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MEASURING THE RELATIVE PARTICLE FOLIAR COMBUSTIBILITY OF WUI FOREST SPECIES LOCATED NEAR ATHENS

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The relative particle foliar combustibility of seven dominant Mediterranean plant species from a wildland/urban interface (WUI) area near Athens has been determined, using thermal analysis (TG, DTG and SDTA) under oxygen atmosphere, calorimetry and a new lab-scale flame spread test. In addition, the moisture content, total ash content and elemental composition of forest species were determined, in order to correlate them with their combustibility. Based on the thermal-calorimetry analysis and flame spread test data, the examined forest species were ranked into categories. Thus, the most combustible fuel was *Pinus halepensis* and the least one was *Cistus incanus*.

Keywords: *combustibility, flame spread test, mediterranean forest species, thermal-calorimetry-XRF analysis, wildland/urban interface*

Introduction

Wildland fires burn thousands of hectares all over the world each year. The flammability study of forest species is very important towards the management of forest fires, i.e. facilitates the selection of the appropriate afforestation species for reducing wildfire danger.

During the last 30 years, Greece has gradually acquired a serious fire problem in wildland/urban interfaces, mostly intensified around metropolitan and tourist locations [1]. The development of wildland/urban interface (WUI) areas, either due to the expansion of large cities or the development of summer housing, coincides with the increase in both forest fire numbers and burnt areas [2]. The WUI is the area where houses meet or intermingle with undeveloped wildland vegetation and is composed of both interface and intermix communities [3]. Intermix WUI are areas above a threshold of 6.17 housing units/km^2 that are dominated by wildland vegetation (>50%) and interface WUI are areas above 6.17 housing units/km^2 that contained <50% wildland vegetation, but are within 2.4 km of an area that is heavily vegetated (>75% wildland vegetation) [3, 4]. Both of these areas can be classified depending on housing density and vegetation percentage at low, medium and high housing density.

The thermal degradation of forest fuels can be simplified by considering two consecutive steps [5]. The first is the pyrolysis, which is an endothermic process and breaks down the forest matter into low molecular mass gases, known as volatiles, tars, carbonaceous char and mineral ash. Pyrolysis and its products have been extensively studied using various analytical methods [6–13].

The second step is the burning process, which is a rapid exothermic physical chemical process, known as combustion [5]. There are two different types of combustion, flaming and smoldering (or glowing) combustion, which are markedly different phenomena and contribute to the diversity of combustion products. The combustion of volatiles is known as gas-phase combustion (or flaming combustion) and takes place when the mixture of volatiles and air is of the right composition, in a temperature range of about 300 and 500°C. The heat produced from flaming reaction accelerates the rate of pyrolysis releasing great quantities of combustible gases. Smoldering or glowing is the solid-phase combustion of char (without flame) and normally follows flaming combustion. Smoldering combustion usually is distinguished from glowing combustion (final part of the smoldering process) when most of the volatile gases have been driven off and air comes into direct contact with the surface of the charred fuel. The solid phase combustion takes place at around 200°C, with two peaks in intensity reported at 360 and 520°C, until only ash residue remains [5, 14]. The combustion properties of various forest species has been studied by previous workers using thermal analysis techniques under air flow conditions [15, 16].

Ignition is the transition between pyrolysis and combustion. Two types of ignition are distinguished: pilot and spontaneous. In piloted ignition, flaming is initiated in a flammable vapour–air mixture by a pilot, such as an electrical spark or a flame. In spontaneous ignition, flaming is developed spontaneously within the flammable vapour-air mixture. Spontaneous ignition

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characteristics of various forest fuels have been studied by previous workers [17], using thermal analysis.

The flammability of forest species, according to Anderson aspects [18], includes three components: ignitability, combustibility and sustainability. The ignitability determines how easily the fuel ignites. Combustibility is the rate of burn after ignition and is related to fire intensity. Sustainability is the stability of flame spread or how well the fuel continues to burn and is related to the rate of fire spread.

An important factor related to the combustibility is the heat of combustion (heat content) which is the energy that maintains the chain reaction of combustion. Heat of combustion is expressed either as higher heating value (HHV) or lower heating value (LHV). HHV is the amount of energy released by complete combustion of a mass unit of sample, at constant volume in oxygen atmosphere. LHV can be calculated from HHV assuming that water in combustion products remains in a vapor form. The knowledge of LHV has been found very helpful for evaluating forest resources from the energetic point of view [19, 20]. Dimitrakopoulos and Panov [21, 22] have ranked some dominant Mediterranean species according to their heat content and Siafaca *et al.* [23] have reported the caloric content of leaves, barks and woods of various plant species found dominating maquis ecosystems in Mediterranean region.

However, most of the above flammability studies are based on analytical scale methods. The small samples used and the rapid removal of pyrolysis or combustion products, can lead analytical methods to erroneous interpretations in terms of forest fuel flammability performance in actual situations. Therefore, the information provided by the analytical methods on pyrolysis and combustion of forest species should be supported by other fire tests [17, 24-26].

