in a south oriented bay, with varying aspect (SW-S-SE). Here all six tree species of interest were present within the same location.

The six tested species were: Aleppo pine (*Pinus halepensis* Mill.), Holm oak (*Quercus ilex* L.), olive (*Olea europaea* L.), strawberry tree (*Arbutus unedo* L.), carob (*C. siliqua* L.), and pomegranate (*P. granatum* L.). These species were chosen as we wanted to include main forest (*P. halepensis* and *Q. ilex*) and agricultural species (*O. europaea*), as well as species which are neglected and underutilized in the study area, but have a potential to be used both in forestry and agriculture (*A. unedo* and *C. siliqua*). The last species (*P. granatum*) was included due to its deciduousness and unique leaf morphology (e.g., relatively small and remarkably thin leaves).

Sampling Schedule and Protocol

Leaf litter of all six species was sampled in May, July, and September/October 2010 on all sites, if possible (Table 1). *P. granatum* was not sampled in May at any of the sites as litter decomposition was too advanced for identifiable leaf litter fragments to be found. Furthermore, at Zadar, all *P. granatum* trees grew on stony terrain making retrieval of sufficient amounts of material unfeasible. *C. siliqua* samples were not gathered in Istria as winters are too cold for this species to establish; they were not gathered in May in Zadar (Marina) as there were problems identifying the sampling location.

May samples were mainly composed of leaf litter fallen during previous year's abscission, exposed to the local environmental conditions since and partly decomposed, thus both whole leaves and bigger leaf litter fragments that could be identified as belonging to the species of interest were gathered. July samples were gathered as soon as possible after leaf abscission of evergreen species and were composed only of recently fallen leaves, which formed a recognizable, uniform top litter layer. In the case of *P. granatum*, leaf litter gathered in July was recently abscised due to environmental stress. *P. granatum* trees in the Trstenik area shed only a limited amount of litter during early summer, resulting in a reduced number of *P. granatum* flammability tests in July for this site (Table 1). Our intention was to gather the same material, i.e., leaf litter fallen in the year of study, during the September/October sampling in order to assess the influence of short-term summer exposure of leaf litter of evergreen species to environmental conditions on flammability. This was shown to be unfeasible as changes in the material were too large. Litter fallen in the year of study was no longer easily distinguished and it was naturally mixed with that of the previous year. As a result, September/October samples of evergreen species contained also some litter fallen in the previous year. The last sampling of all evergreen species was performed in September, whereas *P. granatum* samples were gathered in October, as soon as enough litter had fallen. The number of trees from which material originated varied between three and more than 30. It was governed by

Table 1 Number of flammability tests performed with regard to sampling location and sampling time

Location	Istria			Zadar			Trstenik		
Sampling time	May	July	Sep/Oct	May	July	Sep/Oct	May	July	Sep/Oct
Arbutus unedo	6	5	5	6	5	6	5	5	7
Ceratonia siliqua	–	–	–	–	6	5	6	5	7
Olea europaea	5	5	6	6	5	7	6	5	5
Pinus halepensis	5	5	5	6	5	6	9	5	5
Punica granatum	–	5	5	–	–	–	–	3	5
Quercus ilex	6	5	6	6	5	6	6	5	5

the presence of individuals, amount of leaf litter produced and possibility to attribute leaf litter to an individual tree. Three *P. granatum* individuals were sampled in Istria and five *C. siliqua* plants in Zadar (Marina). All the other samples were comprised of material originating from more than ten trees. Samples gathered after and during rain events were spread in a thin layer and air dried for 2 weeks before storing. Samples were stored in open paper bags at room temperature and humidity.

Fuel Moisture Content Determination and Morphological Measurements

During leaf litter flammability testing, one or two random subsamples per sample were taken for fuel moisture content (FMC) measurements. These samples were equal in size to the flammability test samples (3.0 ± 0.1 g) and their FMC was calculated on dry mass basis according to Eq. (1) and expressed as a percentage (%):

$$\mathrm{FMC}\,(\%) = \frac{\mathrm{FM}\,(\mathrm{g}) - \mathrm{DM}\,(\mathrm{g})}{\mathrm{DM}\,(\mathrm{g})} \times 100 \qquad (1)$$

FM presents the initial mass and DM the dry mass of the sample. DM was determined by reweighing the samples after drying for 24 h at 85 °C. The duration of 24 h was considered sufficient, as the samples were relatively small and a temperature of 85 °C was chosen to ensure fast drying without charring the sample (Turner 1981).

The same subsamples were used to determine leaf litter area. Fragile leaf litter was soaked in warm tap water and flattened with a cloth flatiron before its area was measured with a portable area meter. Specific leaf area (SLA) was calculated by dividing leaf litter area by the corresponding dry mass. Dry mass and leaf litter area of a sample were divided by their corresponding number of individual pieces in order to obtain the average dry mass (AM) and average area (AA) of a single particle, respectively. As *C. siliqua* leaves separate into petiole and leaflets during and after abscission, leaflet, bigger leaflet, or petiole fragments defined an individual particle; for the rest of the species a particle was an individual leaf or a bigger leaf fragment. All measured areas are expressed in cm^2 and masses in grams (g).

Flammability Testing

Leaf litter flammability testing was performed using an epiradiator-based method. After consulting previously conducted research on epiradiator-based leaf litter flammability testing (Ormeño et al. 2009; Petriccione et al. 2006; Trabaud1976) and extensive pretesting, we chose to test 3.0 ± 0.1 g sample material at 400 ± 5 °C epiradiator surface temperature. This combination allowed us to achieve flaming combustion more often than Petriccione et al. (2006) and have longer ignition delay than Ormeño et al.(2009), while using comparable equipment (Kauf et al. 2014). In order to achieve the above specified temperature, a 500 W epiradiator with 10 cm diameter radiant disc and a nominal surface temperature of 420 °C (Alessio et al. 2008a; Delabraze and Valette 1982; Ganteaume et al. 2011a; Ormeño et al. 2009; Petriccione et al. 2006; Saura-Mas et al. 2010; Valette 1990) was connected to a variable voltage transformer allowing us to reduce the surface temperature, which was constantly monitored using a K-type temperature probe (GES 900, Greisinger, Germany). As measurements showed that the temperature across the epiradiator surface varied with a variability coefficient of approximately 10 % (data not shown), temperature was measured at a fixed point on the surface and the test would start only if the temperature reading was steady in the aforementioned range. The same temperature probe was used to monitor surface temperature and measure temperature related flammability parameters. All the temperature readings were in °C. Even though the used temperature probe has a relatively long response time, it was the same for all the samples allowing us to compare temperature results within our set of measurements.

Additionally, the chosen amount of material was sufficient to form a layer covering the whole epiradiator surface ensuring a similar heat exposure for all the samples and counterbalancing the potential influence of variable temperature across the epiradiator surface. The horizontal pilot flame was positioned 4.5 cm above the epiradiator surface. Four parameters were measured: (i) ignition delay (ID)—the time elapsed between placing a sample on the epiradiator surface and the appearance of a flame, (ii) flame extinguish time (FET)—the time elapsed between placing a sample on the epiradiator surface and the end of the flaming combustion, (iii) ignition temperature (IT)—the temperature measured at the moment of ignition, and (iv) max temperature (MT)—the maximal temperature reached during the test. Flame residence time (FRT) was calculated as the difference between FET and ID, representing the duration of flaming combustion. ID is considered to be a measure of ignitability and FRT a measure of the sustainability component of flammability (Blackhall et al. 2012; Ganteaume et al. 2011b; Ormeño et al. 2009). FET is taken as an additional sustainability measure. Flame intensity was not determined. Time variables were measured using a stopwatch and expressed in seconds (s). Our targeted minimum number of individual tests for different samples was five. An exception was made for *P. granatum* at the location Trstenik in July (Table 1).

Flammability tests were performed on three separate occasions: beginning of September (5–6.9.2010), beginning of October (4–5.10. 2010), and end of October (30.10.2010). May samples were tested on the first and second flammability testing occasion, July samples on the second and September/October samples on the third. Samples were tested in series with breaks between series. In every series, all samples tested on the given occasion were tested once in random order. There was an exception made for *P. halepensis* leaf litter gathered in May at Trstenik, which was tested twice in three separate series. This was because ID was obviously shorter than that of corresponding materials and we wanted to make sure that this was not due to a mistake in the testing procedure. Samples that were tested fewer times were randomly assigned to the series. Testing was performed in a closed room under a simple chamber, minimizing disturbance due to external air movement. As the samples were air dry before bagging, the bags were open and their position frequently changed and stored for a relatively long period under the same environmental conditions, we attributed differences in final moisture content to intrinsic characteristics of the material (Anderson 1990; Kreye et al. 2013) and did not additionally condition them before testing.

Statistical Analysis

IBM SPSS Statistics 21 software was used for statistical analysis of the results. The relationships between FMC, the measured morphological characteristics and flammability parameters were examined through correlation and regression analysis on the sample level. Correlation analysis was based on Pearson's correlation coefficient and regression on ordinary least square method. Regression results are reported if they were significant and with a coefficient of determination (r^2) higher than 0.30. Exceptionally, FMC results are reported despite a lower r^2. As SLA of *P. granatum* is much higher than that of any other species included in this study, regressions examining the influence of SLA might be distorted and the significance level overestimated due to *P. granatum* values. In order to check for this possibility all regressions involving SLA were performed with and without *P. granatum* data. They were reported only if both analyses were significant and had similar coefficients. Pearson's coefficient was used to assess correlations between parameters. For correlation analysis, the reciprocal of SLA was used as it was normally distributed.

The effect of species, location and sampling time, and their interactions on the determined parameters was explored by means of a generalized linear-mixed model (GLMM). Sampling time presented repeated measurement; location, species, and individual replicate number defined the data structure. Accounting for data structure was necessary since the subjects (location, species, and individual replicate) were not independent from each other. Rather, they were nested in each other, thus the samples were not completely random. In our study, species were nested within location, and individual replicates were nested within species, thereby creating a hierarchical structure in the data. We accounted for this hierarchy by indicating location as the highest, species as intermediate and individual replicate number as the lowest level of the hierarchy in the data. A separate model was created for each parameter, respectively. For all flammability parameter models species, location, sampling time, and all possible interactions were treated as fixed effects; with the final model being the one in which all effects were significant and further removal of any of them led to a substantial increase of the absolute value of the Akaike information criterion (AIC), indicating a reduced goodness of fit.

Additional analysis, using the same procedure while excluding repeated measurements and the influence of sampling time, was performed only on July samples in order to determine if different populations of the same species produced leaf litter with different flammability characteristics. This analysis was performed exclusively on July samples as they were gathered as soon as possible after leaf abscission of evergreen species, thus exposure to environmental conditions was minimal and it could be presumed that differences in leaf litter flammability, if present, were inherited from living vegetation.

When determining the influence of species, location, and sampling time on non-flammability related parameters, analysis was performed on sample means with exclusion of interactions. This was due to a lower number of measurements. Furthermore, all three main effects (species, location, sampling time) remained in the model even if their influence was not statistically significant, as their removal increased the absolute value of AIC to such an extent that retaining them was considered justified.

In all GLMM-Satterthwaite approximation was used to account for unbalanced data. Possible differences between levels of fixed effects left in the model were tested by pairwise contrast adjusted for multiple comparisons using the sequential Sidak method. Results were considered statistically significant at $P < 0.05$. Nevertheless, some of the results that failed to fulfill this criterion are discussed as well.

Results

Correlation and Regression Analysis

Due to the multi-collinearity of parameters (Table 2) and the relatively small number of variables, only simple regression analyses were performed. All reported regressions were significant at $P < 0.001$ (Table 3). When examining the relationship between morphology and flammability parameters, SLA was the morphology parameter exhibiting the highest r^2. An increase of SLA led to a decrease in FRT ($r^2 = 0.446$) and an increase in IT ($r^2 = 0.432$). Furthermore, our results revealed a relationship between particle size (AA and AM) and ignitability (ID and IT), since increasing particle size led to a prolonged ignition delay and a higher ignition temperature. Regressions involving FMC had lower r^2 in comparison to morphology parameters, with an increase in FMC leading to an increase of IT and a decrease of both FET and FRT.

Influence of Species, Sampling Time and Location on Fuel Moisture Content, Measured Morphology, and Flammability Parameters

FMC values were relatively low for all samples and ranged from 6.3 to 13.7 %. Despite the identical storing conditions and low values, both species and sampling time had a significant effect on FMC (Table 4). At the species level, the average FMC ranged from 8.4 % for *O. europaea* to 11.6 % for *C. siliqua*, with three homogenous subsets identified by pairwise contrasts. During the sampling period, the average FMC decreased from May (11.4 %) to September/October (9.5 %). Pairwise contrasts separated May from the other two sampling times, with no significant differences between July and September/October.

Species had highly significant effects on morphology parameters. While SLA was significantly affected only by species, AA and AM were significantly affected by location as well. Both AA and AM increased along the climate gradient, from north to south, and had significant pairwise contrasts between Istria and Trstenik. Zadar did not differ

Table 2 Pearson's correlation coefficient for all measured parameters

	ID[a]	FET[b]	FRT[c]	IT[d]	MT[e]	1/SLA[f]	FMC[g]	AA[h]
FET[b]	0.046	1						
FRT[c]	−0.438**	0.878***	1					
IT[d]	0.567***	−0.461**	−0.686***	1				
MT[e]	0.131	0.320*	0.226	0.194	1			
1/SLA[f]	−0.382*	0.396**	0.553***	−0.658***	−0.147	1		
FMC[g]	0.189	−0.490**	−0.532***	0.541***	0.147	−0.166	1	
AA[h]	0.592***	−0.019	−0.306	0.555***	0.430**	−0.480**	0.315*	1
AM[i]	0.633***	0.142	−0.154	0.412*	0.417*	−0.319*	0.138	0.966***

Data are pooled from all six species collected at three locations in Croatia on three sampling dates, respectively.

Significant at * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$

[a] Ignition delay—the time elapsed between placing a sample on the epiradiator surface and flame appearance

[b] Flame extinguish time—time elapsed between placing a sample on the epiradiator surface and end of the flaming

[c] Flame residence time—duration of the flaming combustion, calculated as FET-ID

[d] Ignition temperature—temperature of the material at the moment of ignition

[e] Max. temperature—maximal temperature of the material reached during the test

[f] Specific leaf area—leaf litter area divided by the corresponding dry mass. For correlation analyses the reciprocal of specific leaf area was used

[g] Fuel moisture content—expressed on dry weight basis

[h] Average area of a single particle—leaf litter area divided by the corresponding number of particles

[i] Average dry mass of a single particle—dry mass of a sample divided by the corresponding number of particles

Table 3 Results of the linear regression analysis performed on the whole data set

Linear regression models, $y = a + bx$

y	a	b	x	r^2	p
ID[a]	10.03	0.25	AA[e]	0.350	0.000058
ID[a]	9.97	16.93	AM[f]	0.401	0.000009
IT[b]	399.96	0.81	AA[e]	0.308	0.000204
IT[b]	390.97	0.25	SLA[g]	0.432	0.000001
IT[b]	379.45	265.63	FMC[h]	0.292	0.000126
FET[c]	60.53	−138.49	FMC[h]	0.240	0.000630
FRT[d]	51.71	−166.91	FMC[h]	0.283	0.000170
FRT[d]	44.40	−0.16	SLA[g]	0.446	$7.345E^{-7}$

Regression coefficients (a = intercept and b = gradient), coefficient of determination (r^2), and P values are reported. Flammability related parameters were taken as dependent (y), morphology parameters and fuel moisture content as independent (x) variable. Data are pooled from all six species collected at three locations in Croatia on three sampling dates, respectively

[a] Ignition delay—the time elapsed between placing a sample on the epiradiator surface and flame appearance

[b] Ignition temperature—temperature of the material at the moment of ignition

[c] Flame extinguish time—time elapsed between placing a sample on the epiradiator surface and end of the flaming

[d] Flame residence time—duration of the flaming combustion, calculated as FET-ID

[e] Average area of a single particle—leaf litter area divided by the corresponding number of particles

[f] Average dry mass of a single particle—dry mass of a sample divided by the corresponding number of particles

[g] Specific leaf area—leaf litter area divided by the corresponding dry mass

[h] Fuel moisture content—expressed on dry weight basis

from either location, based on AM, and built a group together with Trstenik based on AA. Even though the effect of sampling time on AA and AM was not significant, both of these parameters were highest in July.

