Flammability of some fuel beds common in the South-European ecosystems

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ABSTRACT: In order to assess the capability of several fuel beds to start a fire as a consequence of the fall of a flaming firebrand on them, a set of laboratory tests have been carried out. The present work reports on the results obtained on litters of 8 woody species, and grasses. For each type of fuel beds, the effects both of bulk density and fuel moisture content have been analysed. Grasses have lower times to ignition, higher rates of initial fire spread and of combustion as well as higher flame heights than litters. Among litters, those belonging to the species of *Pinus* genus and the *U. europaeus* are the most flammables of all of them. *E. globulus* litter has intermediate characteristics On the whole, an increase of moisture content and of bulk density of litters implies an increase of the time to ignition and a decrease of the rates of initial fire spread and of combustion, of the flame height and of the fuel consumption ratio.

1 INTRODUCTION

Spot fires are projections of flaming or burning particles (firebrands) ahead of the flame front of a wildfire that may be at the origin of secondary wildfires ahead of the main forest fire itself. This phenomenon has important consequences for fire prevention and firefighting strategies, because it affects the fire propagation, reduce the efficiency of firebreaks and can threaten the firefighters. Spotting depends on different factors as meteorological conditions, topography profile and vegetation at the starting point of the spot fire as well as vegetation at the receiving zone where firebrands land. Thus, the characteristics of the receiving fuel (nature, structure, moisture, cover, compactness, etc) influence the eventual appearance and propagation of a secondary fire.

Due to the main role played by litter in fire propagation, many authors have investigated, in laboratory tests, the fire behaviour in several pines fuel beds (Rothermel & Anderson, 1966; Delaveaud, 1981; Ventura *et al.*, 1988; Viegas & Neto, 1990; Vega et *al.*, 1993; Valette et *al.*, 1994; Mendes-Lopes *et al.*, 1998; Guijarro & Hernando, 2000…). All these works focus on the study of equilibrium spread rate, using a line ignition. But studies of point-source ignition in litters and grasses, as it occurs in the spotting process, have been few. Blackmarr (1972) measured the influence of moisture content on the ignitibility of *Pinus elliottii* litter, dropping lighted matches onto fuel beds. Ferreira (1988) also studied the ignitibility of *Pinus pinaster* needles, *Eucalyptus globulus* leaves and fuel beds, dropping lighted matches. Mc Alpine & Wakimoto (1991) conducted a series of point-source experimental fires in a wind tunnel using *Pinus ponderosa* needles and excelsior fuel beds to develop predictive equations to describe the fire growth phases in each fuel.

In this frame, the objective of the present work is to assess the capability of several fuel beds to start a fire as a consequence of the fall of a flaming firebrand on them. This capability has been evaluated through the study of flammability of some fuel beds, under laboratory conditions. Following the definitions given by Anderson (1970) and Martin *et al.* (1994), flammability has been understood as a result of four phenomena: *ignitibility,* which describes the time required until ignition of the fuel occurs; s*ustainability,* which describes the property of a fuel to continue burning; *combustibility* which is the rate at which a fuel burns and *consumibility* which describes the quantity of burned fuel.

According to these definitions, the evaluation of flammability of the fuel beds has taken into account the following parameters: the time required until the flame appears on the fuel bed, the rate of initial fire spread, the rate of combustion and the fuel consumption ratio. In addition to this, the ignition frequency of each fuel bed and the flame height have been considered. All these parameters are related to the initial state of the fire, representative of the moment of an eventual spot fire occurrence as a possible consequence of the fall of a firebrand; thus, the steady state of spread fire is not addressed.

2 METHOD

2.1 *Fuel beds*

The fuel beds selected for this study have been litters of *Arbutus unedo* L., *Eucalyptus globulus* Labill., *Pinus halepensis* Miller, *P. pinaster* Ait., *P. pinea* L., *Quercus faginea* Lam., *Q. pubescens* Willd. and *Ulex europaeus* L., and grasses. These fuels are common in the South-European ecosystems frequently affected by wildfires.

Fuels were collected in pure stands of each species. Whereas coniferous and hardwood litters were constituted of needles or leaves of the respective species, fuel beds of *Ulex europaeus* were constituted of fine ground stems of this species. This type of fuel bed represents the brushing out with grinding of *Ulex europaeus*, a process frequently accomplished as a silvicultural treatment in Galicia (North-West of Spain), where this type of litter is laid down on the ground in order to protect and fertilize the ground itself, having detected several cases of fire reproduction by the falling of firebrands on these fuel accumulations.