The objective of the present work is to determine the combustion properties of various forest species, using analytical techniques (TG/DTG/SDTA and Calorimetry) as well as new lab-scale flame spread test. The experiments were performed after reducing plant leaves into a fine, uniform substance (particle foliar combustibility) in order to achieve satisfactory reproducibility. The main purposes of this study are:

- to determine the relative foliar combustibility of some very common forest materials from a WUI zone near Athens
- to correlate the combustion properties of forest species with their chemical composition
- to rank forest species into categories, according to their combustibility and
- to provide data for developing fire spread models in WUI zones.

Experimental

Samples

The forest materials examined were: *Pinus halepensis* Mill. (Aleppo pine), *Quercus coccifera* L. (Holly oak), *Pistacia lentiscus* L. (Mastic tree), *Arbutus unedo* L. (Strawberry tree), *Cistus incanus* L. (Pink rockrose), *Erica manipuliflora* Salisb. (Heather), *Phillyrea latifolia* L. (Mock privet) and forest litter (leaf litter). These species are very common in the Mediterranean region and frequently devastated by forest fires, especially in WUI zones near Athens and generally in coastal of Greece. The foliage samples were collected on October 2005 from Thrakomacedones, an area at the confines of the national park of mountain Parnitha, northern of the city of Athens. Samples were collected, after a long drought period in order to avoid moisture effects, such as microbes (i.e. fungi, molds and bacteria) growth [27]. Collection site data of forest samples are shown in Table 1.

Sample preparation

The foliage forest samples gathered were placed into firmly closed polyethylene bags, brought immediately to the laboratory and dried into a vacuum oven for 24 h under pressure of 10 Torr and temperature of 60°C. The above vacuum drying procedure was chosen in order to avoid the vaporization of volatile constituents.

The dried samples were ground and a fraction size between 0.1 and 0.2 mm was separated and used for the tests. We do not expect that the ungrounded samples exhibit the same flammability properties as

Table 1 Collection site data of forest species

Site	Geographical coordinates	Altitude/m	Average inclination/%	Exposition	Dominated petrological formation
1	38° 07′ 50′′ N 23° 46′ 22′′ E	323	10	E (97°)	marls, sandstones, conglomerates
2	38° 08′ 46′′ N 23° 45′ 26′′ E	590	60	S (190°)	limestone, dolomites limestone and dolomite
3	38° 07′ 31′′ N 23° 45′ 38′′ E	327	15	SE (130°)	old scree and talus cones

Remarks: The geographical coordinates, the altitude and the exposition where determined by GPS. The sampling area was 50 m around the above-mentioned geographical coordinates and the species selected had a ground cover higher than 5%

the grounded ones. According to previous studies the flammability depends on the surface area, the volume and the particle density of forest leaves [22].

However, the tests were performed after reducing plant leaves into a fine uniform substance (particle foliar combustibility) in order to eliminate the influence of plant structure, the external characteristics of combustion (i.e. climate, location) and the problems related to heat and mass transfer [15]. Thus, the results taken are more consistent, counting the intrinsic components (i.e. chemical composition) of forest species, suitable for comparison use.

The grounded samples were placed into a conditioning box, set at temperature of 32°C and relative humidity of 12%. The equilibrium moisture content of forest samples was found 2.8% by linear insertion, according to the tables given in a standard method [28].

Methods

Moisture, total ash, apparent density and heat content measurements

The moisture content of the forest species was determined by drying the samples into a vacuum oven under pressure of 10 Torr and temperature 60°C, to constant mass (about 24 h). Total ash content was determined using a standard method [29, 30]. The ash content was expressed as the percentage of residue after dry oxidation at 600°C for 24 h. The apparent density of forest species was determined based on a standard method [31].

The higher heating value (HHV) of forest species was measured using a Parr Instruments 6200 Isoperibol oxygen bomb calorimeter using samples of 1.0 g. The lower heating value (LHV) was determined by the equation:

$$\mathrm{LHV}=(\mathrm{HHV})_\mathrm{d}-24.42(W+9H_\mathrm{d})$$

where $(\mathrm{HHV})_\mathrm{d}$ is the higher heating value of dry sample, W the moisture content of samples (%) and H_d the hydrogen percentage (%) of dry sample.

For the above calculations we have considered that the heat of vaporization of the water is 2441.8 kJ kg^{-1} and the quantity of water formed during combustion is 9 times the hydrogen content (H_d) [19, 20].

Elemental analysis

The elemental composition (Ca, K, Fe, Mg, Mn, S, Al, P, Na, Si, Cl and Zn) was determined using an Arl Advant XP Sequential X-Ray Fluorescence (XRF) apparatus and a Euro EA elemental analyzer (C, H, N and O). The samples used for XRF and elemental analysis were in form of cylindrical pellets of 1.0 g made from ground forest species 0.1–0.2 mm.