ID and IT were the only flammability related parameters that were significantly affected by location (Table 4). For both of these parameters, the average value decreased from north to south, but pairwise contrasts were significant only for IT showing significant differences between Istria and Trstenik, whereas Zadar did not differ from the other sites. Species and sampling time had a significant effect on all flammability related parameters. Pairwise contrasts at the species level identified four groups based on ID. *C. siliqua* was identified as the least and *P. halepensis* as the most ignitable species, with both differing from all other species. *P. halepensis* was followed by *Q. ilex* and *P. granatum*. There were no significant differences in ID between *P. granatum*, *O. europaea*, and *A. unedo*. Nevertheless, these three species were significantly different when comparing their IT, FET, and FRT. *P. granatum* had the highest, *A. unedo* an intermediate and *O. europaea* the lowest IT. Their ordering based on sustainability was opposite to that based on IT. *O. europaea* was the most, *A. unedo* intermediate and *P. granatum* the least sustainable among them, regardless of the parameter used (FET or FRT). For the rest of the species FRT and FET resulted in different grouping.

Sampling in September/October yielded both the highest sustainability (FET and FRT) and ignitability (ID and IT). July samples had an intermediate (FET) to low (FRT) sustainability and low ignitability (ID), whereas May samples had an intermediate ID, the highest IT, and a low sustainability (FRT and FET).

Species × location was the only significant interaction (Table 4). It influenced all time related parameters revealing species-specific responses of these parameters to the local environmental conditions (Fig. 3). Out of six species included in our study, four (*A. unedo*, *C. siliqua*, *O. europaea*, and *P. halepensis*) showed a decrease in the ID value from north to south along the climate gradient, with pairwise contrasts being significant for *A. unedo* and *P. halepensis* (Fig. 3a). *Q. ilex* and *P. grantum* did not follow the same trend: *Q. ilex* reached the lowest ID value in Zadar and *P. grantum* in Istria. These two species (*Q. ilex* and *P. granatum*) together with *A. unedo* were the ones whose ranking changed the most when comparing species differences within one location. In contrast, *P. halepensis*, *O. europaea*, and *C. siliqua* had a stable ranking between locations as the species with the shortest, an intermediate and the longest ID, respectively.

Regardless of the sustainability parameter used *C. siliqua*, *O. europaea*, and *P. halepensis* showed an increase in sustainability from the northernmost to the southernmost location. Within species and between locations pairwise contrasts of both FRT and FET were significant for *C. siliqua* (Fig. 3b, c). FRT comparisons almost reached the significance threshold for *O. europea* ($P = 0.057$) and *P. halepensis* ($P = 0.061$). The same was true for the FET value of *Q. ilex* ($P = 0.088$), with the highest value reached in Istria, an intermediate in Trstenik and the lowest in Zadar.

None of the interactions involving sampling time had a significant effect in any of the models. Nevertheless, the influence of sampling time was not consistent across locations for all species, as can be seen when looking at ID (Fig. 4). The inconsistent effect of sampling time on different species can be best observed by ID results at the site Trstenik (Fig. 4c), where three species showed almost no change throughout the testing period, while the other three showed a very pronounced increase of ID values in July.

Influence of Location on Flammability Parameters of Different Species in July

The effect of location was not significant for any of the flammability parameters measured in July, while the effect

Table 4 Results of the generalized linear mixed models for all measured parameters

	ID[a] (s)	FET[b] (s)	FRT[c] (s)	IT[d] (°C)	MT[e] (°C)	SLA[f] (cm^2/g)	FMC[g] (%)	AA[h] (cm^2)	AM[i] (g)
AIC	1,035.294	1,494.751	1,496.444	1,723.430	2,099.232	239.56	−203.291	124.322	−122.447
	P	*P*	*P*	*P*	*P*	*P*	*P*	*P*	*P*
Fixed factors									
Species (S)	<0.001	<0.001	<0.001	<0.001	0.007	<0.001	<0.001	<0.001	<0.001
Location (L)	0.001			0.030		0.240	0.423	0.004	0.0013
Samp. time[f]	0.018	0.027	0.005	0.005	0.023	0.313	<0.001	0.439	0.139
S × L	<0.001	0.044	0.046						
	Mean (SE)	Mean (SE)	Mean (SE)	Mean (SE)	Mean (SE)	Mean (SE)	Mean (SE)	Mean (SE)	Mean (SE)
Species									
A. unedo	12.230 (0.287)^{c}	46.006 (0.780)^{b}	33.836 (0.783)^{b}	408.65 (1.17)^{b}	561.26 (2.51)^{b}	69.192 (1.829)^{c}	10.9 (0.3)^{c}	11.153 (0.423)^{d}	0.162 (0.009)^{d}
C. siliqua	15.787 (0.395)^{d}	46.711 (1.040)^{b,c}	30.861 (1.058)^{b}	416.85 (1.61)^{c}	559.80 (3.32)^{a,b}	62.816 (2.574)^{c}	11.6 (0.4)^{c}	17.180 (0.578)^{e}	0.281 (0.012)^{e}
O. europaea	12.000 (0.287)^{c}	50.085 (0.781)^{c}	38.185 (0.784)^{c}	398.52 (1.17)^{a}	553.47 (2.51)^{a,b}	46.131 (1.829)^{b}	8.4 (0.3)^{a}	4.021 (0.423)^{b}	0.086 (0.009)^{b}
P. halepensis	9.112 (0.285)^{a}	46.839 (0.779)^{b}	37.709 (0.781)^{c}	400.49 (1.15)^{a}	551.65 (2.48)^{a,b}	36.466 (1.829)^{a}	10.4 (0.3)^{b,c}	0.632 (0.558)^{a}	0.014 (0.011)^{a}
P. granatum	12.072 (0.495)^{b,c}	35.534 (1.282)^{a}	23.471 (1.313)^{a}	418.00 (2.07)^{c}	545.68 (4.35)^{a}	111.778 (3.334)^{d}	11.0 (0.4)^{b,c}	3.925 (0.721)^{b}	0.034 (0.013)^{a}
Q. ilex	10.797 (0.287)^{b}	48.127 (0.781)^{b,c}	37.233 (0.784)^{c}	406.47 (1.16)^{b}	558.42 (2.50)^{a,b}	62.593 (1.829)^{c}	9.4 (0.3)^{a,b}	7.479 (0.423)^{c}	0.122 (0.009)^{c}
Location									
Istria	11.965 (0.242)^{a}			409.92 (1.01)^{b}		65.572 (1.551)^{a}	10.5 (0.2)^{a}	6.333 (0.372)^{a}	0.101 (0.008)^{a}
Zadar	11.769 (0.232)^{a}			408.17 (1.00)^{a,b}		66.072 (1.594)^{a}	10.3 (0.2)^{a}	7.745 (0.382)^{b}	0.117 (0.008)^{a,b}
Trstenik	11.580 (0.219)^{a}			406.39 (0.88)^{a}		62.844 (1.420)^{a}	10.1 (0.2)^{a}	8.113 (0.357)^{b}	0.132 (0.007)^{b}
Sampling time									
May	11.594 (0.237)^{a,b}	44.945 (0.714)^{a}	33.360 (0.685)^{a}	410.23 (0.98)^{b}	559.55 (2.11)^{b}	66.552 (1.560)^{a}	11.4 (0.2)^{b}	7.493 (0.505)^{a}	0.110 (0.010)^{a}
July	12.291 (0.246)^{b}	46.016 (0.602)^{a,b}	33.726 (0.633)^{a}	408.21 (0.98)^{a,b}	553.35 (1.90)^{a}	63.147 (1.684)^{a}	10.0 (0.4)^{a}	7.630 (0.339)^{a}	0.129 (0.008)^{a}
Sep/Oct	11.390 (0.206)^{a}	47.341 (0.552)^{b}	35.955 (0.556)^{b}	406.04 (0.89)^{a}	552.24 (2.08)^{a}	64.788 (1.311)^{a}	9.5 (0.1)^{a}	7.072 (0.388)^{a}	0.110 (0.005)^{a}

Presented are: Akaike information criterions (AIC) for individual models, *P* values (*P*) for the included fixed factors, means and standard errors (SE) of different levels of the main factors. The measuring unit is indicated in the brackets under the parameter acronym. Differences between levels of factors were determined by pairwise contrasts adjusted for multiple comparisons using the sequential Sidak method. Statistically significant differences ($P < 0.05$) are indicated by different letters right to the values. Data are pooled from all six species collected at three locations in Croatia on three sampling dates, respectively

[a] Ignition delay—the time elapsed between placing a sample on the epiradiator surface and flame appearance

[b] Flame extinguish time—time elapsed between placing a sample on the epiradiator surface and end of the flaming

[c] Flame residence time—duration of the flaming combustion, calculated as FET-ID

[d] Ignition temperature—temperature of the material at the moment of ignition

[e] Max. temperature—maximal temperature of the material reached during the test

[f] Specific leaf area—leaf litter area divided by the corresponding dry mass

[g] Fuel moisture content—expressed on dry weight basis

[h] Average area of a single particle—leaf litter area divided by the corresponding number of particles

[i] Average dry mass of a single particle—dry mass of a sample divided by the corresponding number of particles

[j] Sampling time

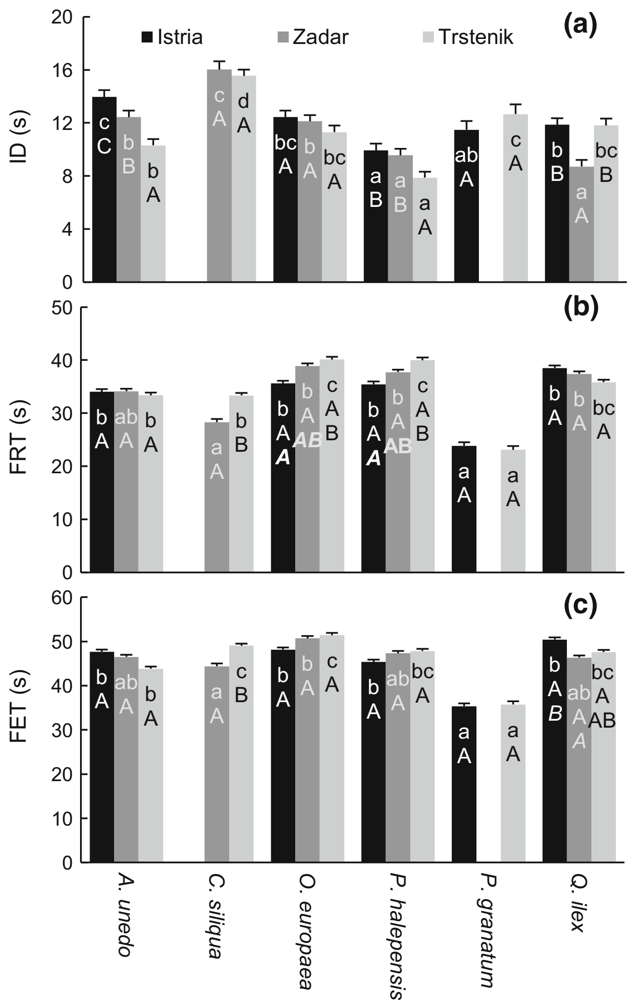

Fig. 3 Time-related flammability parameters for individual species at different locations expressed in seconds (s): **a** ignition delay (ID), **b** flame residence time (FRT), and **c** flame extinguish time (FET). Data represent means and standard errors, with all values in seconds (s). *Lowercase letters* indicate significant differences between species within one location, and *capital letters* indicate between locations within one species significant differences. Differences were considered significant at $P < 0.05$. In the case of flame residence time for olive (*O. europaea*) and Aleppo pine (*P. halepensis*), differences between locations at $P < 0.10$ are indicated with *bold-italic capital letters*

of species was significant for all of them. Even though the species × location interaction was not significant ($P = 0.148$), two of the species, *P. halepensis* and *Q. ilex*, showed similar differences between locations (Fig. 5) compared to the overall results (Fig. 3).

Discussion

Our study confirms the presence of relationships between moisture content, morphology parameters, and flammability. Nevertheless, our results, combined with those previously published, suggest complex interrelations between these characteristics. Furthermore, we showed that sampling location has an inconsistent and species-specific effect on flammability parameters, and that significant changes of leaf litter characteristics occurred within the fire season. One could argue that the relationships found and effects observed represent the result of an inappropriate method used for flammability testing [i.e., testing masses larger than 1 g (Ormeño et al. 2009) at low heat flux (Fernandes and Cruz 2012)]. Nevertheless, we consider the applied method appropriate for simulating the initial stage of wildland fires and testing ignitability of leaf litter with further justification being given in Kauf et al. (2014).

Fuel Moisture Content and Flammability

FMC is widely recognized as an important characteristic influencing flammability and fire behavior (Anderson and Anderson 2009; Chuvieco et al. 2004; Gill and Moor 1996; Pérez-Harguindeguy et al. 2013; White and Zipperer 2010). As adsorption and desorption of moisture has been shown to be species specific and related to litter characteristics (Anderson 1970; Kreye et al. 2013; Schunk et al. 2013), we chose to use air-dried litter without additional conditioning. The significant effect of sampling time, with the highest value reached for most decomposed May samples, is in accordance with findings of Anderson (1990) who showed that weathering shifts the equilibrium moisture content (EMC) to higher values and argued that this should be taken into consideration when estimating EMC throughout the year. As the air-drying period in our study was relatively long, we can presume that the measured FMC represents EMC. Unlike Kreye et al. (2013), we did not find a clear relationship between FMC and morphological characteristics of the samples, but we measured a lower number of morphology parameters, which covered a much smaller variability in parameters and dealt only with low FMC values.

Small differences and low values of FMC can explain the lack of a significant relationship between FMC and ID. An increase in FMC was shown to lead to an increase in ID (Alessio et al. 2008b; Bernard and Nimour 1993; Ganteaume et al. 2011a; Gill and Moor 1996; Saura-Mas et al. 2012; Trabaud 1976; Weise et al. 2005). Nevertheless, if moisture content is low its differences may have a moderate effect on ignition delay, but a significant influence on the mass loss at ignition (Consalvi et al. 2011). A negative relationship between FMC and FRT can be accounted for by a higher moisture content, which led to lower mass available for combustion at the moment of ignition (Bernard and Nimour 1993; Consalvi et al. 2011). Combustion does not start with the appearance of a flame (Trabaud 1976). Glowing combustion preceding flaming results in a pre-ignition reduction of mass and an increase in temperature of the material (Quintiere 2006). For piloted ignition of a solid to occur, pyrolysis products containing gaseous fuels need to be mixed with air in order to provide a flammable mixture at the igniter (Quintiere 2006; Rich et al. 2007). The presence of moisture in the fuel delays the thermal decomposition and water vapor dilutes the released gaseous fuels leading to both a prolonged ignition delay and a higher temperature of the surface exposed to the heat source at the moment of ignition (Atreya and Abu-Zaid 1991). The diluting effect of water vapor might explain the positive relationship between FMC and IT found in our study and previously reported by numerous authors (e.g., Alessio et al. 2008b; De Lillis et al. 2009; Dimitrakopoulos and Papaioannou 2001).