Grasses also frequently constitute the receptive fuel in the development of secondary fires. This type of fuel beds has been collected in turfs from the ground in order not to alter its structure in any way (Figs.1.a and 1.b).

Figure 1.a. Grasses type 1.

Figure 1.b. Grasses type 2.

For each type of litter, the effects both of bulk density (quantity of fuel mass per volume unit of the fuel stratum, BD in kg/m^3) and fuel moisture content (percentage of dry weight FMC) have been analysed. Concerning grasses, two different types, with different height, density and horizontal continuity have been considered: grasses type 1, with higher height, density and horizontal continuity (Fig. 1.a) and grasses type 2, with lower height, density and horizontal continuity (Fig.1.b)

In litters, the thickness of the fuel stratum considered for the bulk density calculation is the mean thickness of said stratum, measured at six different points. In grasses, the thickness considered refers, not to the total height of the stratum, but to the lower part of it, that is denser.

In litters, the moisture content values ranged between 0.5 and 22.9 %, while the fuel moisture content ranged between 9.6 and 49.9 % in grasses.

Fuel beds properties under which this study has been conducted are reported in Table 1.

Table 1. Fuel load, fuel moisture content and bulk density for each fuel bed considered in this study

Fuel bed	N	Fuel load (kg/m^2)		Fuel moisture content		Bulk density (kg/m^3)	
		minimum	maximum	minimum	maximum	minimum	maximum
Arbutus unedo	87	1.377	1.480	1.0	8.7	45.4	49.6
Eucalyptus globulus	68	0.841	1.185	1.1	17.5	15.8	72.5
Pinus halepensis	64	1.039	1.896	1.0	9.5	34.3	60.6
Pinus pinaster	56	0.866	1.227	0.5	19.8	20.1	70.7
Pinus pinea	36	0.494	0.552	2.5	14.5	9.1	25.1
Quercus faginea	44	0.495	0.546	3.6	15.2	15.4	43.8
Quercus pubescens	129	0.961	1.039	1.0	14.4	15.2	34.8
Ulex europaeus	29	0.842	1.127	0.8	22.9	11.2	34.6
Grasses type 1	10	0.192	0.251	9.9	43.4	0.9	3.6
Grasses type 2	16	0.095	0.130	9.6	49.9	0.8	2.6

2.2 *Experimental device*

The experimental burnings were conducted in fire benches (Fig. 2), on which the different fuel beds were laid, forming either square fuel layers of 0.70 m x 0.70 m or round layers with 0.70 m diameter. The experimental devices were located in the inside of an area equipped with a smoke evacuator. Fire benches were placed on a scale, with sensitivity 1 g, connected to a computing, enabling a continuous register of weight loss of the fuel bed during its combustion, and/or incorporate on one side a scale, in cm, which enables visual assessment of flame height during the tests.

Figure 2. Experimental devices for the study of flammability of fuel beds

In order to set up ignition of the fuel bed under similar conditions, pieces of 2 x 2 x 1 cm, made of *Pinus sylvestris* wood, with 12 % moisture content (defined as "standard firebrand") were used. Standard firebrands were ignited in contact with an electric radiator, gauged according to the Standard UNE 23729-90-1R, corresponding to the Standard NF P 92-509-1985. These firebrands provide a source of flaming combustion for ignition.

2.3 *Test procedure*

For each test, the fuel is conditioned in chamber to obtain the selected moisture content. On the bench, a homogeneous layer of fuel is constituted with the necessary quantity to obtain the selected load. The thickness is determined (as the mean value obtained from 6 measures) as well as the moisture content of the layer of fuel (by means of a representative sample, oven-dried at 100º C). Ignition is done with a "standard firebrand" ignited with the electric radiator, then the flaming firebrand is placed on the central point of the fuel layer surface.