Thermal analysis

Thermogravimetric analysis (TG), differential thermogravimetry (DTG) and differential thermal analysis (SDTA) were conducted using a Mettler TGA/SDTA 851 apparatus. The analyses were carried out on 15 mg samples, using open type alumina (Al_2O_3) sample holders. The samples were heated under non-isothermal conditions (25 to 600°C) with a linear heating rate of 10°C min^{-1}. All runs were conducted in oxygen atmosphere with a flow rate of 20 mL min^{-1}, in order to ensure complete oxidation.

Flame spread test

Apparatus: A diagrammatic presentation of the apparatus used for the flame spread tests is shown in Fig. 1. It consists of an aluminum heating plate of 410 mm·260 mm with temperature control accuracy of ±0.5°C in the range of ambient to 350°C. The heating plate ensures standard initial temperature conditions in samples (e.g. 70°C). A PT 100 probe sensor 0.2 mm diameter, directly connected to the heating plate, was used to monitor plate temperature and another one placed 20 cm above the heating plate to measure the air temperature (e.g. 35°C). The whole process was video recorded by a web camera connected to a PC, whereas the time of flame spread was also measured by a stopwatch.

The forest species samples were formed into a powder train mold 250 mm in length which had a triangular cross section 20 mm wide and 10 mm height (Fig. 2a), constructed from aluminum [32, 33]. Then, the sample was placed on the alumina (Al_2O_3) sample holder plate 40×10 cm, on which a line was clearly marked indicating the start of sample path (point A). Three additional lines were marked on the top surface of sample holder, at 50 mm (point B), 150 mm (point C) and 250 mm (point D), away from the start of the sample path (Fig. 2b).

Method: First, the side support was tightened on the mold and the mold was placed on the base plate (Fig. 2a). Approximately, 10–12 g of forest species sample with particle size 0.1–0.2 mm were poured to fill up the triangular cross section of the mold loosely.

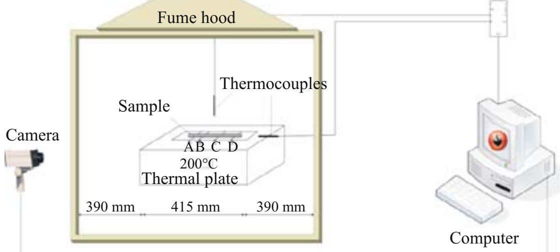
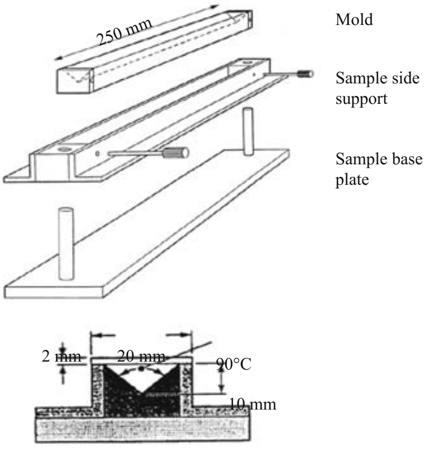
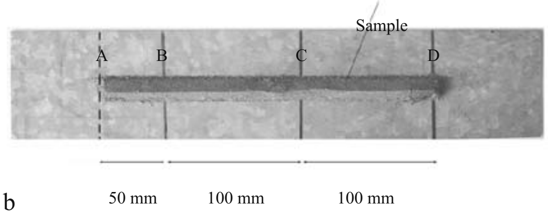


Fig. 1 Diagrammatic presentation of flame spread apparatus



a Cross-section of 250 mm mold



b

Fig. 2 a – Train mold for preparing samples for the flame spread test, b – sample holder plate (top view)

The filled mold with the side plates on was raised up to 2 cm height and dropped down to the base plate (3 times) to settle down the powder. Then, the side support was removed and the mold was lifted off the base plate. A clean sample holder with the appropriate timing marks (Fig. 2b) was placed faced down on the top of the mold and then the set up was inverted in order to remove the mold [32, 33].

The sample holder with the loaded sample was placed on the heating plate to keep the sample at 70°C. Then, a hot flame from a gas burner (minimum diameter 5 mm) was applied to the start of the sample path until ignition. When combustion occurred, the stopwatch was set to measure the time of flame from line B to C (100 mm distance) and from C to line D (100 mm). Thus, the mean flame spread rate was determined in mm s^{-1}. In addition, the flame duration was recorded by measuring the time of flame from line B until the flame is extinguished. The test was performed six times, using a clean cool sample holder each time and the average and RSD values were determined [32].

The whole process was video recorded in order to observe the flame height and the flame intensity. The flame height measurements were taken every 20 mm during each of the experiment committed and the flame intensity was determined by the equation: $I=273h^{2.17}$, where I is the flame intensity (kW m^{-1}) and h is the flame height (m) [5].

Results and discussion

The following properties of forest species were measured: apparent density, total ash content, moisture content, calorific values and elemental composition (Tables 2 and 3).