Specific Leaf Area and Flammability

In our study, an increase in SLA led to an increase in IT and a decrease in FRT. In previous studies, no such relationship was found (de Magalhães and Schwilk 2012; Scarff and Westoby 2006). This might be due to the fact that previous analyses were performed on SLA of fresh leaves originating from the same location (de Magalhães and Schwilk 2012). SLA of fresh material may differ from leaf litter SLA due to nutrient retrieval before abscission, decomposition and leaching (Gill and Moor 1996). In addition, a comparably larger data set distributed over a broader range of SLA values was presented here compared by Scarff and Westo (2006).

SLA can be defined as the reciprocal of the product between leaf thickness and density. These two parameters may vary independently in response to environmental conditions (Witkowski and Lamont 1991). Due to the independent variation of leaf thickness and density, we cannot exclude that the relationship found here is due to alterations in either of these parameters. Unlike SLA, these parameters were shown to influence flammability (Kane et al. 2008; Montgomery and Cheo 1971; Papió and Trabaud 1990). Elucidating this problem further would require examining the influence of all three morphology parameters (SLA, leaf thickness, leaf density) on fire behavior.

Particle Size and Flammability

Our study shows that an increase in AA and AM leads to an increase in ID and lower ignitability. In contrast, numerous studies indicate that an increase in size of leaf litter particles leads to higher flammability (de Magalhães and Schwilk 2012; Engber and Varner 2012; Kane et al. 2008; Scarff and Westoby 2006; Schwilk and Caprio 2011). Due to the complexity of vegetation flammability, it is of great importance to (i) determine all measured parameters and flammability components, (ii) know possible limitations of the method used, and (iii) reflect on the definition of flammability in a particular study, when comparing results of various flammability studies. In experimental studies, which reported a positive relationship between particle size and leaf litter flammability, material was exposed to a flaming ignition source which provided enough energy for the appearance of a sustained flame in the material (de Magalhães and Schwilk 2012; Engber and Varner 2012; Kane et al. 2008; Scarff and Westoby 2006). As the material ignited relatively fast and a high variability in the ignition data was present, this approach is considered inappropriate for measuring the ignitability component of flammability (de Magalhães and Schwilk 2012). Nevertheless, it can provide valuable information on other flammability components and an insight on how vegetation material will behave once sustained flaming is reached. Most of these studies focused on sustainability and combustibility, some of them on consumability, while ignitability parameters were not measured (Engber and Varner 2012; Kane et al. 2008; Scarff and Westoby 2006), or did not relate well to any other measured parameter (de Magalhães and Schwilk 2012). These studies imply that bigger particles result in better aeration of litter beds, leading to higher intensity and faster spread of fire, and thus higher flammability. Nevertheless, if sustainability is taken into account as well, the relationship between particle size and flammability becomes less straightforward as an increase in particle size leads to lower sustainability (de Magalhães and Schwilk 2012).

In our study, we focused on the initial stage of fire development. By applying low heat flux we were able to determine ignitability, but at the same time the prolonged ignition delay distorted information on sustainability (Kauf et al. 2014). Our ignitability results provide information on the tendency of litter materials to reach flaming combustion when they come in contact with a low heat flux ignition source, such as common negligence ignition sources. Better aeration of the litter beds might lead to a higher intensity and a faster fire spread in later stages of fire development. However, if ignition is induced by low heat flux, as in our study, a lower packing ration of bigger particles (Scarff and Westoby 2006), which is in turn leading to a higher heat transfer loss between them (Rothermel 1972), might account for the major part of the relationship between ID and particle size found. Our results, together with those previously published, indicate that particle size can have an opposite effect on different flammability components. An increase in particle size reduces ignitability and sustainability, but at the same time increases the combustability of leaf litter.

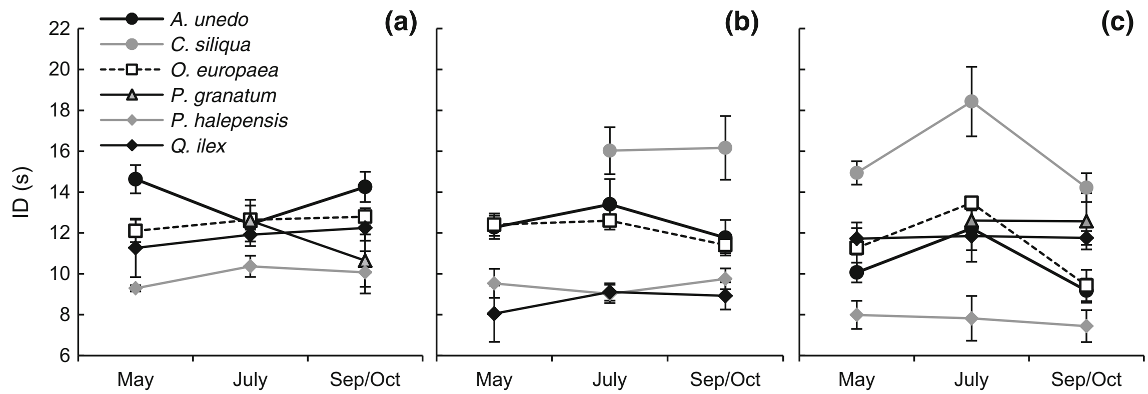

Fig. 4 Mean ignition delay (ID) and standard errors of species at all locations across all sampling times. Sampling was performed in Croatia and graphs present following sampling locations: **a** Istria, **b** Zadar, and **c** Trstenik. Values are expressed in seconds (s)

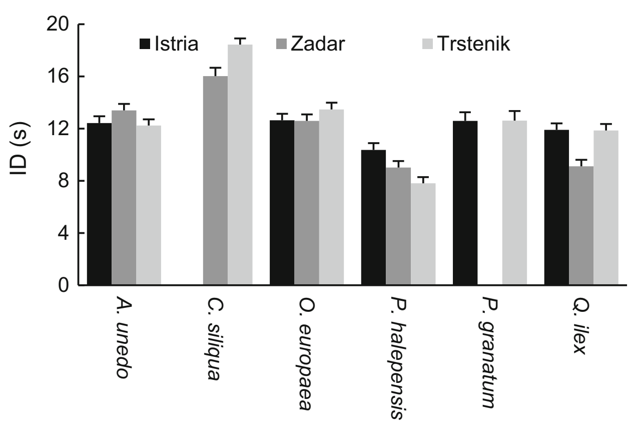

Fig. 5 Means and standard errors of ignition delay (ID) in July for individual species at different locations. Values are expressed in seconds (s)

Effect of Species, Location, and Sampling Time on Flammability

The significant effect of species on flammability parameters is not surprising in view of the large differences in species morphology characteristics and the relationship between morphology and flammability.

The low overall effect of the location can be accounted for by significant species × location interactions, which show that location had a species-specific effect (Fig. 3). As July samples, which represented only freshly fallen leaf litter, did not show any significant within species and between locations differences, it can be presumed that most of these differences are induced by exposure of litter to different environmental conditions and different rates of leaching and decomposition between locations as well as between species. Nevertheless, two species, *P. halepensis* and *Q. ilex*, showed the same order of locations in July as compared to the whole data set. Presumably for these species the lack of a significant effect of location for July samples results from too few replications and low statistical power. The same might hold true for the lack of significant interactions involving sampling time. Though the lack of significant interactions could be interpreted as sampling time having a consistent effect on all the species across all the locations, our data revealed that this was not the case (Fig. 4). The observed overall effect of sampling time on flammability parameters (Table 4) and the results at the sample level (Fig. 4) were unexpected. We expected the highest flammability in July, at the peak of the drought season, and only a gradual change of flammability parameters through the research period. Nevertheless, our results show that flammability parameters of leaf litter change even within a relatively short-time frame. At the current state of knowledge and with the information gathered in this study, we cannot fully explain the mechanisms behind these findings.

July samples were gathered as soon as possible after leaf abscission; they were the least decomposed samples and had the largest AA and AM. On the other hand, decomposition and weathering led to fragmentation of leaf litter particles of May and September/October samples, thereby reducing their area and mass. Taking into account the relationship between particle size and flammability found in our (Table 3) and in previous studies (de Magalhães and Schwilk 2012; Engber and Varner 2012; Kane et al. 2008; Scarff and Westoby 2006; Schwilk and Caprio 2011), it can be presumed that these changes result in an increased ignitability and sustainability with a decreased combustibility and fire intensity. Nevertheless, decomposition also leads to chemical changes (e.g., Aponte et al. 2012; Fioretto et al. 2003; Murphy et al. 1998) and increases the ability of material to retain moisture (Anderson 1990), making the relationship between decomposition and flammability even more complex. Additionally, the fact that leaf litter of *P. granatum* was too far decomposed for us to find recognizable particles in May implies that decomposition influences flammability not only through changing chemical and physical properties on the particle level, but also by being one of the factors governing the fuel load.

Conclusions

Our work does not create a new management option for fire prone ecosystems, but it provides information for improvement of already existing ones and identifies gaps in knowledge relevant for further improvement and development of management options for these ecosystems. We demonstrated that change in a single leaf litter trait can have an opposite effect on different flammability components. This finding shows that, in order to avoid misinterpretation, the relationship between vegetation traits and fire behavior should address individual flammability components. Furthermore, interpreting trait—flammability relationships in terms of individual flammability components would provide more relevant information for fire managers, as different components have different importance in specific situations. For example, increased combustibility and consumability could be beneficial for belowground organisms as heating up of the soil would be reduced (Gagnon et al. 2010). Nevertheless, an increased combustibility in WUI could reduce the time available for evacuation of endangered areas and increase the total WUI area affected by the fire event, resulting in a higher probability of negative socio-economic consequences. Furthermore, the species-specific response at different sampling locations calls for caution when transferring flammability lists from one area to another. Additionally, the significant effects of sampling time on flammability parameters and the fuel moisture content indicate a change in intrinsic characteristics of the material within the fire season, in contrast to the presumptions made in fire danger systems. Further research investigating the relationship between the time of abscission, the amount of litter produced, the climatic conditions, the decomposition rate, and their influence on flammability related properties of litter beds, such as fuel load, bulk density, moisture retention, and drying, could provide important information not only for fire ecology and management, but also for a better understanding of carbon cycles in general.

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8.3. Seasonal and local differences in fresh leaves ignitibility of six Mediterranean tree species

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Title: Seasonal and local differences in fresh leaves ignitibility of six Mediterranean tree species

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Article Type: Research Paper

Keywords: fire, flammability, climate gradient, epiradiator testing, sclerophylly.

Highlights:

- Relationship between drought and moisture content is not governed by rooting depth
- Moisture content of fresh leaves is highly influenced by phenology
- Plant diseases can induce short term change in fresh leaves ignitability
- Higher level of sclerophylly is associated with higher ignitibility

Abstract

Numerous ecosystems worldwide are shaped by and dependent on the accompanying fire regime. Recent land use and climate change resulted in shifts in the fire regimes and made ecosystems more vulnerable to wildland fires. In order to predict extents and effects of the fire regime change a better understanding of the interactions between the driving factors of fire regimes is necessary. In our study we investigated the relationship between weather conditions, fuel moisture content (MC) and ignitability of leaf samples collected from 20-25 centimetre long terminal branches of six Mediterranean tree species. Sampling was performed through the fire season at three locations positioned along the climate gradient in the Mediterranean biogeographic region of Croatia. Epiradiator based ignitability testing showed significant relationships between MC and both ignition frequency and ignition delay when results for all the species was analysed together. Values and fluctuation patterns of MC were species specific and no overall relationship between MC and weather conditions (expressed as Keetch-Byram Drought Index) was found. Additionally, we found that plant diseases can have short term, measurable effects on MC and ignitability. Furthermore, our study, in which samples were within the natural range of MC, indicated that an increase in sclerophylly results in increased ignition frequency; whereas studies which were performed on dried leaves showed increasing “fire retardance” with increasing leaf thickness.

The high range of fresh leaves’ MC, its species specific fluctuations and values, together with the strong relationship between MC and ignitibility call for further investigation of the relationship between leaf morphology, MC and thermal properties of the live vegetation before deciding on the importance on leaf thickness/sclerophylly as a trait governing fire behaviour. Furthermore, species specific MC values, fluctuations and responses point out to the importance of accounting for species composition when predicting fire probability, behaviour and effects.

Introduction

Fire is an integer part of numerous ecosystems worldwide, with as much as 40% of the world's ecosystems owing their distribution and ecological properties to the accompanying fire regime (Bond, Woodward, & Midgley, 2005). In Mediterranean ecosystems fire had a crucial role in governing community composition, maintaining habitat heterogeneity and biological diversity (Bros, Moreno-Rueda, & Santos, 2011). In recent decades, land use coupled with climate change resulted in shifts in fire regimes and higher ecosystem vulnerability to wildfire (Kauf, Fangmeier, Rosavec, & Španjol, 2015). In order to predict the extent of the fire regime change and impacts of these changes on ecosystem functioning, understanding of the interactions between the drivers of fire activity is crucial. At the landscape level, initiation and spread of fire result from complex interactions between ignitions, fuel characteristics, climate and topography (Rothermel, 1983). Investigating the effects of weather elements on moisture content (MC) of fuels, and effects of MC on fire behaviour could provide promising and usable results for fire managers (Gisborne, 1928; Slijepcevic, Anderson, Matthews, & Anderson, 2015). MC of dead fuels is governed by physical processes, whereas live vegetation actively responds to environmental conditions and regulates water content. MC of live fuels depends on morphological and physiological adaptation strategies, as well as on the phenological stage of the plant (Pellizzaro, Cesaraccio, Duce, Ventura, & Zara, 2007) making predictions of live vegetation MC challenging. MC is identified as one of the most important characteristics of fuels governing fire behaviour (Fernandes, Botelho, Rego, & Loureiro, 2008) and it is often included in models as predictor of fire crowning potential (Alexander & Cruz, 2013). Thus, data on fluctuation pattern and variation range of different species could provide useful information for fire danger assessment. Even though it is generally accepted that an increase in MC reduces the probability of ignition, some species readily ignite at relatively high MC (Alessio et al., 2008). Thus, complementing studies on MC fluctuation with ignition tests should provide more complete information on the risk of crown ignition.

This study aimed to examine the relationships between weather, MC and ignitibility of live fuels. Furthermore, we were interested in determining whether there are explanations, other than weather, for the observed relationships. We measured natural fluctuation of MC and laboratory determined ignitability of six Mediterranean shrub/tree species through a fire season, across three locations positioned along a climate gradient in the Mediterranean biogeographic region of Croatia. We focused on shrub and tree species as previous studies showed that they exhibit highly variable MC response to weather conditions (Pellizzaro, Duce, Ventura, & Zara, 2007).

We expected that, despite significant differences between species and species specific variations, there exits universal rules of parameter fluctuation and relationships between parameters.