From the measurements done during the tests, the parameters that enable to evaluate the flammability of the fuel beds are calculated:

- Time-to-ignition of the fuel bed (TIB, in s) calculated from the moment the firebrand is placed on the fuel bed.
- Rate of fire spread (RoS, in cm/s) obtained from the mean value of the time required by fire to reach the four edges of the fuel layer since the firebrand is settled in the fuel.
- Rate of fuel bed combustion (RoC, in g/s), obtained from data registered by the scale on which the tray holding fuel lays.
- Maximum and mean flame height (FH and MFH, in cm), visually determined through the usage of a plate placed in the experimental device.
- Fuel consumption ratio (FCR, dimensionless) calculated as the quotient of the weight consumed by combustion and the initial weight of fuel.

In addition, the ignition frequency (IFB, in percentage) for each fuel bed is determined, as the percentage of test in which ignition of fuel bed occurs.

3 RESULTS

3.1 *Flammability parameters*

The results obtained for the flammability parameters described in Section 2.3 are shown in Table 2 for each of the studied fuel beds.

As can be seen in Table 2, grasses registered the lowest time-to-ignition and the highest rate of spread and rate of combustion, as well as the highest height of flames, thus revealing its higher flammability compared with the litters, in spite of the fact that tests were carried out with higher values of fuel moisture in the case of grasses than in litters (Table 1).

Among grasses, those of type 1 showed an IFB of 100 %, frequency that dropped to 44 % for grasses type 2. This remarkable difference in ignition frequency is due to a higher density and a horizontal continuity of grasses type 1. Denser grasses showed also lower TIB and higher RoS, RoC, FH, MFH and FCR.

Among litters, the species belonging to the genus *Pinus* as well as *Ulex europaeus* litter showed a higher ignition frequency, lower time-to-ignition, higher rates of spread and rates of combustion and higher flame heights. *Arbutus unedo* litter showed the lowest IFB, the higher TIB and the lowest RoS and RoC. Medium values were obtained in litter of hardwood species (*Eucalyptus globulus*, *Quercus faginea* and *Q. pubescens*).

Referring to hardwood, special mention has to be done about the results obtained for *Eucalyptus globulus* whose litter reached high values of IFB and FH, along with relatively low values for TIB and RoS. These results accord with those obtained by Trabaud (1976) and denote that the essential oils and terpenes contained in the fuel (as is *Eucalyptus* litter) enhance the flame height more than the time-to-ignition.

Table 2. Parameters of flammability of the fuel beds: mean (minimum and maximum values)
--: Non measured parameter

Fuel bed	IFB (%)	TIB (s)	RoS (cm/s)	RoC (g/s)	FH (cm)	MFH (cm)	FCR (%)
Arbutus unedo	64 %	11.92 (1.75-52.50)	0.088 (0.042-0.146)	0.691 (0.239-1.141)	--	--	--
Eucalyptus globulus	90 %	9.09 (2.00-58.95)	0.167 (0.054-0.302)	--	74.1 (30-110)	65 (24-110)	79 (0-94.9)
Pinus halepensis	90 %	4.51 (1.34-25.48)	0.231 (0.113-0.376)	1.332 (0.704-2.081)	--	--	--
Pinus pinaster	96 %	5.82 (1-29.5)	0.190 (0.076-0.319)	--	65 (15-100)	58 (10-95)	82 (0-96)
Pinus pinea	100 %	5.51 (2-11)	0.259 (0.149-0.393)	1.227 (0.755-1.719)	58 (25-80)	43 (18-63)	93 (86-95)
Quercus faginea	80 %	12.80 (4-60)	0.181 (0.095-0.287)	0.680 (0.119-1.023)	21 (5-50)	17 (5-38)	53 (0-81)
Quercus pubescens	67 %	8.60 (1.37-117.9)	0.232 (0.078-0.445)	1.158 (0.505-2.651)	--	--	--
Ulex europaeus	100 %	5.19 (1.32-44.54)	0.293 (0.084-0.511)	--	100 (35-160)	93 (30-157)	91 (41-101)
Grasses type 1	100 %	1.90 (1-4)	0.296 (0.395-1.296)	2.837 (1.450-3.451)	100 (60-110)	79 (43-100)	97 (77-100)
Grasses type 2	44 %	3.53 (1—22)	0.654 (0.550-0.772)	1.524 (0.512-1.966)	58 (15-100)	40 (15-80)	85 (0-96)

3.2 *Effect of fuel moisture content and bulk density on the flammability parameters*

The effect of fuel moisture content (FMC) and fuel bulk density (BD) on the flammability parameters for each fuel bed has been analysed fitting multiple regression equations of the form:

$$\text{Parameter (TIB, RoS, RoC, FH, MFH and FRC)} = a + b\ \text{FMC} + c\ \text{BD}$$

The fitted equations and the corresponding adjusted R^2 and p-values are reported in Tables 3.a to 3.f. The equations provide a test for the effect of FMC and BD on each flammability parameter.