The fuels with high calorific values and low total ash content are considered as most combustible ones. The ash content is related to the ignition and combustion properties, since the least flammable species contain less volatiles and higher inorganic matter [26]. Based on ash content criterion, *Pinus halepensis* is the most combustible fuel and the least combustible are *Cistus incanus* and forest litter (Table 2).

Based on the calorific value criterion, *Pinus halepensis* has the highest HHV and forest litter the lowest one, whereas forest litter has the highest LHV and *Cistus incanus* the lowest one. The LHV is correlated with the moisture content (the lower the moisture content the greater the LHV, 'Moisture, total ash, apparent density and heat content measurements') and the ash content is correlated with the HHV (the lower the ash content the greater the HHV). Thus, the LHV of forest litter is sufficiently higher than that of

Table 2 Properties of WUI forest species samples

Forest species	Apparent density/ g mL^{-1}	Moisture content/ mass%	Ash content/ mass%	HHV/ kJ g^{-1}	LHV/ kJ g^{-1}
Forest litter	0.33 (0.03)	13.70 (0.02)	10.92 (0.02)	18.17 (0.02)	11.13 (0.01)
Cistus incanus	0.57 (0.04)	64.30 (0.03)	6.46 (0.03)	19.15 (0.02)	6.37 (0.01)
Arbutus unedo	0.45 (0.02)	53.38 (0.03)	4.21 (0.04)	19.75 (0.01)	7.91 (0.01)
Phillyrea latifolia	0.51 (0.04)	45.58 (0.02)	5.62 (0.03)	20.22 (0.01)	9.04 (0.02)
Pistacia lentiscus	0.47 (0.00)	51.24 (0.04)	5.75 (0.04)	20.50 (0.01)	9.12 (0.01)
Quercus coccifera	0.62 (0.02)	44.66 (0.04)	4.69 (0.02)	20.75 (0.01)	10.07 (0.02)
Erica manipuliflora	0.56 (0.04)	48.59 (0.04)	4.44 (0.02)	20.83 (0.02)	9.93 (0.01)
Pinus halepensis	0.38 (0.03)	52.94 (0.03)	3.17 (0.03)	20.84 (0.01)	9.26 (0.02)

Note: The data given are the mean values of three replicate measurements and in parenthesis are the RSD values. The species were arranged according to their HHV values (for minor to maximum value).

Table 3 Elemental composition (mass%) of WUI forest species

Elements	Species							
	Cistus incanus	*Pistacia lentiscus*	*Arbutus unedo*	*Quercus coccifera*	*Phillyrea latifolia*	*Erica manipuliflora*	Forest litter	*Pinus halepensis*
C	49.410	48.580	49.470	50.080	48.990	51.000	47.910	50.772
H	6.750	6.690	6.955	6.650	7.100	6.450	6.130	6.720
O	38.100	38.300	38.100	38.500	39.200	38.050	36.010	39.200
N	1.250	1.350	1.240	1.060	1.270	1.100	1.350	1.110
Ca	2.010	2.470	2.080	1.815	1.870	1.550	3.710	0.816
K	1.620	1.530	1.270	0.880	0.877	0.785	0.781	0.545
S	0.119	0.258	0.191	0.231	0.211	0.288	0.385	0.169
Mg	0.130	0.388	0.222	0.258	0.184	0.250	0.397	0.132
Si	0.119	0.101	0.125	0.166	0.105	0.129	1.650	0.170
P	0.125	0.132	0.144	0.131	0.073	0.091	0.114	0.121
Cl	0.256	0.096	0.040	0.017	0.023	0.157	0.182	0.077
Fe	0.024	0.026	0.030	0.050	0.019	0.024	0.453	0.021
Al	0.041	0.028	0.045	0.091	0.042	0.060	0.691	0.051
Mn	0.032	0.005	0.002	0.022	0.003	0.002	0.018	0.003
Na	0.005	0.002	0.003	0.002	0.001	0.016	0.060	0.041
Ti	0.002	0.003	0.036	0.005	0.002	0.003	0.053	0.002
Zn	0.003	0.002	0.039	0.003	0.003	0.002	0.007	0.001
Ni	0.001	0.001	0.002	0.002	0.001	0.001	0.008	0.002
Cu	0.001	0.001	0.001	n.d	0.001	0.001	0.006	0.001
Cr	n.d	n.d	n.d	n.d	0.001	n.d	0.005	n.d
V	n.d	n.d	n.d	n.d	n.d	n.d	0.077	n.d
Ag	n.d	n.d	n.d	0.002	n.d	n.d	0.002	n.d
Sum	99.998	99.963	99.995	99.965	99.976	99.959	99.999	99.954

Note: n.d.: not determined. The data given are the mean values of three replicate measurements with RSD value lower than 0.05. The species were arranged according to their potassium content (from maximum to minor value).

other species, which can be attributed to its low moisture intake (13.7%). In addition, forest litter has the lowest HHV because its ash content is the highest among all other species examined (Table 2). Another example of the correlation between moisture/ash content and calorific values is seen in *Cistus incanus*: it has the highest moisture percentage (64.3%), relatively high total ash content (6.46%) and accordingly has low calorific values. The above correlations agree with previous studies [34, 35].