In particular, we expected that:

- Samples with the highest proportion of young leaves will have the highest MC.
- Decrease in MC will result in an increase of ignitability, i.e. increase of ignition frequency (IF) and decrease of ignition delay (ID).
- Species will exhibit minimal MC and maximal ignitability at the end of the drought period.
- Ignitability will increase along the climate gradient, following an increase in temperature parameters.

Material and methods

Study area

The present study was conducted in the Mediterranean biogeographic region of Croatia (Fig 1.) where a distinct climate gradient can be observed. From northwest to southeast there is an increase in: all temperature indices (average, max and min), precipitation amounts outside the drought period, severity and duration of drought. Three main sampling locations which represent a transect of these conditions were chosen.

The northernmost main sampling site was located in the vicinity of the city of Rovinj (45°6'N, 13°36'E) with an average annual temperature of 13.8°C and 811 mm of precipitation a year. The intermediate main sampling site was located in Kožino, near the city of Zadar, (44°10'N, 15°11'E) with an average annual temperature of 15.3°C and yearly precipitation of 853.9 mm. The southernmost sampling site was located in the Trstenik area (42°54'N, 17°23'E). It is characterised by average annual temperature of 16.5°C and yearly precipitation of 1016.8 mm. Details on meteorological conditions and climate of the sampling sites can be found in the supplementary material.

Two auxiliary sites, with climatic conditions comparable to the corresponding main sites, were established as we were unable to find all the individuals of interest at the main sampling sites. *Punica granatum* samples were gathered in Frančeskija (45°28'N, 13°31'E) as all the individuals in the Rovinj area were intensely managed. Information from Rovinj and Frančeskija were analysed together and referred to as "Istria". A similar problem was encountered in Zadar area for *Ceratonia siliqua*, thus *C. siliqua* samples were gathered in Marina (43°30'N, 16°6'E). Zadar and Marina data were analysed together and referred to as "Zadar". At Trstenik all species of interest were present within the same location.

Sampling procedure and schedule

Six species were included in our study. *Quercus ilex* and *Pinus halepensis* are the most important forest trees and *Olea europaea* the most important agricultural tree crop in the region. *Arbutus unedo* is a forest species with potential agricultural uses and *C. siliqua* an agricultural species with abundant volunteer populations. *P. granatum* is a deciduous species which was included due to its specific leaf morphology (small and remarkably thin leaves).

All species were sampled at the three locations, except *C. siliqua* which was not sampled in Istria, as winters there are too cold for establishment of this species.

In order to capture extreme values our intention was to identify two individuals with contrasting characteristics for all species at every location, and sample them throughout the study period. If the chosen individuals were small, a bulk sample of similar individuals presented a sample. Exceptions were made for *P. granatum* at all three sampling locations and *C. siliqua* in Marina. In these cases all available specimens were similar and one bulk sample was gathered during each sampling occasion. Sampling was performed on a monthly base, from May to October 2010 at Zadar and Trstenik, and from June to October in Istria. Samples were comprised of 20-25 centimetre long, south exposed, lower terminal branches gathered between 12 and 15 o'clock. They were tightly wrapped into plastic foil and placed into a cooler box until reaching the laboratory, where they were brought within 24 hours after sampling. Even though the time elapsed between sampling and testing was relatively long it was same for all the samples making obtained results comparable within the study.

Laboratory measurements

Upon arrival to the laboratory leaves were separated from the branches. In the process two subsamples were taken for determining MC. The rest of the leaves were stored in the refrigerator in a tight plastic bag until ignitability testing. MC was expressed on dry weight basis according to Turner (Turner, 1981). Dry mass of a sample was determined by reweighing the samples after drying for 24 hours at 85°C.

We started with epiradiator based ignitability testing (Alessio et al., 2008; Valette, 1990) as soon as possible. We used the same equipment and recorded all the parameters as we did for leaf litter (Kauf, Fangmeier, Rosavec, & Španjol, 2014). Additionally, ignition frequency (IF) was determined for fresh leaves as flames did not appear in all the tests. IF was defined as ration between number of tests in which flames appeared (positive tests) and total number of tests. Here we present results of testing 5±0.1 gram samples at 400±5°C epiradiator surface temperature. We choose to focus on ignitability related parameters, ignition delay (ID) and IF, as our previous work showed that sustainability data determined by the epiradiator based method can be distorted in case of prolonged ID (Kauf, Fangmeier, Rosavec, & Španjol, 2014). ID was measured with a stop watch and presents the time between placing a sample on the epiradiator surface and appearance of flames. For each sample testing was repeated until 3 positive or 3 negative tests were obtained, resulting in 3 to 5 replications per sample.

Keetch-Byram Drought Index (KBDI)

KBDI was calculated according to tables provided by Keetch and Byram (1968). It was chosen as drought indicator as data necessary for its calculation is readily available. Furthermore, it was shown to correlate well with moisture content of soil, litter and grass fuels in Mediterranean conditions (Ganatsas, Antonis, & Marianthi, 2011). The weather data was taken from Portorož –airport (Source: ARSO - meteo.si), Rovinj, Zadar, Split-airport and Korčula (Source: DHMZ – meteo.hr) meteorological stations for the Frančeskija, Rovinj, Zadar, Marina and Trstenik sampling sites, respectively.

Statistical analysis

SPSS 22 was used for statistical analysis. In order to elucidate relationships between measured parameters (MC, ID and IF) and drought index (KBDI) we performed simple regression analyses between all pairs of variables. Regression analyses were performed on two different levels: overall results and within species relationships. Input data at the overall level represented species averages for sampling occasion and location (n=97), whereas within species regression analysis were performed using sample averages as the input data (n=173).

Influence of species, sampling site and sampling time on MC, IF and ID were investigated by means of generalized linear mixed models (GLMM). In case of ID all main factors (species, sampling time and location), two-way and three-way interactions were included in the model as fixed effects. For MC and IF three-way interaction was not included as insufficient number of input data was available. When creating individual models we accounted for the hierarchical structure present in the data and applied Satterthwaite approximation due to unbalanced data. Significant differences between levels of fixed factors were determined by pairwise contrasts adjusted for multiple comparisons using sequential Sidak method.

Results

Regression analyses

On the overall level there was no significant relationship between KBDI and any other parameter (Table 1.). Nevertheless, MC and ID of *A. unedo* and *O. europaea* were significantly affected by KBDI. Additionally, *A. unedo* exhibited a significant relationship between KBDI and IF. Change of MC affected both ID and IF on the overall level. Both of these relationships were significant for four species; MC-IF relationship had r^2>0.3 for all of them, and MC-ID only for *O. europaea*. Neither ID nor IF of *C. siliqua* were affected by change in MC. This was also the case for IF of *P. halepensis* and ID of *P. granatum*.

Effects of species, sampling time and site on the measured parameters

All the factors included in ID and MC model had a significant effect, whereas sampling site and sampling site x sampling time interaction had no significant effect on IF (Table 2.). ID and MC both identified four homogenous subsets, with same ordering and grouping of species (Fig 2a, c). *A. unedo* and *C. siliqua* had the longest ID and the highest MC; they were followed by *P. granatum* and *P. halepensis*. *P. halepensis* did not significantly differ from *O. europaea* either; whereas *Q. ilex* differed from the rest of the species and had the lowest ID and MC. Based on IF three groups of species were identified. *Q. ilex*, *P. halepensis* and *O. europaea* formed the group of species with the highest IF; *A. unedo* and *C. siliqua* had intermediate and *P. granatum* the lowest IF.

Seasonal fluctuations of ID (Fig. 2d) revealed a decrease of the value during summer months, with the minimum reached in June, recovery in August and a second drop in September. There were no significant differences between spring (May, June) and autumn (October) ID; August ID significantly differed only from July value. Average IF (Fig. 2e) increased from June to September, followed by a decrease in October. In the same time period (June – October) fluctuations of the average MC (Fig. 2f) were opposite to those of IF. Between location differences indicate a decrease of MC and an increase of ignitability from the northernmost to the southernmost sampling site, but none of the pairwise contrast was significant.

Species results for individual months (Fig. 3a-c) and locations (Fig. 3d-f) show species specific responses to environmental conditions. Through the study period ID of *A. unedo* and *C. siliqua* was higher than that of any other species included in the study. ID of *Q. ilex*, *O. europaea* and *P. halepensis* was similar in May, but afterwards ID of *Q. ilex* decreased and was lower than that of *O. europaea* and *P. halepensis* for the rest of the study period. *P. grantum* first reached flaming combustion in July, with July ID similar to that of *O. europaea* and *P. halepensis*. For the rest of the study period *P. granatum* ID was higher than that of *P. halepensis,* and lower than *A. unedo* and *C. siliqua*.

Monthly fluctuations of IF of different species (Fig. 3b) revealed that *Q. ilex* and *P. halepensis* readily reached flaming combustion through the whole study period; *O. europaea* had lower IF in May and June. IF of *A. unedo* and *C. siliqua* did not significantly differ at species level (Fig. 2b), but these species showed remarkably different monthly fluctuation (Fig. 3b). In June average IF of *C. siliqua* was higher by 0.56 than that of *A. unedo,* whereas it was lower by 0.31 in July. From July on the average IF of *C. siliqua* steadily increased, whereas that of *A. unedo* showed only slight fluctuations. First positive tests of *P. granatum* were obtained in July (IF = 0.08), followed by a maximum (IF=0.5) in August, and steadily decreased towards October.

Maximal MC corresponded to samples with the highest proportion of young leaves for all the species, except *P. halepensis*. Nevertheless, timing and extend of MC increase was variable (Fig. 3c). *Q. ilex* had the lowest value and variability of MC, exhibiting only a slight increase in June. *P. granatum* and *A. unedo* were the species with the highest values and variability of MC. They reached the highest values in May and the minimum in August and September, respectively, with an increase in MC towards the end of the study period. MC of *O. europaea* peaked in June, followed by lower values through the summer and a slight increase in October. The peak of MC for *C. siliqua* occurred in July; it was preceded by steady increase and followed by steady decrease of MC. MC of *P. halepensis* steadily increased from June onwards.

Within species monthly fluctuations of parameters added to the variability of data for a single species at any given location. Due to high variability only a few within species between locations differences were statistically significant. *P. halepensis* had significantly lower ID at Trstenik location in comparison to the other two. MC and ID of *O. europaea* showed a statistically significant decrease along the climate gradient, from Istria to Trstenik, whereas *A. unedo* exhibited a significant increase of the IF in the same direction.

Discussion

Relationship KBDI, MC and ignitability

Based on the results of previous studies we expected no significant relationship between KBDI and MC of deep rooting trees (Dimitrakopoulos & Bemmerzouk, 2003; Pellizzaro et al., 2007). Even though the relatively shallow root system might explain the presence of KBDI-MC relationship in the case of *A. unedo*, the significance of this relationship for *O. europaea* indicates that increasing drought can induce MC reduction in deep rooting trees as well. As previously reported, drought induces a drastic decrease of relative water content and stomatal closure in *O. europaea* (Lo Gullo & Salleo, 1988; Lo Gullo, Salleo, Rosso, & Trifilò, 2003). This could explain the strong negative relationship between KBDI and MC for this species found in our study. Furthermore, *A. unedo* and *O. europaea* exhibited a significant increase of ignitability along the climate gradient, confirming that their ignitability is highly affected by environmental conditions.

In our study the highest MC was reached for all species except *P. halepensis* in those samples with the highest proportion of young leaves, confirming that flushing induces an increase of MC regardless of the water availability (Dimitrakopoulos & Bemmerzouk, 2003; Pellizzaro, Duce et al., 2007). As leaves age their dry weight and scleromorphy increase leading to decrease in MC (Kozlowski & Clausen, 1965). Higher MC increases the thermal capacity of the tissues and water vapour dilutes the released gaseous fuels resulting in prolonged ignition delay or absence of flaming combustion (White & Zipperer, 2010), thus the presence of an overall relationship between MC and both ID and IF is not surprising. Whether or not hydrocarbon relocation (Kozlowski & Clausen, 1965) can explain the MC fluctuation pattern of *P. halepensis* remains to be investigated.

At species level the low number of positive tests could explain the lack of a significant relationship between MC and ID for *P. granatum*, whereas constantly high IF despite MC fluctuations accounts for the lack of MC-IF relationship in the case of *P. halepensis*. High ignitability of *P. halepensis*, despite high MC, was previously reported and attributed to high content of isoprenoids in glandular reservoirs and resin ducts (De Lillis, Bianco, & Loreto, 2009).

Ignitability of species and its fluctuation

With the lowest MC, highest IF and shortest ID throughout the study period *Q. ilex* was identified as the most ignitable species tested. Furthermore, fluctuation of the measured parameters was minimal making it reasonable to presume that *Q. ilex* foliage is prone to ignition within the range of environmental conditions covered in our study regardless of phenological stage. The second ignitability group was formed by *P. halepensis* and *O. europaea*. These two species exhibited higher levels of fluctuation for both MC and ID than *Q. ilex*. Unlike *Q. ilex* and *P. halepensis* which readily ignited through the study period, IF of *O. europaea* significantly decreased in June. This decrease can be attributed to olive peacock spot (*Spiloceaea oleaginea*) infection which led to partial defoliation of trees at Zadar. *O. europaea* samples gathered in June at Zadar were composed only of young leaves developed in the year of study and had an IF of 0.38, compared to 0.88 and 1.00 reached in Istria and Trstenik, respectively. The duration of defoliation induced ignitibility reduction was very short, as all the *O. europaea* samples readily ignited in July. The lack of a pronounced decrease of IF at Istria and Trstenik indicates that *O. europaea* would have readily reached flaming through the study period, if there was no *S. oleaginea* infection.

The third group of species is formed by *A. unedo* and *C. siliqua*, species which exhibited very high, unsynchronised, phenology driven fluctuation of MC and ignitability. With its low IF and short ID *P. granatum* formed a separate ignitability group. In our previous work, we argued that extremely low IF can occur in extremely flammable fuels if an inappropriate fuel load-heater temperature combination is applied (Kauf, Fangmeier, Rosavec, & Španjol, 2014). Taking into account crown arrangement and density of *P. granatum*, it would be unreasonable to increase fuel load in the present study. Thus we identify *P. granatum* as the species with the lowest ignitability. Nevertheless, the testing procedure applied here indicates the probability of crown ignition in the early stage of fire development, with resilience to low energy heat fluxes potentially slowing down initial fire spread. Once fire reaches high heat fluxes, different responses might be observed.

The relatively high ignitability of *Q. ilex*, *P. halepensis* and *O. europaea* in comparison to *A. unedo* and *C. siliqua* is in accordance with previous studies (Massari & Leopaldi, 1998; Valette, 1990), whereas information on the fire behaviour of *P. granatum* is limited. In our study, grouping of species based on IF corresponded to the level of sclerophylly of the species: the highest IF was recorded for the typical sclerophyllous species (*P. halepensis, Q. ilex, O. europaea*), the intermediate group included species (*A. unedo* and *C. siliqua*) with low degree of sclerophylly (Gratani & Ghia, 2002; Lo Gullo, Salleo, & Rosso, 1986), and the lowest IF was reached by a typical mesophilic species (*P. granatum*). Increasing leaf thickness was previously identified as a characteristic leading to prolonged combustion and “fire retardance” when single, dehydrated or partially dehydrated leaves were exposed to temperatures higher than or equal to 750°C (Engstrom et al., 2004; Montgomery & Cheo, 1971). In these studies MC was outside the natural range for live leaves of the tested species, thus effects of natural MC fluctuations were excluded. Opposite results obtained in our study (i.e. increasing IF with increased level of sclerophylly), in which MC was within its natural range, confirm the importance of MC as a characteristic governing fire behaviour of vegetation fuels (Fernandes et al., 2008) .