Table 3.a. Multiple regressions for time-to-ignition of the fuel bed.
Signification level for the coefficients: $^{(*)} = p < 0.05$; $^{(**)} = p < 0.001$

Fuel bed	Multiple regressions for TIB	Adjusted R^2	P
Arbutus unedo	TIB = 4.619 + 2.345 FMC$^{(*)}$	0.239	0.003
Eucalyptus globulus	TIB = 5.614 + 0.608 FMC$^{(*)}$ – 0.037 BD	0.079	0.036
Pinus halepensis	TIB = -0.578 + 0.294 FMC – 0.084 BD	0.180	0.001
Pinus pinaster	TIB = 2.742 + 0.123 FMC + 0.060 BD	0.013	0.270
Pinus pinea	TIB = 1.215 + 0.194 FMC + 0.170 BD$^{(*)}$	0.176	0.017
Quercus faginea	TIB = 13.668 + 0.901 FMC – 0.534 BD	0.047	0.209
Quercus pubescens	TIB = 7.466 + 0.881 FMC$^{(*)}$ – 0.204 BD	0.036	0.087
Ulex europaeus	TIB = -5.760 + 0.542 FMC$^{(*)}$ + 0.290 BD	0.229	0.013
Grasses Type 1	TIB = -0.553 + 0.030 FMC + 1.031 BD$^{(*)}$	0.535	0.028
Grasses Type 2	TIB = -7.833 + 0.857 FMC$^{(*)}$ – 0.172 BD	0.267	0.061

Table 3.b. Multiple regressions for rate of fire spread
Signification level for the coefficients: $^{(*)}$ = p < 0.05; $^{(**)}$ = p < 0.001

Fuel bed	Multiple regressions for RoS	Adjusted R²	p
Arbutus unedo	$RoS = 0.113^{(**)} - 0.008\ FMC^{(**)}$	0.570	0.000
Eucalyptus globulus	$RoS = 0.284^{(**)} - 0.009\ FMC^{(**)} - 0.001\ BD^{(*)}$	0.525	0.000
Pinus halepensis	$RoS = 0.391^{(**)} - 0.010\ FMC^{(*)} - 0.002\ BD^{(*)}$	0.800	0.000
Pinus pinaster	$RoS = 0.368^{(**)} - 0.009\ FMC^{(**)} - 0.003\ BD^{(**)}$	0.809	0.000
Pinus pinea	$RoS = 0.455^{(**)} - 0.013\ FMC^{(**)} - 0.005\ BD^{(**)}$	0.870	0.000
Quercus faginea	$RoS = 0.352^{(**)} - 0.013\ FMC^{(**)} - 0.003\ BD$	0.468	0.000
Quercus pubescens	$RoS = 0.416^{(**)} - 0.017\ FMC^{(**)} - 0.004\ BD^{(**)}$	0.708	0.000
Ulex europaeus	$RoS = 0.520^{(**)} - 0.014\ FMC^{(**)} - 0.005\ BD^{(*)}$	0.723	0.000
Grasses Type 1	$RoS = 1.470^{(**)} - 0.024\ FMC^{(**)} - 0.017\ BD$	0.858	0.000
Grasses Type 2	$RoS = 0.623 - 0.005\ FMC + 0.054\ BD$	0.030	0.418

Table 3.c. Multiple regressions for rate of fuel bed combustion
Signification level for the coefficients: $^{(*)}$ = p < 0.05; $^{(**)}$ = p < 0.001