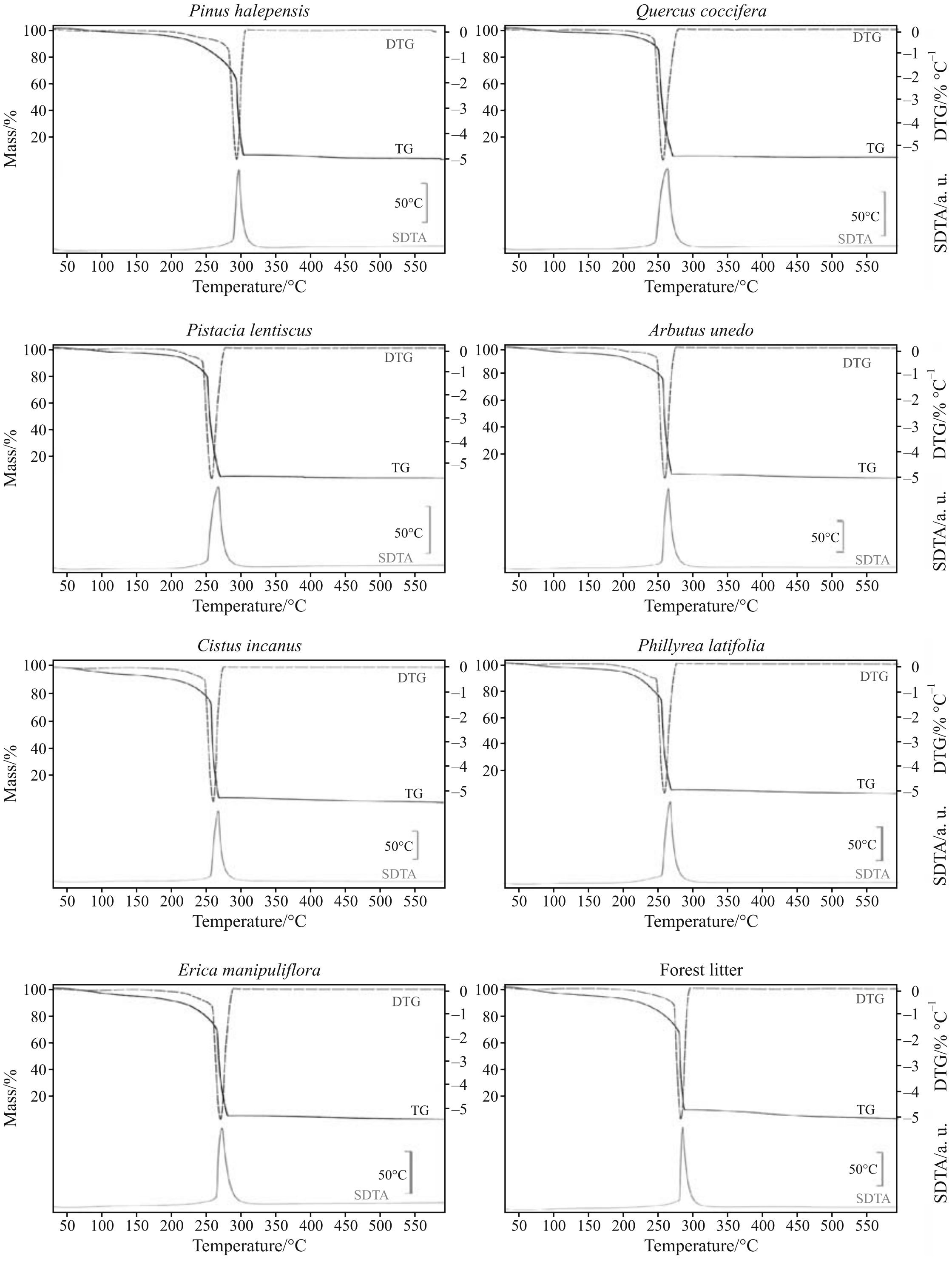
Regarding the apparent density measurements, it is considered that this parameter affects the thermal conductivity of the fuel and therefore its ignition time, as well as the flame spread rate which discussed later on TG and flame spread results interpretation.

Among the combustibility parameters examined the most important is considered the HHV value. Thus, the forest species examined were arranged in Table 2 according to their HHV values (from minor to maximum values and combustibility increases from top to bottom).

According to the elemental composition presented in Table 3, the percentage content of carbon, hydrogen and potassium of WUI forest species examined can be correlated with their combustion properties. Obviously, the higher the percentage of C and H the greater the combustibility, since C and H are the main combustible elements of all lignocellulosic materials. The presence of K in forest species seems to be acting as a fire retarding agent. According to the literature, K acts as a catalyst in pyrolytic and oxidation reactions resulting in formation of carbon dioxide [36, 37]. The dilution of the combustion gases formed by the pyrolysis of the fuels with non-combustible gases (i.e. CO_2) retards the combustibility of forest species [25]. Thus, the lower the percentage of K the greater the combustibility of the species. On the basis of the above statements the most combustible species should be: *Pinus halepensis* and *Erica manipuliflora*.