Overall monthly fluctuation results of ID (Fig 2d) were in accordance with our initial hypotheses of ignitability reaching its maximum at the end of drought period. The increase of average ID in August can be attributed to the rain event occurring at all the sampling sites at the end of July/beginning of August. Nevertheless, species specific responses to changes in environmental conditions indicate that results might differ depending on the species included in the research.

Conclusions

Our study confirmed the importance of MC as a factor governing fire behaviour of fresh leaves, with an increase of MC leading to a decrease of ignitability. Nevertheless, within species variations and external factors governing them were species specific. *Q. ilex* showed limited variations of MC and ignitability despite changes in phenology and environmental conditions. Flushing of vegetation resulted in considerable increase of MC and reduction of ignitability of *A. unedo*, *C. siliqua* and *P. granatum* regardless of water availability whereas *O. europaea* showed that plant disease can result in short term measurable effects on ignitability. Furthermore, the significant effect of KBDI on *O. europaea* demonstrates that a strong response of MC and ignitability to increasing drought is not limited to shallow rooting tree/shrub species. Species specific values of MC and ignitability parameters, and their specific response to environmental conditions stress the importance of accounting for species composition when assessing fire danger of an area.

Comparison of our results with previously conducted studies indicates that effects of leaf thickness and/or sclerophylly may be contrary when testing fire behaviour of dehydrated samples *vs*. samples which are within the natural range of MC values for a given species. Thus, before leaf thickness and/or sclerophylly are accepted as a trait which either increase or decrease ignitability of live vegetation, fuels relationship between leaf morphology, MC and thermal properties of the live vegetation should be further investigated.

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Figure capitations:

Fig 1. Map of Croatia with indicated position of sampling sites.

Fig 2. Results of the pairwise contrasts between: species (a-c), sampling times (d-f) and sampling locations (g-j). Bars represent average values and standard errors. Different letters indicate statistically significant differences ($p<0.05$) determined by pairwise contrasts adjusted for multiple comparisons using sequential Sidak method. Parameters are indicated as following: ID - ignition delay, IF – ignition frequency and MC – moisture content. Species are listed as: Au – *Arbutus unedo*, Cs – *Ceratonia siliqua*, Oe - *Olea europaea*, Pg – *Punica granatum*, Ph - *Pinus halepensis*, Qi – *Quercus ilex*. Locations are indicated as: I – Istria, Z – Zadar and T- Trstenik.

Fig 3. Results of the monthly fluctuation of the parameters (a-c) and their differences between locations (d-f) on the species level. Species are listed as: Au – *Arbutus unedo*, Cs – *Ceratonia siliqua*, Oe - *Olea europaea*, Pg – *Punica granatum*, Ph - *Pinus halepensis*, Qi – *Quercus ilex*. Sampling time (a-c) x-axes represents months from May (M) to October (O). Sampling sites (d-f) are indicatedas: I – Istria, Z – Zadar and T- Trstenik. Parameters are: ID - ignition delay, IF – ignition frequency and MC – moisture content. All differences which were significant had $p<0.001$ and are indicated with ***

Table capitations:

Table 1. Results of simple linear regressions determined by the method of least square and represented with the equations $y=ax+b$. x - independent variable, y – dependent variable, a –regression gradient and b-regression intercept. Additionally coefficient of determination (r2) and probability (p) are reported. Analyses were performed on the overall data and at species level. Parameters are: KBDI - Keetch-Byram Drought Index, MC – moisture content, ID – ignition delay and IF – ignition frequency.

Table 2. Effects of species (S), sampling site (L), sampling time (M) and their interactions on ignition delay (ID), ignition frequency (IF) and moisture content (MC). Presented are results of the generalized linear mixed models (GLMM). All the effects were included as fixed factors. Significance of effects is indicated as: * $p<0.05$, **$p<0.01$, ***$p<0.001$. "nt" indicates effects which were not tested due to small number of input data.

Figure 1.

N
Zagreb
Osijek
Frančeskija
Rijeka
Istria
Rovinj
Large cities
Main sampling sites
Auxiliary sampling sites
Biogeographic regions
Mediterannean
Continental
Pannonian
Alpine
Kožino
Zadar
Dalmatia
Marina
Split
Trstenik
0
50
100 km

Figure 2.

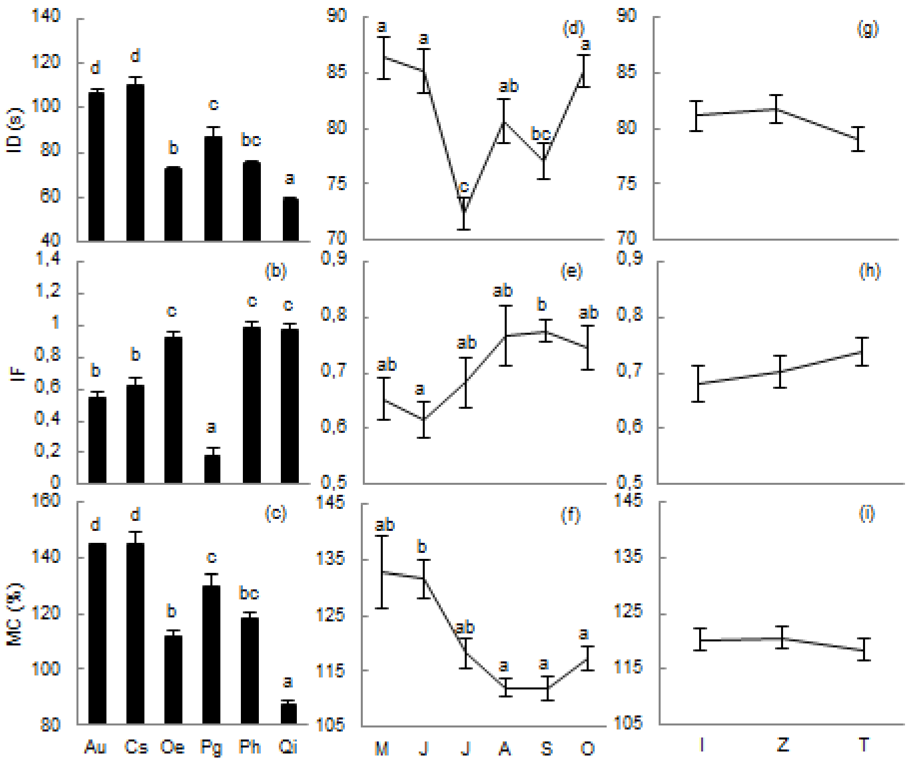


Figure 3.

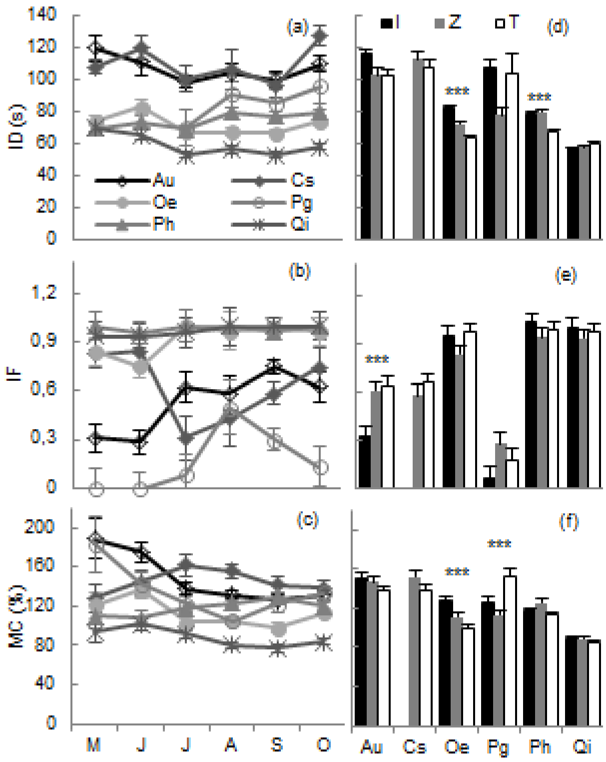


Table 1.

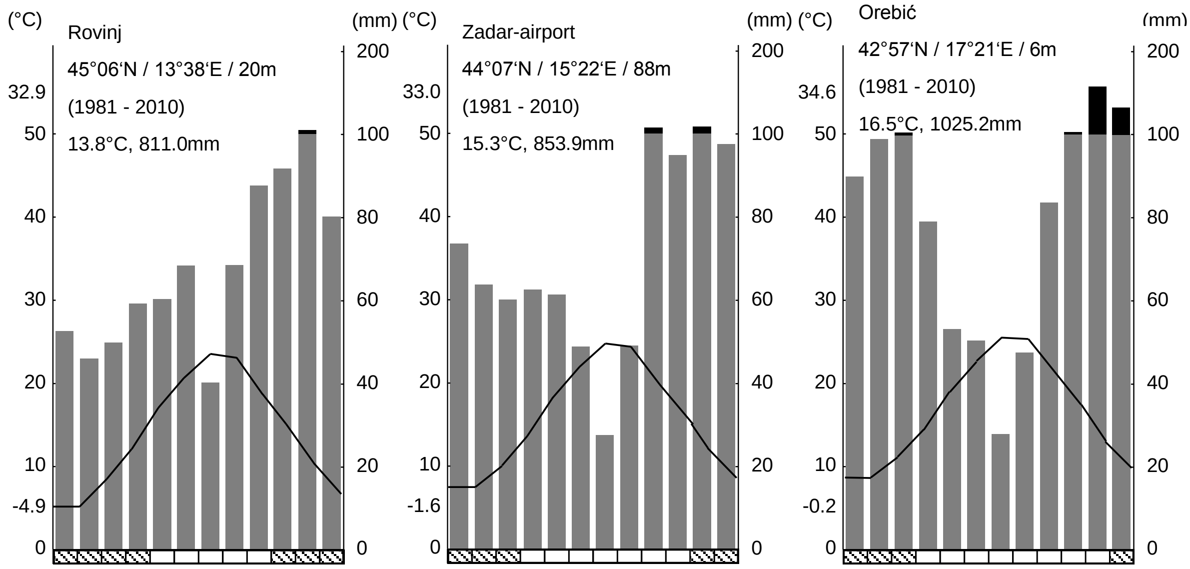
		overall	*A. unedo*	*C. siliqua*	*O. europaea*	*P. granatum*	*P. halepensis*	*Q. ilex*
KBDI-MC	r^2	0.032	0.424	0.160	0.713	0.119	0.083	0.183
	p	0.078	0.005	0.198	<0.001	0.176	0.263	0.087
	a	-0.028	-0.092	0.028	-0.090	-0.057	0.017	-0.030
	b	130.315	169.731	134.554	136.266	147.577	114.086	95.447
KBDI-ID	r^2	0.023	0.568	0.265	0.610	0.091	0.093	0.266
	p	0.161	0.001	0.084	<0.001	0.562	0.234	0.034
	a	-0.018	-0.050	-0.030	-0.052	-0.025	-0.015	-0.021
	b	88.331	120.470	122.119	86.746	96.254	79.787	64.631
KBDI-IF	r^2	0.006	0.308	0.225	0.135	0.107	0.002	0.066
	p	0.465	0.021	0.119	0.146	0.201	0.869	0.321
	a	0.000	0.001	-0.001	0.000	0.001	$8.826E^{-6}$	$8.124E^{-5}$
	b	0.671	0.326	0.917	0.840	0.048	0.985	0.953
MC-ID	r^2	0.691	0.267	0.007	0.621	0.298	0.226	0.202
	p	<0.001	0.002	0.752	<0.001	0.263	0.004	0.008
	a	0.701	0.325	-0.060	0.479	0.591	0.390	0.252
	b	0.357	60.381	119.269	19.211	23.532	29.809	37.205
MC-IF	r^2	0.371	0.338	0.113	0.320	0.356	0.092	0.572
	p	<0.001	<0.001	0.159	<0.001	0.010	0.082	<0.001
	a	-0.008	-0.007	-0.007	-0.004	-0.006	-0.001	-0.003
	b	1.664	1.528	1.673	1.411	0.934	1.104	1.266

Table 2.

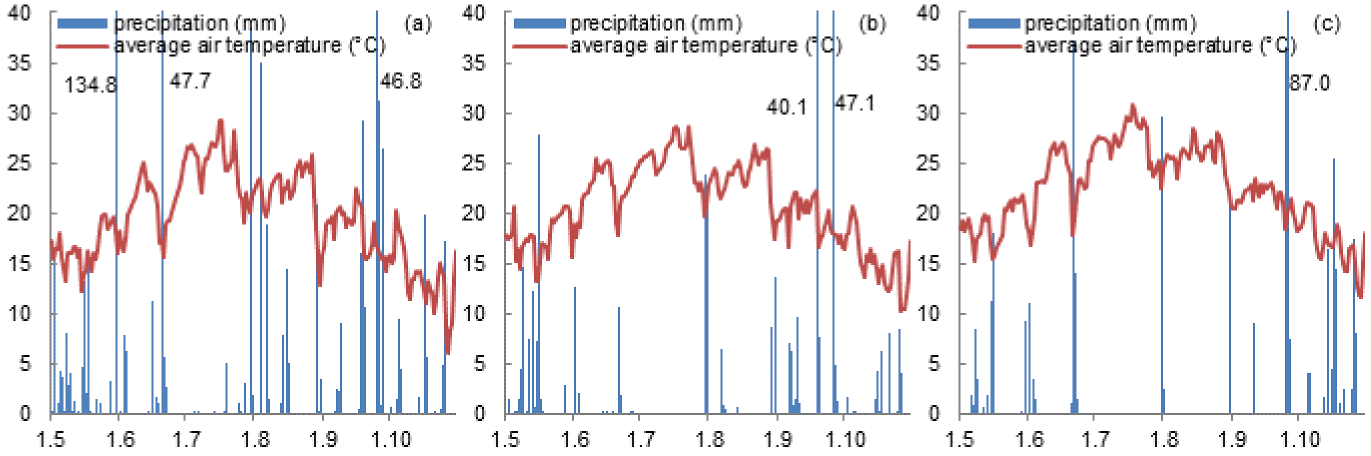
Fixed effects	ignition delay (ID)	ignition frequency (IF)	moisture content (MC)
species (S)	134.373***	60.265***	59.270***
sampling site (L)	9.960***	2.690^{ns}	6.847**
sampling time (M)	10.431***	3.195*	6.875***
SxL	5.456***	3.883**	7.314***
SxM	2.122**	2.902**	3.680***
LxM	3.233**	1.186^{ns}	3.639**
SxLxM	1.661*	nt	nt

Appendix

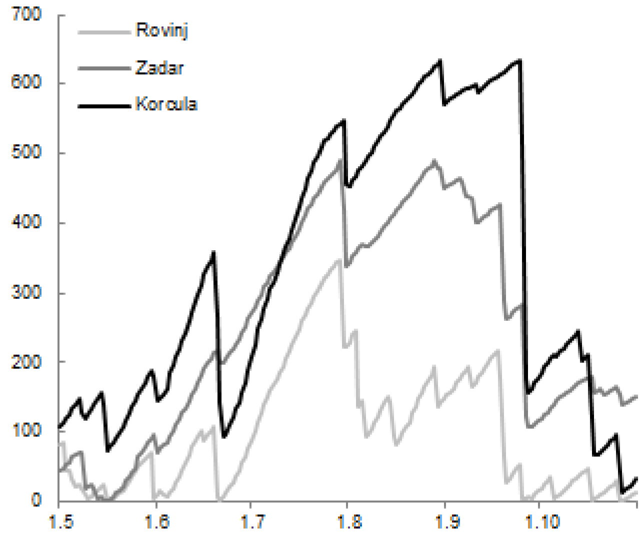
Climate diagrams of the meteorological stations closest to the main sampling sites. Data source: DHMZ – meteo.hr



Weather conditions from 1.5. to 31.10.2010 recorded at the meteorological stations (a) Rovinj, (b) Zadar-airport, (c) Korčula corresponding to main sampling sites Rovinj, Zadar and Trstenik, respectively. Precipitation amounts exciding the length of y-axes (40 mm) are indicated with the exact value next to corresponding column. Orebić meteorological station malfunctioned in the year of study, thus data for Trstenik sampling site was taken from Korčula meteorological station. This station was chosen as the one best correlated the meteorological data available for Orebić, for 2009 and 2010. Data source: DHMZ – meteo.hr



Keetch-Byram Drought Index (KBDI) for the time period between 1.5. – 31.10. 2010 for meteorological stations closest to the main sampling sites: Rovinj, Zadar and Korčula meteorological stations corresponding to main sampling sites Rovinj, Zadar and Trstenik, respectively.