In Table 3, the most important parameter considered is the potassium content. Thus, the forest species were arranged according to their potassium content (from maximum to minor value and combustibility increases from left to right).

Under the specific thermal analysis conditions (i.e., oxygen atmosphere) used, a gas-phase oxidation occurred [15, 38]. The TG, DTG and SDTA curves of the forest species analysed are shown in Fig. 3. The similarity of TG/DTG/SDTA curves (Fig. 3) indicates a unique combustion mechanism for all forest species examined. This information could be valuable for developing a universal chemical retardant for forest fires. However, further analysis on TG curves indicates a variation between the combustibility of forest species examined (Table 4).


Pinus halepensis

Quercus coccifera

Pistacia lentiscus

Arbutus unedo

Cistus incanus

Phillyrea latifolia

Erica manipuliflora

Forest litter

Fig. 3 TG, DTG, SDTA curves of WUI forest species in oxygen atmosphere

Table 4 Thermogravimetric analysis data of WUI forest species in oxygen atmosphere

WUI Forest species	Ignition delay time/ min	Initial combustion temperature/°C	Maximum mass loss rate/ mg $°C^{-1}$	Final combustion temperature/°C	Combustion duration/s	Mass residue at 600°C/ mass%
Cistus incanus	26.6 (0.01)	265.8 (0.01)	0.90 (0.04)	328.2 (0.00)	374 (0.03)	6.2 (0.03)
Phillyrea latifolia	26.6 (0.00)	266.4 (0.00)	0.91 (0.02)	327.7 (0.01)	368 (0.02)	5.9 (0.02)
Erica manipuliflora	27.7 (0.00)	277.0 (0.00)	0.91 (0.04)	337.5 (0.00)	363 (0.00)	3.3 (0.03)
Pistacia lentiscus	25.9 (0.01)	259.8 (0.01)	0.87 (0.04)	318.4 (0.01)	351 (0.01)	5.7 (0.01)
Quercus coccifera	26.5 (0.01)	265.5 (0.01)	0.96 (0.03)	323.4 (0.01)	347 (0.03)	4.2 (0.02)
Arbutus unedo	26.2 (0.01)	262.2 (0.01)	0.94 (0.04)	317.7 (0.00)	333 (0.03)	4.5 (0.01)
Forest litter	28.3 (0.01)	283.4 (0.01)	1.02 (0.04)	336.0 (0.01)	315 (0.05)	6.1 (0.01)
Pinus halepensis	28.1 (0.01)	280.8 (0.01)	0.92 (0.02)	331.0 (0.01)	302 (0.05)	1.2 (0.05)

Note: The data given are the mean values of three replicate measurements and in parenthesis are the RSD values. The species were arranged according to their combustion duration (for maximum to minor value).

The data: ignition delay time, initial (onset) and final (endset) gas-phase combustion temperatures, combustion duration, maximum mass loss rate (MWLR) and mass residue, presented in Table 4, were derived by the STAR^e software system of Mettler Toledo TG/SDTA 851 apparatus.

The self-ignition temperature (or ignition delay time) is related to the pilot ignitability, mainly involved in real forest fires. According to the literature, the fuels with high self-ignition temperature (or ignition delay time) have low flash point values. Thus, they are the most ignitable fuels and burn easily by flame [24, 39]. Based on the ignition delay time criterion, forest litter and *Pinus halepensis* is the most ignitable fuel and *Pistacia lentiscus* the least one. The combustion duration is related to the combustibility, as well to the sustainability of fuels, with the most combustible fuels having shorter combustion duration and the most sustainable having longer ones. Based on the combustion duration criterion we found that *Pinus halepensis* is the most combustible fuel and *Cistus incanus* is the most sustainable one.

In addition, the maximum mass loss rate (MWLR) of the sample during gas-phase oxidation, expressed in mg $°C^{-1}$, is related to the combustibility, with the least combustible fuels having lower values [15]. Regarding the MWLR criterion, *Pistacia lentiscus* has the lowest MWLR and forest litter the highest one. Thus, the most combustible fuel is forest litter and the least one is *Pistacia lentiscus*.

The previous results are in agreement with the apparent density measurements (Table 2). Among the combustibility parameters examined the most important is considered the combustion duration value. Thus, the forest species examined were arranged in Table 4 according to their combustion duration (from maximum to minor values and combustibility increases from top to bottom).

The forest litter, one of the most flammable fuels, consists of pine-needles at a percentage of 90%. Thermal analysis measurements confirm this correlation between forest litter and *Pinus halepensis* (Table 4, Fig. 3). Furthermore, forest litter exhibits higher fire hazard than *Pinus halepensis* because of its low moisture content (lower than 15% o.d.w., Table 2).

Forest litter does not match well to some of the aforementioned criteria for combustibility: it has the highest ash content and the lowest C percentage. The latter can be attributed to the partial loss of volatiles as well as to the decomposition of hemicelluloses and cellulose to CO_2. This is also confirmed by the high percentage of metallic elements found in forest litter (Table 3).

The data derived from the flame spread test: flame spread rate, flame duration, flame and maximum flame height and flame intensity are presented in Table 5. A snapshot of a running flame spread test it shown in Fig. 4.

Flame spread is related to both combustibility and sustainability of fuels. Combustibility is related to flame intensity and flame spread rate. Thus, forest species with high flame intensity, high max flame height and high flame spread rate are considered as the most combustible, whereas species with high flame duration are the most sustainable ones.

Based on the above criteria, forest litter and *Pinus halepensis* are characterized as highly combustible and *Pistacia lentiscus* is characterized as highly sustainable. These results are in agreement with the apparent density measurements (Table 2). Among the combustibility properties examined the most important is considered the flame spread rate. Thus, the forest species examined were arranged in Table 5 according to their flame spread rate (from minor to maximum values and combustibility increases from top to bottom).

It is reported that, granular substances are highly flammable when the time of flame spread according

Table 5 Flame spread test of WUI forest species

Forest species	Flame spread rate/ mm s^{-1}	Flame duration/ s	Flame height/ mm	Max flame height/ mm	Flame intensity/ kW m^{-1}
Pistacia lentiscus	0.48 (0.04)	426 (0.03)	17.5 (0.10)	30.3 (0.09)	136 (0.06)
Arbutus unedo	0.52 (0.05)	422 (0.02)	19.3 (0.10)	30.7 (0.09)	168 (0.06)
Cistus incanus	0.57 (0.05)	412 (0.04)	15.9 (0.11)	27.7 (0.05)	111 (0.05)
Quercus coccifera	0.69 (0.04)	386 (0.03)	21.9 (0.09)	54.8 (0.07)	221 (0.03)
Phillyrea latifolia	0.79 (0.03)	373 (0.01)	25.7 (0.10)	75.0 (0.04)	313 (0.05)
Erica manipuliflora	0.91 (0.04)	359 (0.04)	19.5 (0.12)	42.0 (0.07)	172 (0.03)
Pinus halepensis	0.96 (0.02)	288 (0.04)	23.6 (0.09)	63.0 (0.06)	260 (0.02)
Forest litter	1.47 (0.03)	229 (0.02)	26.3 (0.09)	68.3 (0.06)	329 (0.02)

Note: The data given are the mean values of six replicate measurements and in parenthesis are the RSD values. The species were arranged according to their flame spread test (for minor to maximum value).

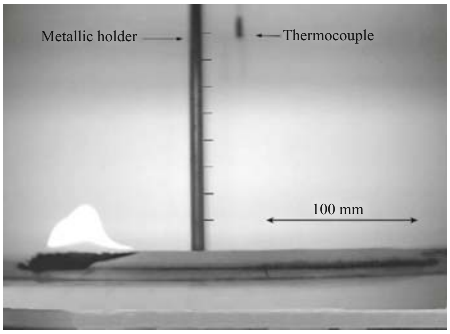


Fig. 4 Snapshot of a flame spread test

to the test procedure described in ‘Method’ is less than 45 s or the rate of flame spread is more than 2.2 mm s^{-1} [32, 33]. Based on this concept, the forest species examined in this work have relatively low combustibility in comparison to other substances (i.e. plastics, polymers).

This simple, low cost, lab-scale test method has the potential of measuring various combustibility properties, providing reliable and reproducible results. These data are in agreement with those taken from analytical methods (TG/DTG/SDTA, calorimetric and elemental analysis).

Conclusions

The data provided in this work constitute a consistent set of combustion properties of WUI Mediterranean forest species, obtained under identical conditions, and could be used for comparing reasons. In addition, the above results could be used to develop fire models for WUI zones in the Mediterranean region.

Various criteria were used to determine the combustibility of WUI forest species based on:

- Elemental analysis, where high C and H content and low K content increase the combustibility.
- Calorimetry, where high HHV and LHV increase the combustibility.
- Thermogravimetric analysis (TG/DTG/SDTA), where high MWLR, low combustion duration and high ignition delay time increase the combustibility.
- Flame spread test, where high flame spread rate, high flame height and high flame intensity increase the combustibility.
- Total ash content, where low ash content increase the combustibility.

The combustibility indices derived from the above criteria do not necessarily coincide with each other. However, according to the statistical analysis’ results (Duncan’s test) [15] the forest species examined can be ranked into three groups:

- The most combustible group: *Pinus halepensis*, Forest litter, *Erica manipuliflora*.
- The moderate combustible group: *Phillyrea latifolia*, *Quercus coccifera*, *Arbutus unedo*.
- The least combustible group: *Pistacia lentiscus*, *Cistus incanus*.