9. Discussion

9.1. Epiradiator-based flammability testing and flammability score

At the starting point of the study presented here, results of epiradiator-based tests were reported with little to no justification for the method used. The authors mostly tested 10 g samples with observations of the initiation of different combustion phases (Trabaud 1976; Massari and Leopaldi 1998; Alessio *et al.* 2008a; Alessio *et al.* 2008b); or 1 g samples focusing solely on flaming combustion (Delabraze and Valette 1982; Valette 1990; Alexandrian and Rigolot 1992; Viegas and Viegras 1997; Moro 2004; Pellizzaro *et al.* 2006a; Petriccione *et al.* 2006; Pellizzaro *et al.* 2007c; Ormeño *et al.* 2009). Further details on the methods used can be found in Section 4.3.4. If not specifically indicated, parameters were used as defined in that section.

It was originally intended to use the same method as Alessio *et al.* (2008a; 2008b) for testing fresh leaves, and the same as Petriccione *et al.* (2006) for testing leaf litter. Whereas the method proposed by Alessio *et al.* (2008a; 2008b) was not followed due to technical reasons, and so was modified in order to obtain relevant results with the available equipment, the method proposed by Petriccione *et al.* (2006) was deliberately modified due to the results obtained during method pretesting. Although the original intention of this work was not to tackle the problem of laboratory vegetation testing, results of the method pretesting (Kauf *et al.* 2014), criticism of the whole approach of testing flammability in the laboratory (Fernandes and Cruz 2012), and the increasing body of work on relating plant traits to flammability, encouraged me to do so.

The pretesting results (Kauf *et al.* 2014) identified two purely technical sources of variation in ignition delay, and challenge one of the basic presumptions of the epiradiator flammability testing. The observed substantial variation of the temperature across the epiradiator surface indicates that if the sample is placed directly on the epiradiator surface, and it does not cover the whole surface area, positioning of the sample might influence ignition delay. The significant effect of sample positioning is confirmed by Pausas *et al.* (2012), who reported discarding some of their test results as the sample was not correctly positioned in the middle of the epiradiator; and Ormeño *et al.* (2009), who stress that samples were positioned in the middle of the epiradiator. Our unpublished pretesting results indicate that if only a part of the epiradiator surface is covered by the sample, samples positioned in the centre will have a shorter ignition delay than those that are not positioned exactly in the centre of the epiradiator surface area.

In addition, the finding that after each test the temperature stabilises at a higher value indicates that measuring the surface temperature is essential for ensuring similar conditions at the beginning of each test. This finding shows that a standardised waiting time between the end of one test and the beginning of the following one, as proposed by Petriccione *et al.* (2006), does not suffice for ensuring uniform temperature exposure at the beginning of each test. Moro (2004) stressed a need for monitoring surface temperature, but most of the authors do not give information on whether or not surface temperature was monitored during the experiment.

Furthermore, comparison of our results with those of Petriccione *et al.* (2006) indicates that extremely low ignition frequency does not guarantee low flammability. This presumption is one of the bases of epiradiator flammability testing (Section 4.3.4.). Petriccione *et al.* (2006) tested 1 g leaf-litter samples at 250°C, and for three out of 14 species, including mastic (*Pistacia lentiscus* L.), reported that flame did not appear in any of the 50 individual tests (ignition frequency = 0). These species were considered to have "null flammability". In our study (Kauf *et al.* 2014), where 3 g samples were tested at 400°C, leaf litter of *P. lentiscus* had the shortest ignition delay, indicating high ignitibility. These results clearly show that different testing procedures can lead to opposing conclusions regarding the fire behaviour of a species.

They also raise a question regarding the choice of the laboratory testing procedure and its relevance when compared to natural conditions. Fernandes and Cruz (2012) argue that none of the epiradiator-based methods has practical relevance, as they employ heat fluxes that are several orders of magnitude lower than the peak heat-release rates of wildland fire. Nevertheless, as shown in Section 3.2, fire does not start at the peak of its intensity. The first prerequisite for any fire to spread is successful ignition (Section 2.1), and ignition sources differ in their heat fluxes. One could argue that as long as there is a potential ignition source that has similar temperature/heat flux to that used in the testing procedure, any temperature/heat flux of the heat source could be acceptable for ignitibility testing, so justifying both (250°C and 400°C) temperatures used. Nonetheless, if one is interested in a response of the material to an incoming flame front, the claim made by Fernandes and Cruz (2012) would hold true, and testing performed at the peak heat-release rate of the ecosystem in which the given material occurs would be a more reasonable option.

The second prerequisite for successful fire spread is sufficient readily available fuel to initially carry the fire. This should also be taken into consideration when choosing the amount of the material to be tested. Ormeño *et al.* (2009), in an experiment in which they were interested in the influence of chemical composition on flammability parameters, argued that samples bigger than 1 g should not be tested with epiradiator-based methods, "as larger fuel masses increase the possibility that other fuel properties, such as fuel height, are involved in flammability changes". Fuel height affects fire behaviour, and there is a clear relationship between sample height and ignition, when holding sample density and specific heat constant (Anderson 1970). In our case, the mass was held constant, and it is very likely that differences in heights and densities were present and influenced the measured parameters. Nevertheless, these differences were governed by particle geometry—an inherit characteristic of material. Unlike Ormeño *et al.* (2009), we were interested in fuel as a whole, and we wanted to include possible influences of the particle geometry on measured parameters, and so testing of bigger fuel masses was justified. Furthermore, testing 1 g samples at an epiradiator with a 10 cm disc diameter corresponds to a leaf-litter fuel load of 0.13 kgm^{-2}, a litter fuel load much lower than that reported for Mediterranean shrublands and woodlands (*e.g.* Santa Regina 2001; Ganteaume *et al.* 2009; Curt *et al.* 2011). Thus, if the focus of the study lies in determining potential differences between species, epiradiator testing of 1 g of leaf litter might be further from the natural conditions than the testing of 3 g.

As explained in the article by Kauf *et al.* (2014), low heat flux combined with the small amount of the material could account for the lack of flaming for *P. lentiscus* reported by Petriccione *et al.* (2006). At low heat flux, glowing combustion precedes flaming (Quintiere 2006), with lower heat flux leading to longer ignition delay and a larger amount of material being combusted before initiation of flaming (Atreya 1998). Thus, testing of 1 g of highly ignitable leaf litter at 250°C might lead to complete combustion of the material before the critical mass flux of gaseous fuels for initiation of flaming is reached.

Furthermore, in both of the articles dealing with leaf litter material (Kauf *et al.* 2014; Kauf *et al.* 2015), we demonstrated the importance of the mass loss occurring before the appearance of flames, and its influence on the duration of flaming (flame residence time). In the first article (Kauf *et al.* 2014), this issue was addressed in light of the heat fluxes that material is exposed to; and in the second (Kauf *et al.* 2015) in light of the moisture content of the fuel. Decrease in ignition-source heat flux and increase in moisture content have a similar effect on the mass loss before the initiation of flaming. Increase in moisture content is commonly related to prolonged ignition delay (Section 1.3.1.1). Nevertheless, if differences in moisture content are relatively low, as they were in our study of leaf litter, these differences might have a limited effect on the ignition delay, but a significant effect on the mass loss before the initiation of flaming (Bernard and Nimour 1993; Consalvi *et al.* 2011).

As well as leading to lower sample mass at the moment of flame appearance (Bernard and Nimour 1993; Consalvi *et al.* 2011), an increase in moisture content leads to an increase in ignition temperature (Atreya and Abu-Zaid 1991; Dimitrakopoulos and Papaioannou 2001; Alessio *et al.* 2008b; De Lillis *et al.* 2009).

The argument that mass available at the beginning of flaming combustion affects its duration indicates that it is not advisable to use the same combination of epiradiator temperature and sample mass for determining ignition delay and flame residence time, as significant differences in ignition delay might distort flame residence time as a measure of sustainability (Kauf *et al.* 2014). Furthermore, this argument indicates a general need to account for inter-sample mass differences at the beginning of the combustion stage of interest. A concern about the effects of the initial mass on the test results was previously raised by White *et al.* (1996). They showed that, when performing cone calorimetry, time to peak heat release rate, time to sustained ignition, and total heat release rate are affected by initial sample mass; whereas peak heat release rate is not. Despite the obviousness of the statement and the compelling evidence that large differences in mass influence combustion duration, there are recent examples of studies in which authors did not account for these differences (*e.g.* Ganteaume *et al.* 2013b; Cornwell *et al.* 2015).

Lastly, the first article (Kauf *et al.* 2014) questioned the meaningfulness of a single flammability score. As can be seen in the Section 4.2, flammability experiments cover a broad range of approaches. Even though there is no validated method of integrating all flammability components into one single index of plant flammability (Behm *et al.* 2011), a flammability score is often attributed to a material. The flammability score is attributed to a material based on diverse parameters, and employing varying complexities in its computation, ranging from a combination of two parameters that address only the ignitibility component of flammability (Section 4.3.4) to hierarchical cluster analysis of 12 parameters derived from cone calorimetry (Liu *et al.* 2013). Contrasting results for the same species are also possible if different testing procedures are used, as shown in our study (Kauf *et al.* 2014) and indicated by Della Rocca *et al.* (2015). Thus, even though flammability as a term is relatively well-defined (Section 4.1), it is loosely used (Fernandes and Cruz 2012), and interpretation of the results often depends on the interpreter (Gagnon *et al.* 2010). We demonstrated (Kauf *et al.* 2014) that comparing species based on their relative flammability is not always possible because sometimes species exhibit different fire behaviours which cannot be compared in terms of “higher” or “lower” flammability, as different parameters may indicate different relative flammability of the material. For these reasons, we advocated reporting the parameters themselves and interpreting them in terms of flammability components or fire behaviour, while paying attention to the testing procedure used.

9.2. Relationship between plant traits and flammability

Investigating the relationship between plant traits and flammability was one of the initial objectives of the work presented here. In both cases, when testing leaf litter (Kauf *et al.* 2015) and fresh leaves (Section 8.3), the results obtained seemingly contradicted those previously published.

When testing leaf litter (Kauf *et al.* 2015), we found a positive relationship between particle size (expressed as average area and average mass of an individual particle) and ignition delay, implying that increase in particle size reduces ignitibility. In contrast, previous studies exploring leaf litter indicated that increase in particle size leads to increase in flammability (Section 1.3.2.4) (*e.g.* Scarff and Westoby 2006; Kane *et al.* 2008; Schwilk and Caprio 2011; de Magalhães and Schwilk 2012; Engber and Varner III 2012). Studies that show a positive relationship between leaf-litter particle size and flammability used a flaming ignition source, and so they tested behaviour of the material once sustained flaming is reached. These studies indicated that larger particles create better-aerated litter beds, resulting in higher flame intensity and faster flame spread. Even though the measured parameters predominantly address combustibility, they were interpreted as representing higher flammability. However, if sustainability is taken into account, and longer flaming duration is interpreted as higher sustainability, results of these studies become less straightforward, as bigger particles might lead to lower sustainability (de Magalhães and Schwilk 2012). In our study we were interested in the initiation of the wildland fires, and thus we tested ignitibility by applying relatively low-energy heat flux to the fuels. In this case, the low packing ratio of bigger particles (Scarff and Westoby 2006) might lead to higher heat transfer loss between them (Rothermel 1972), and consequently prolong ignition delay.

Furthermore, in our study, testing of both leaf litter and fresh leaves showed a significant influence of specific leaf area (SLA) on measured flammability parameters. The leaf-litter results, which show that an increase in SLA leads to an increase in ignition temperature and a decrease in flame residence time, were included in the published manuscript (Kauf *et al.* 2015); whereas the results with fresh leaves indicating an overall (when using sample average as input data) negative relationship between SLA and ignition frequency were not included in the final manuscript, due to the word limit set by the publisher. Nevertheless, the observed relationship between SLA and ignition frequency for fresh leaves added to our confidence when making a statement that in the case of fresh leaves, an increase in sclerophylly leads to higher ignitibility (Section 8.3).

Previous studies on leaf litter found no significant relationship between SLA and flammability parameters, but they either measured SLA of fresh leaves from the same location (de Magalhães and Schwilk 2012), which might differ from leaf litter SLA due to nutrient retrieval before abscission, decomposition and leaching (Gill and Moor 1996); or they covered a smaller range of SLA values (Scarff and Westoby 2006) in comparison to our study. Furthermore, SLA can be defined as a reciprocal of the product of leaf density and thickness. As these two parameters vary independently in response to environmental conditions (Witkowski and Lamont 1991), it cannot be excluded that variation of either of these parameters is responsible for the observed significant influence of SLA on fire-ignitibility of the fuels. In contrast to SLA, both particle density (van Altena *et al.* 2012) and thickness (Montgomery and Cheo 1971; Engstrom *et al.* 2004; Kane *et al.* 2008) were shown to influence fire behaviour of the material.

The statement made in the unpublished article (Section 8.3), that increasing sclerophylly leads to higher ignitibility of fresh leaves, is partly in contrast with previous studies that identify increase in leaf thickness as a "fire-retarding" characteristic (Montgomery and Cheo 1971; Engstrom *et al.* 2004). However, the latter studies were conducted on oven-dry leaves, excluding inter-sample differences in moisture content. Moisture content is generally accepted as one of the most important fuel characteristics influencing fire behaviour (Section 1.3.1.1), and species differ in their natural moisture content range (*e.g.* Dimitrakopoulos and Bemmerzouk 2003; Pellizzaro *et al.* 2005; De Lillis *et al.* 2009; Alexander and Cruz 2013b); thus testing of dried samples and samples within their natural moisture content range might lead to opposite conclusions. This can be seen when comparing results of the oven-dry reconstructed litter beds (Scarff and Westoby 2006; Plucinski and Anderson 2008; de Magalhães and Schwilk 2012; Engber and Varner III 2012; Cornwell *et al.* 2015), which identify leaf size as an important parameter governing fire behaviour, with results of reconstructed litter beds at equilibrium moisture content (van Altena *et al.* 2012) showing no significant effect of particle size. These contradicting results might be explained by the work of Kreye *et al.* (2013b) and Gerrits *et al.* (2010) who showed that traits that promote flaming in dry leaves (*e.g*. thinner and curled leaves) increase equilibrium moisture content (Kreye *et al.* 2013b) and water-storing capacity of leaf-litter fuels (Gerrits *et al.* 2010).

In the case of fresh leaves, the same profound effect of the moisture content can be seen in the work of Murray *et al.* (2013), where native and exotic groups of species had significantly different ignition delays when dry leaves were tested, but showed no differences when fresh leaves were tested. In the latter case, between-group differences in leaf size were counterbalanced by differences in moisture content of fresh leaves. Based on their results Murray *et al.* (2013) called for further investigation of the relationship between leaf morphology, moisture content, and influence of leaf morphology on the rate of water loss. Our observation of lower moisture content and higher ignitibility in schlerophyllous species also calls for further investigation of these relationships before a final conclusion on the influence of leaf size and thickness on fire behaviour is made.

9.3. Seasonal and local differences in ignitibility

We demonstrated that the flammability testing procedure used is best suited for testing ignitibility (Kauf *et al.* 2014); and thus our focus will be on this component of flammability. Combined results of all species and both materials were partially in agreement with our hypothesis (Section 7) that drier and warmer conditions result in a higher tendency of material to burn (in our case, a higher tendency to ignite). Seasonal fluctuation in fresh leaves showed lower ignition delay values during summer in comparison to autumn and spring. The increase in ignition delay in fresh leaves in August was attributed to a high precipitation event occurring at all the sapling locations at the beginning of the month in question (Section 8.3). Locally, ignitibility of both fresh leaves (Section 8.3) and leaf litter (Kauf *et al.* 2015) showed a tendency to increase between northernmost (the coolest) and southernmost (the warmest) location, also in agreement with our hypothesis. Nevertheless, only one between-locations pairwise contrast was statistically significant (*i.e.* leaf-litter ignition temperature between Istria and Trstenik). The low number of significant differences can be attributed to species-specific seasonal (for fresh leaves) and local variability in ignitibility (for both fresh leaves and leaf litter). Furthermore, the species-specific response indicates that choice and number of species might influence the conclusions reached about the influence of the environmental conditions on the ignitibility, and thus a need to account for species composition when assessing fire danger was identified (Section 8.3).

Our results on seasonal, species-specific variations of ignitibility of fresh leaves and moisture content are in agreement with the results presented by Pellizaro *et al.* (2005; 2006a; 2007b; 2007c), which indicate that phenology plays an important role in determining the water status of live fuels. Furthermore, our results confirm that species differ in the level of variation in moisture content they exhibit during the vegetation cycle.

With the exception of *P. halepensis*, the species included in our study showed an increase in moisture content during flushing and a decrease with leaf maturation—a behaviour that is in agreement with previously conducted studies, and can be explained by the increasing dry matter content of maturing tissues (Kozlowski and Clausen 1965). Whether or not hydrocarbon relocation (Kozlowski and Clausen 1965) can account for the unusual moisture-content fluctuation pattern observed in *P. halepensis* remains to be investigated. It also remains an open question whether a shift in *C. siliqua* phenology (*i.e.* flushing during the period of increasing drought) could be partly attributed to its predominantly anisohydric nature (Lo Gullo *et al.* 1986; Salleo and Lo Gullo 1989; Lo Gullo *et al.* 2003) and low drought stress in the study area.

Furthermore, contrary to previously made statements (Dimitrakopoulos and Bemmerzouk 2003; Pellizzaro *et al.* 2007c), our study demonstrated that a significant relationship between drought index and moisture content of fresh leaves is not limited to shallow-rooting species. It can also occur in deep rooting species (*e.g. O. europaea*), indicating that adaptation mechanisms other than rooting depth play an important role in determining the relationship between fluctuation in moisture content of fresh leaves and water availability.

Whereas seasonal fluctuations in ignitibility of fresh leaves were in agreement with our initial hypothesis, our results on ignitibility of leaf litter contradicted it (in this case, the longest ignition delay being recorded in July and the shortest in September/October) (Kauf *et al.* 2015). As leaf-litter ignitibility was tested under standardised conditions with the test mass being held constant, we did not expect to be able to detect seasonal differences in leaf-litter ignitibility. Part of the differences can be attributed to a decomposition-induced increase in the affinity towards water (Anderson 1990), resulting in a higher equilibrium moisture content in the May samples.

As freshly fallen leaf litter of none of the species exhibited significant between-location differences (Kauf *et al.* 2015), significant within-species between-location differences can be attributed to the species-specific weathering and decomposition rate. These results, together with the total lack of identifiable leaf litter particles of *P. granatum* in May, call for further investigation of the relationship between decomposition and fire behaviour.

A recently published article dealing with the relationship between decomposition and flammability stated that there are three possible scenarios for species' influence on litter fates: (i) fast decomposition overriding any possible influence of litter flammability, as not enough material is present to support fire; (ii) slow decomposing coupled with high flammability; and (iii) slow decomposition coupled with low flammability (Grootemaat *et al.* 2015). However, this approach neglects the importance of the timing of leaf abscission in relation to the fire season, the non-linearity of the decomposition process, and the potential influence of the amount of litter produced. These parameters could play a very important role in the seasonal fluctuation of fire danger, and they should be investigated before reaching conclusions about decoupling of flammability and decomposition.

9.4. Do laboratory experiments make sense?

It was suggested that laboratory-scale flammability experiments offer limited information on the vegetation–fire dynamics relationship, and that in contrast full-scale properly instrumented experimental fires offer information that can be easily transferred to wildland fire scenarios (Fernandes and Cruz 2012). The same authors promoted modelling as an alternative or an addition to experimental fires, and suggested that the practical relevance of vegetation flammability has already been dismissed by Dickinson and Johnson (2001). Dickinson and Johnson (2001) did not challenge the concept that species might respond differently to fire or modify fire behaviour, but they raised a concern about the vague definition and broad usage of the term “flammability” in ecology. They stated that before discussing flammability, ecologists should gain a better understanding of the combustion process. They also suggested models as an answer to the problem.

The statements made by Fernandes and Cruz (2012) that laboratory experiments offer limited information on vegetation fire dynamics, and by Dickinson and Johnson (2001) that flammability is loosely used in environmental sciences, are appropriate in the context of this study. Furthermore, throughout the preceding text, examples have been indicated where conclusions made based on the flammability experiments were, in this author’s opinion, reaching beyond the obtained results (*e.g.* Liodakis *et al.* (2008), (Section 4.5.2)); or where results could be at least partially attributed to the confounding effect of the testing procedure (*e.g.* the influence of initial mass on the test results (Section 9.1)).

Nevertheless, laboratory experiments can provide useful information if results are critically viewed and interpreted with caution. Alexander and Cruz (2013a) suggested the same when it comes to modelling fire behaviour, and offered a critical overview of currently used fire-behaviour models. Alexander and Cruz (2013a) also stressed that, when it comes to wildland fires, misuse of models and misguided management can have detrimental consequences. In addition, they called for higher level of scientific responsibility in the field of wildland fire modelling. The same can be said about vegetation flammability testing.

Any approach has its advantages and disadvantages, depending on where the interest of the researcher lies. Properly instrumented experimental fires do provide information that is the closest to wildland fires, but they are costly and potentially dangerous, have low repeatability, and are usually conducted under marginal burn conditions (Section 4.2.1). They require relatively homogenous topography and vegetation composition, and are thus unsuitable if one is interested in fire behaviour of rare species, or uncommon species assemblages located in topographically complex environments (as it is the case in the study presented here). Scale also plays a role, and large-scale experiments are more similar to natural fires (Santoni *et al.* 2015), but they also allow for fewer repetitions. Furthermore, recreated litter beds do not have the same structure as natural ones (Ganteaume *et al.* 2014), but undisturbed litter beds can be collected only under limited stand conditions. In the case of undisturbed litter testing, one should account for possible age differences and their influence on fuel accumulation. Additionally, in the case of undisturbed litter testing, higher variability of the material can be expected.

It would also be true to say that any approach offers only limited information on the relationship between vegetation fuel and the combustion process, partly due to the remarkable complexity of both vegetation fuels and the combustion process. Nevertheless, by combining a significant amount of limited information, we might get better insight into the problematics. Furthermore, any approach should be adjusted in accordance with the research question, while being aware of potential limitations of the applied methodology.

In the study presented here, epiradiator-based testing was applied as it is inexpensive, and allows for fast screening of numerous samples while testing small amounts of material. A method requiring small amounts of material was necessary due to the need for repeated sampling of the same individuals; thus harvesting larger canopy portions could significantly influence obtained results. We were interested in the initial stages of fire spread, and so we applied low heat flux. Chosen test masses were reasonable when taking into account the species of interest and the ecosystems in which they occur. In addition, the results were viewed critically, and it was demonstrated that sustainability results obtained by the applied method might be distorted (Kauf *et al.* 2015). Nevertheless, it should be noted that Fernandes and Cruz (2012) were correct when stating that heat transfer of comparable methods does not mimic conditions of the wildland fire. Despite this flaw, the method used allows for comparison of materials based on their ignitibility when exposed to low heat fluxes, simulating the initial stages of fire development, and providing information on the species' effect on the probability of successful fire initiation. Additional information is necessary in order to address other components of flammability or stages of fire development.

9.5. Management implications of the presented work

The results presented here show that out of the six species tested through the whole study, both leaf litter and fresh leaves of *P. halepensis*, *Q. ilex* and *O. europaea* exhibit relatively higher ignitability when compared to the other three species included in the study. Despite seasonal and local fluctuations, all tested fuels of *C. siliqua* (including dead and live branches, for which data was not presented here) in all cases showed significantly lower ignitibility in comparison to the previously mentioned group of species. *A. unedo* exhibited ignitibility behaviour more similar to *C. siliqua* than to *P. halepensis*, *Q. ilex* and *O. europaea*. Nevertheless, some of the tested *A. unedo* fuels were occasionally grouped together with the latter species. These relationships between species are in agreement with results of previously conducted studies (Valette 1990; Massari and Leopaldi 1998), which showed relatively lower "flammability" of *C. siliqua* and *A. unedo* in comparison to *P. halepensis*, *Q. ilex* and *O. europaea*. Up to now, to the author's knowledge, *P. granatum* has not been included in any flammability studies. Even though, when ignited, *P. granatum* had intermediate ignition delay, its fresh leaves rarely ignited, and its leaf litter was rarely present in sufficient quantities to sustain ignition. These characteristics, together with its generally low fuel load, low canopy density, low accumulation of standing dead fuel, and high moisture content of live canopy fractions (Section 1.3), justify a conclusion that the presence of this species does not increase the probability of fire initiation.

As the tendency of the material to ignite is only a part of the problematic related to combustion (Section 1.2), fire development and spread (Section 3.2.), and vegetation flammability (Section 4.1), vegetation characteristics other than ignitibility should be taken into consideration when giving management suggestions.

In addition to having higher measured ignitibility and lower moisture content of live fuel fractions, it was observed that unmanaged *P. halepensis*, *Q. ilex* and *O. europaea* stands have a higher proportion of fine fuel, higher retention of dead fuel in the canopy, a higher fuel load, and a more complex understorey in comparison to *C. siliqua*. These observations, together with the measured low ignitibility, indicate that promotion of *C. siliqua* could potentially decrease the probability of successful fire initiation in comparison to currently highly promoted species (*P. halepensis*, *Q. ilex* and *O. europaea*). Nevertheless, before promotion of *C. siliqua* as a species with the potential to reduce the risk of fire initiation, further investigation of any potential negative consequences of such a management strategy should be undertaken. Furthermore, it would be advisable to screen higher number of species before any management suggestions are made. *A. unedo* showed high morphological plasticity, and was observed in stands with remarkably diverse species compositions and fuel structures, making it difficult to assess its general influence on the probability of fire initiation.

The higher measured ignitibility of commonly used species in comparison to neglected ones, and the higher measured ignitibility of species that can form tall trees in comparison to species that mostly grow in the form of shrubs, indicates that a shift in promoted species and stand structures might decrease ignition probability and fire intensity. These findings call for screening of other neglected species, as well as for accounting for the potential plant associations that could be formed following a shift in promoted species.

Furthermore, it should be noted that fire cannot be excluded from fire-prone environments, and that other environmental and social factors (Section 2) will also influence the probability of fire initiation and spread. Additionally, changing vegetation composition is only one of the possible management options for reducing the negative consequences of wildland fires (Fernandes 2013).

10. Conclusions

The work presented here shows the complexity of the combustion process, and has demonstrated that experimental setup can have a tremendous impact on the results of flammability tests and their interpretation. The following findings have been demonstrated: a different experimental setup can lead to opposite conclusions regarding species ignitibility; the same leaf trait can have opposite effects on different flammability components; and conclusions about the influence of a single trait on a single flammability component can differ depending on whether samples are tested dried, or with their natural moisture content. All of these findings call for caution when choosing an experimental setup for addressing specific vegetation fire-related questions, as well as when interpreting the obtained results. Additionally, different results obtained when testing dry samples and samples with their natural moisture content confirm the tremendous effect of the moisture content on fire behaviour, and indicate that natural ranges in moisture content should be taken into consideration when discussing or testing the fire behaviour of any fuel.

It was demonstrated that a single flammability score, which is currently readily attributed to vegetation materials upon termination of fire-related experiments, is not always meaningful, as different flammability-related parameters may indicate different relative positions of the material. As a way to overcome the problem of the current, unstandardised utilisation of the term “flammability”, it was suggested that, instead of attributing flammability score, individual parameters could be reported and interpreted in relation to individual flammability components, while taking into account advantages and disadvantages of the experimental setup used.

The experimental setup used here tested the ignitibility of small samples in response to a low-intensity ignition source, simulating the initial stage of fire development. Reported results for leaf litter tested with its equilibrium moisture content indicate that weathering and/or decomposition can result in a higher affinity of leaf litter towards water, and thus lower its ignitibility. This finding, together with the total lack of identifiable leaf litter particles of *P. granatum* in the early fire season, indicates that more attention should be given to the influence of decomposition on changes in fire behaviour. Further research investigating the relationship between the time of leaf abscission in relation to main fire season; the amount of litter produced; the climatic conditions; the decomposition rate; and their influence on fire-related properties of litter beds, might provide important information not only for fire ecology purposes, but also for a better understanding of carbon cycling in general.

Contrary to results of oven-dry sample testing, which identify leaf thickness as a “fire-retarding” trait, results of the study presented here indicate that increasing sclerophylly results in increased ignitibility. As we tested only a limited number of species, further investigation of the relationship between leaf traits, morphology, moisture content, moisture release rate, and fire behaviour would be advisable before final conclusions on the relationship between leaf thickness/sclerophylly and fire behaviour are made.

Investigation of the seasonal and local differences in ignitibility demonstrated a general increase in ignitibility from the northernmost (the coldest site with the shortest summer drought) to the southernmost (the warmest with the longest summer drought) site, with increased ignitibility of fresh leaves and decreased ignitibility of leaf litter during summer. Nevertheless, reported species-specific responses to environmental conditions indicate that conclusions might differ depending on the number and choice of species included in the analysis. Thus, species composition should be taken into consideration when assessing the impact of climate change on the local fire regime. Furthermore, the observed decrease in ignitibility upon flushing suggests that the inclusion of phenological development in fire behaviour models might improve their accuracy.