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References

1 A. P. Dimitrakopoulos, Urban Forests and Trees, COST action E12 (2002) 157.
2 G. Xanthopoulos, IFFN, 23 (2000) 76.
3 V. C. Radeloff, R. B. Hammer, S. I. Steeart, J. S Fried, S. S. Holcomb and J. F. McKeefry, Ecol. Appl., 15 (2005) 799.
4 USDA and USDI, Federal Register, 66 (2001) 751.

5 L. F. DeBano, D. G. Neary and P. F. Folliott, Fire's Effects on Ecosystems, John Wiley and Sons, New York 1998, pp. 20, 24, 57.
6 S. F. El-Kalyoubi and N. A. El-Shinnawy, Thermochim. Acta, 94 (1985) 231.
7 M. Statheropoulos, S. Liodakis, N. Tzamtzis, A. Pappa and S. Kyriakou, J. Anal. Appl. Pyrolysis, 43 (1997) 115.
8 J. Kaloustian, A. M. Pauli and J. Pastor, J. Appl. Polym. Sci., 77 (2000) 1629.
9 R. A. Susott, Forest Sci., 28 (1982) 839.
10 R. A. Susott, Forest Sci., 26 (1980) 347.
11 M. Stenseng, A. Zolin, R. Cenni, F. Frandsen, A. Jensen and K. Dam-Johansen, J. Therm. Anal. Cal., 64 (2001) 1325.
12 A. Pappa, K. Mikedi, N. Tzamtzis and M. Statheropoulos, J. Therm. Anal. Cal., 84 (2006) 655.
13 P. M. Stefani, D. Garcia, J. Lopez and A. Jimerez, J. Therm. Anal. Cal., 81 (2005) 315.
14 R. H. White, M. A. Dietenberger, Gen. Tech. Rep. FPL-GTR-113. USDA (1999), pp. 17.6–17.13.
15 A. P. Dimitrakopoulos, J. Anal. Appl. Pyrolysis, 60 (2001) 123.
16 A. P. Dimitrakopoulos and V. Mateeva, Proc. III Int. Conf. Forest Fire Research, Vol. II (1998) p. 2579.
17 S. Liodakis, D. Bakirtzis and A. P. Dimitrakopoulos, Thermochim. Acta, 390 (2002) 83.
18 H. E. Anderson, Fire Technol., 6 (1970) 312.
19 L. Nunez-Regueira, J. Rodriguez-Anon, J. Pourpin and A. Romero-Garcia, Bioresour. Technol., 88 (2003) 121.
20 L. Nunez-Regueira, J. Pourpin-Castineiras and J. Rodriguez-Anon, Bioresour. Technol., 91 (2004) 215.
21 A. P. Dimitrakopoulos and P. I. Panov, Proc. III Int. Conf. Forest Fire Research, Vol. II (1998) p. 2579.
22 A. P. Dimitrakopoulos and P. I. Panov, Int. J. Wildland Fire, 10 (2001) 23.
23 L. Siafaca, S. Adamandianou and N. S Margaris, Oecologia, 44 (1980) 276.
24 S. Liodakis, D. Vorisis and I. P. Agiovlasitis, Thermochim. Acta, 437 (2005) 150.
25 S. Liodakis, D. Vorisis and I. P. Agiovlasitis, Thermochim. Acta, 444 (2006) 157.
26 S. Liodakis, D. Bakirtzis and E. Lois, J. Therm. Anal. Cal., 69 (2002) 519.
27 J. Nurmi and K. Hillebrand, Biomass Bioenergy, 31 (2007) 381.
28 ASTM D 4933-91, Standard Guide for Moisture Conditioning of Wood and Wood-Based Materials, (1997) 520.
29 ASTM D 1102-84, Standard Test Method for Ash in Wood, (2001) 172.
30 S. Liodakis, G. Katsigiannis and G. Kakali, Thermochim. Acta, 437 (2005) 158.
31 ASTM D 1895-96, Standard Test Method for Apparent Density, Bulk Factor and Pourability of Plastic Materials, (2003).
32 Official Journal of the European Communities 92/69/EEC, A.10. Flammability (solids), No. L251/63 (1984), p. 110.
33 US EPA test methods, Method 1030, Ignitability of Solids, SW-846, Dec. 1996.
34 L. Nunez-Regueira, J. Rodriguez-Anon, J. Pourpin-Castineiras and O. Nunez-Fernandez, Thermochim. Acta, 378 (2001) 9.
35 C. Sheng and J. L. T. Azevedo, Biomass Bioenergy, 28 (2005) 499.
36 W. Pan and G. N. Richards, J. Anal. Appl. Pyrolysis, 16 (1989) 117.
37 W. Pan and G. N. Richards, J. Anal. Appl. Pyrolysis, 17 (1990) 261.
38 R. Bilbao, J. Mastral, M. Aldea and J. Ceamanos, J. Anal. Appl. Pyrolysis, 39 (1997) 468.
39 R. J. Lewis, Rapid Guide to Hazardous Chemicals in the Work Place, 2nd Ed., Van Nostrand Reinhold, New York 1990.

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