Of all the species tested, all of the fuel components of *C. siliqua* showed relatively low ignitibility, across all locations and through the whole study period, in comparison to other species included in the study; whereas the opposite holds true for *P. halepensis*, *Q. ilex* and *O. europaea*. Ignitibility results for *P. granatum*, together with its other properties, indicate that the presence of this species should not increase the risk of fire initiation. Due to the high variation of the characteristics of *A. unedo,* and the fluctuation of its measured ignitibility, it was impossible to make a judgement on the effects of this species on the relative risk of fire initiation.

The test results presented here could be used as a valuable input in environmental management. Nevertheless, it should be noted that ignitibility represents only a small part of the vegetation–fire relationship, and that other parameters should be taken into consideration when suggesting species for reforestation and afforestation purposes.

11. **References**

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12. Summary

Fire is an important factor controlling vegetation structure. Distribution and ecological properties of around 40% of terrestrial ecosystems are attributed to the accompanying fire regime. In recent decades climate and land use change led to shifts in fire regimes rendering ecosystems more vulnerable to fire. The greatest effects of these changes are expected in the Mediterranean regions which could, under expected future increase in drought intensity and fire activity, shift to low-vegetation-cover desert shrublands.

Fire regime is governed by interactions between ignitions, weather, topography and vegetation acting as a fuel. Despite its varying relative importance, vegetation is the only factor affecting fire regime which can be directly managed. Promotion of less flammable species is considered to be a valid management option for reducing negative consequences of wildland fires. For this management option to be applied reliable information on vegetation flammability and its fluctuations is required.

This study strived to bring new insight on the relationship between environmental conditions, fluctuations of morphological characteristics, physiological activity and measured flammability related parameters of Mediterranean tree species, with special interest in drought as the most important limiting factor of Mediterranean ecosystems. Despite a bigger scope of the conducted study, only a small part of the field study data is included in the final thesis.

Field campaigns assessed the in situ response of selected species to local weather/climatic conditions. These were conducted from May to October 2010 in the Mediterranean biogeographic region of Croatia, where three sampling locations, positioned along a climate gradient, were chosen. Three locations and multiple sampling occasions allowed for assessment of the influence of the local climatic conditions and within location seasonal weather fluctuations on measured species traits.

Selected species included the most important forest species (*i.e.* Aleppo pine (*Pinus halepensis* Mill.), Holm oak (*Quercus ilex* L.)) and the most important agricultural tree crop (*i.e.* olive (*Olea europaea* L.)) of the region, as well as three neglected tree species with numerous potential uses (*i.e.* carob (*Ceratonia siliqua* L.), pomegranate (*Punica granatum* L.), and strawberry tree (*Arbutus unedo* L.)). If possible, all the species were sampled on all the locations during each sampling event.

Presented results include: results of the leaf litter flammability method pretesting (sampled once), regular measurements on leaf litter samples (sampled in May, July and September/October), and monthly measurements on fresh leaf samples. *P. granatum* samples were not included in the method pretesting, instead laurel (*Laurus nobilis* L.), mastic (*Pistacia*

lentiscus L.) and Japanese mock orange (*Pittosporum tobira* Thunb.) were sampled in order to increase the diversity of the materials included in the method pretesting.

All measured traits (moisture content, morphological characteristics of the leaf litter particles and measured flammability parameters) of leaf litter (method pretesting and regular measurements) are reported and the relationships between them examined. For fresh leaves only ignition related traits and moisture content results are presented, the relationship between them is examined, and potential effects of the Keetch-Byram drought index on these parameters are explored.

Initially, the application of already established epiradiator based methods was intended, without tackling the problem of vegetation flammability testing. Nevertheless, method pretesting identified several flaws of established methods. These results, together with growing criticism towards laboratory flammability testing, led to an overview of the vegetation flammability testing methods being included in the thesis, and publishing of the leaf litter pretesting results.

Method pretesting revealed that an epiradiator is not a stabile heat source as previously thought, recognising a need for monitoring and stabilizing epiradiator temperature to ensure similar heat exposure at the beginning of each tests. Furthermore, presented results demonstrated that materials that rarely flame under certain testing conditions can readily flame if testing conditions are slightly altered, thus challenging the presumption that low ignition frequency (number of tests in which a flame appeared divided by the total number of tests) always corresponds to low fire danger (flammability) – a basic presumption of the epiradiator based vegetation flammability tests.

Results of leaf litter flammability testing showed that properties of the leaf litter particles significantly change within the fire season, and indicated that species specific weathering and decomposition could play an important role in these changes. They demonstrated that a change in a single leaf trait can have opposite effects on different flammability parameters, and that these relationships are dependent on the incoming heat flux. Furthermore, the applied method was identified as reliable for measuring ignition related flammability parameters, but questionable when it comes to other parameters.

Results of fresh leaves testing identified phenological changes as important factor governing fluctuation of moisture content and ignition related parameters, and showed that the relationship between drought indices and moisture content is not limited to shallow rooting species. They demonstrated that plant diseases can have significant short term effects on measured ignition related parameters, and challenged the presumption that increasing leaf thickness is related to “fire retardance” – a relationship found if samples are tested outside their natural moisture content range. Instead, this study, in which fresh leaves were tested within their natural moisture content range, implies that higher sclerophylly is related to higher ignition frequency, indicating an opposite trend and confirming the importance of moisture content as one of the most important factors governing fire behaviour of the materials.

All the gathered data indicated that, *O. europaea*, *Q. ilex* and *P. halepensis* exhibit higher tendency to ignite than *C. siliqua* and *P. granatum*; *A. unedo* showed high variation in ignition related parameters. Nevertheless, ignition related parameters reveal only a part of the information on fire behaviour of the material and further measurements should be undertaken before final conclusions are made.

Overall results demonstrated that the experimental setup can have tremendous impacts on the results of flammability tests, thus data interpretation should be done with caution. Furthermore, instead of attributing single flammability scores based on all measured parameters, interpretation of test results in relation to their influence on fire behaviour is advocated.

13. Zusammenfassung

Feuer ist ein wichtiger Kontrollfaktor für die Vegetationsstruktur. Die Verteilung und die ökologischen Eigenschaften von etwa 40% aller terrestrischen Ökosysteme werden durch das dort herrschende Feuerregime beeinflusst. In den letzten Jahrzehnten führten Klima- und Flächennutzungsänderung zu Verschiebungen in den Feuerregimen und machen Ökosysteme anfälliger für Brände. Besonders im Mittelmeerraum sind weitreichende Auswirkungen zu erwarten, die unter künftig steigender Intensität von Trockenperioden und Feueraktivität bis zur Ausbildung von Buschsteppen mit geringer Vegetationsdeckung führen könnten.

Das Feuerregime hängt vom Zusammenspiel zwischen Entflammung, Wetterlage, Topografie und Vegetation als Brennstoff des Feuers ab. Abgesehen von ihrer veränderlichen Bedeutung, stellt die Vegetation den einzigen Faktor dar, über den durch nachhaltiges Management das Feuerregime direkt beeinflussbar ist. Die Förderung von gering entflammbaren Pflanzenarten kann eine zielführende Maßnahme sein, um die negativen Folgen von Waldbränden zu reduzieren. Um diese Managementstrategie anwenden zu können, sind zuverlässige Informationen über die Vegetationsentflammbarkeit und deren Schwankungen erforderlich.

Die vorliegende Arbeit hatte zum Ziel, neue Erkenntnisse zum Zusammenhang zwischen Umweltbedingungen, Schwankungen innerhalb der morphologischen Eigenschaften, physiologischer Aktivität und direkt gemessenen Entflammbarkeits-Parametern mediterraner Baumarten zu gewinnen, mit Schwerpunkt auf Dürre als wichtigstem limitierenden Faktor mediterraner Ökosysteme. Im Rahmen der Untersuchungen konnte eine große Datenmenge gewonnen werden, von der jedoch nur ein kleiner Teil in die vorliegende Dissertation einfließt.

In Freilandstudien wurde die *in situ* Reaktion ausgewählter Baumarten auf lokale Wetter- und Klimabedingungen beurteilt. Dazu wurden drei Versuchsflächen in der mediterranen, biogeographischen Region Kroatiens entlang eines Klimagradienten angelegt und von Mai bis Oktober 2010 beprobt. Die Auswahl dieser drei Flächen und die mehrfache Beprobung über die Zeit erlaubten es, den Einfluss der regionalen Klimabedingungen und der saisonalen Wetterveränderungen auf die gemessenen Eigenschaften der Testarten zu charakterisieren.

Die Liste der untersuchten Arten enthielt die wichtigsten Waldbaumarten (Aleppo-Kiefer (*Pinus halepensis* Mill.), Steineiche (*Quercus ilex* L.)) und als wichtigste landwirtschaftliche Baumart der Region Olive (*Olea europaea* L.) sowie drei vernachlässigte Baumarten mit vielen Einsatzmöglichkeiten (Johannisbrot (*Ceratonia siliqua* L.), Granatapfel (*Punica* *granatum* L.) und Erdbeerbaum (*Arbutus unedo* L.)). So weit möglich, wurden alle Arten in jeder Beprobung erfasst.

Innerhalb dieser Arbeit werden folgende Resultate präsentiert: die Ergebnisse eines methodischen Vorversuchs für die Untersuchung der Laub-Entflammbarkeit (an einmal gesammeltem Probenmaterial), die Ergebnisse wiederkehrender Messungen von Laubproben (gesammelt im Mai, Juli und September / Oktober), und die Ergebnisse monatlicher Messungen von frischen Blattproben. Laubproben von *P. granatum* sind im methodischen Vorversuch nicht enthalten, stattdessen wurden Lorbeer (*Laurus nobilis* L.), Mastixstrauch (*Pistacia lentiscus* L.) und Chinesischer Klebsame (*Pittosporum tobira* Thunb.) beprobt, um die Vielfalt der untersuchten Materialien im Vortest zu erhöhen.

In der Dissertation werden alle erfassten Parameter (Feuchtigkeitsgehalt und morphologische Eigenschaften der Laubstreu, Entflammbarkeits-Parameter) aus dem Methoden-Vorversuch und den regulären Messkampagnen vorgestellt und ihre Relationen analysiert. Für frisches Blattmaterial wurden Entflammbarkeits-Parameter und Feuchtegehalt in Beziehung zum Keetch-Byram Trocknis-Index gesetzt.

Ursprünglich war beabsichtigt, bereits etablierte, Epiradiator-basierte Methoden anzuwenden, ohne Fragestellungen zu Entflammbarkeitstest an sich zu behandeln. Die methodischen Vorversuche haben jedoch einige gravierende Fehler der etablierten Methoden aufgezeigt. Zusammen mit der wachsenden Kritik gegenüber Labor-Entflammbarkeitsversuchen entstand daraus ein Überblick der Methoden von Entflammbarkeitsversuchen von Vegetation. Dieser Überblick und die veröffentlichten Ergebnisse der Laubvorversuche bilden Bestandteile der Dissertation.

Die methodischen Vorversuche zeigten, dass ein Epiradiator keine verlässliche und stabile Wärmequelle darstellt. Somit ist eine kontinuierliche Beobachtung und Stabilisierung der Epiradiator-Temperatur notwendig, um gleiche Wärmebedingungen zu Beginn eines jeden Tests sicherzustellen. Weiterhin zeigten die Vorversuche, dass Materialien, die unter bestimmten Versuchsbedingungen nur selten entflammen, bei geringfügig geänderten Testbedingungen schnell entzünden. Dies stellt eine Grundannahme von Epiraditor-basierten Entflammbarkeitstests in Frage: dass nämlich eine niedrige Entzündungs-Frequenz (Anzahl der Tests, bei denen eine Flamme erscheint, geteilt durch die Gesamtzahl der Tests) einer niedrigen Brandgefahr (Entflammbarkeit) entspräche.

Die Ergebnisse der Entflammbarkeitsversuche mit Laubstreu zeigten, dass die sich Eigenschaften der Laubpartikel innerhalb der Waldbrandsaison signifikant verändern. Zudem wiesen sie daraufhin, dass die artenspezifische Verwitterung und Zersetzung eine wichtige

Rolle bei diesen Veränderungen spielen. Sie zeigten ferner, dass eine Veränderung einer einzigen Blatteigenschaft gegensätzliche Effekte auf verschiedene Entflammbarkeitsparameter haben kann und diese Beziehungen abhängig vom eingehenden Wärmestrom sind. Darüber hinaus hat sich die angewandte Methode bewährt, um die Entzündung als Entflammbarkeitsparameter zuverlässig zu messen. Bei anderen Parametern ist die Eignung fraglich.

Die Ergebnisse der Versuche mit frischen Blättern konnten phänologische Veränderungen als wichtigen Faktor identifizieren, der Schwankungen von Feuchtigkeitsgehalt und Entzündungs-relevanten Parametern regelt. Ferner zeigten sie, dass die Beziehung zwischen Dürreindizes und Feuchtigkeitsgehalt nicht auf flachwurzelnde Arten beschränkt ist. Des Weiteren wurde ersichtlich, dass Pflanzenkrankheiten einen signifikanten, kurzfristigen Einfluss auf die gemessenen Entzündungs-relevanten Parameter haben können. Dieses Ergebnis steht im Gegensatz zu der Behauptung, dass eine hohe Blattdicke feuerhemmend wirkt – ein Zusammenhang, der bei Materialuntersuchungen außerhalb des natürlichen Feuchtigkeitsgehalts beobachtet wird. Stattdessen implizieren die Ergebnisse der vorliegenden Studie, in der frische Blätter innerhalb des Bereiches ihrer natürlichen Feuchtigkeitsgehalte getestet wurden, dass ein höherer Hartlaubanteil eine höhere Entzündungshäufigkeit nach sich zieht. Dies verdeutlicht die Relevanz des Feuchtigkeitsgehaltes als einen der wichtigsten Faktoren, der das Brandverhalten des Materials beeinflusst.

Die gewonnen Daten belegen, dass *O. europaea*, *Q. ilex* und *P. halepensis* tendenziell schneller entzündlich sind als *C. siliqua* und *P. granatum*; die erfassten Entzündungsparameter für *A. unedo* variierten sehr stark. Jedoch ergibt sich aus den Entzündungs-relevanten Parametern nur ein Teil der Information über das Brandverhalten der untersuchten Materialien. Aus diesem Grund sind weitere Messungen notwendig, um abschließende Aussagen treffen zu können.

Zusammenfassend belegt die vorliegende Arbeit, dass der Versuchsaufbau einen enormen Einfluss auf die Messergebnisse und Folgerungen von Entflammbarkeitstest hat. Frühere Daten sollten daher mit Vorsicht interpretiert werden. Darüber hinaus wird empfohlen, statt einer Einstufung von Arten in einzelne Entflammbarkeitsstufen eine Bewertung von Testergebnissen anhand ihrer Bedeutung für das Verhalten im Brandfall vorzunehmen.

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Peer-Reviewed Publications

Kauf Z, Fangmeier A, Rosavec R, Španjol Ž. Seasonal and local differences in leaf litter flammability of six Mediterranean tree species. *Environmental Management* 2015; 55(3):687-701.

Franzaring J, Holz I, Kauf Z, Fangmeier A. Responses of the novel bioenergy plant species *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. to CO_2 fertilization at different temperatures and water supply. *Biomass and Bioenergy* 2015; 81:574-583.

Kauf Z, Fangmeier A, Rosavec R, Španjol Ž. Testing vegetation flammability: The problem of extremely low ignition frequency and overall flammability score. *Journal of Combustion*. 2014; 10 pages.

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