Fuel bed	Multiple regressions for RoC	Adjusted R²	P
Arbutus unedo	$RoC = 0.825^{(**)} - 0.043\ FMC^{(*)}$	0.283	0.001
Pinus halepensis	$RoC = 2.009^{(**)} - 0.019\ FMC - 0.013\ BD$	0.408	0.000
Pinus pinea	$RoC = 2.028^{(**)} - 0.038\ FMC^{(**)} - 0.029\ BD^{(**)}$	0.611	0.000
Quercus faginea	$RoC = 1.421^{(**)} - 0.046\ FMC^{(*)} - 0.016\ BD$	0.288	0.005
Quercus pubescens	$RoC = 1.701^{(**)} - 0.039\ FMC^{(**)} - 0.015\ BD^{(*)}$	0.218	0.000
Grasses Type 1	$RoC = 3.702^{(*)} - 0.045\ FMC^{(**)} + 0.047\ BD$	0.753	0.003
Grasses Type 2	$RoC = 3.430 - 0.190\ FMC + 0.108\ BD$	0.000	0.683

Table 3.d. Multiple regressions for maximum flame height
Signification level for the coefficients: $^{(*)}$ = p < 0.05; $^{(**)}$ = p < 0.001

Fuel bed	Multiple regressions for RoC	Adjusted R²	P
Eucalyptus globulus	$FH = 120.92^{(**)} - 3.465\ FMC^{(**)} - 0.576\ BD^{(*)}$	0.469	0.000
Pinus pinaster	$FH = 132.12^{(**)} - 3.157\ FMC^{(**)} - 1.209\ BD^{(**)}$	0.755	0.000
Pinus pinea	$FH = 100.28^{(**)} - 2.499\ FMC^{(**)} - 1.303\ BD^{(**)}$	0.668	0.000
Quercus faginea	$FH = 50.30^{(**)} - 2.106\ FMC^{(**)} - 0.469\ BD$	0.299	0.000
Ulex europaeus	$FH = 170.21^{(**)} - 3.821\ FMC^{(**)} - 1.748\ BD^{(*)}$	0.648	0.000
Grasses Type 1	$FH = 124.29 - 1.025\ FMC^{(*)} - 1.434\ BD$	0.408	0.000
Grasses Type 2	$FH = 126.68^{(*)} - 5.669\ FMC^{(*)} + 5.921\ BD$	0.483	0.418

Table 3.e. Multiple regressions for mean flame height
Signification level for the coefficients: $^{(*)}$ = p < 0.05; $^{(**)}$ = p < 0.001

Fuel bed	Multiple regressions for RoC	Adjusted R²	P
Eucalyptus globulus	$MFH = 112.17^{(**)} - 3.374\ FMC^{(**)} - 0.604\ BD^{(*)}$	0.415	0.000
Pinus pinaster	$MFH = 119.98^{(**)} - 2.891\ FMC^{(**)} - 1.110\ BD^{(**)}$	0.700	0.000
Pinus pinea	$MFH = 78.16^{(**)} - 2.142\ FMC^{(**)} - 1.059\ BD^{(**)}$	0.758	0.000
Quercus faginea	$MFH = 41.31^{(**)} - 1.632\ FMC^{(**)} - 0.448\ BD$	0.312	0.002
Ulex europaeus	$MFH = 159.86^{(**)} - 3.835\ FMC^{(**)} - 1.570\ BD^{(*)}$	0.610	0.000
Grasses Type 1	$MFH = 111.97^{(**)} - 1.690\ FMC^{(**)} + 1.614\ BD$	0.812	0.001
Grasses Type 2	$MFH = 82.51^{(*)} - 3.484\ FMC^{(*)} + 3.217\ BD$	0.393	0.025

Table 3.f. Multiple regressions for fuel consumption ratio
Signification level for the coefficients: $^{(*)}$ = $p < 0.05$; $^{(**)}$ = $p < 0.001$

Fuel bed	Multiple regressions for RoC	Adjusted R^2	P
Eucalyptus globulus	$FCR = 126.83^{(**)} – 0.877\ FMC – 1.107\ BD^{(*)}$	0.187	0.000
Pinus pinaster	$FCR = 131.94^{(**)} – 0.418\ FMC – 1.286\ BD^{(**)}$	0.682	0.000
Pinus pinea	$FCR = 95.39^{(**)} – 0.114\ FMC – 0.103\ BD^{(*)}$	0.108	0.061
Quercus faginea	$FCR = 131.59^{(**)} – 3.344\ FMC^{(*)} – 2.275\ BD^{(*)}$	0.320	0.001
Ulex europaeus	$FCR = 106.58^{(**)} – 0.600\ FMC^{(*)} – 0.513\ BD$	0.167	0.035
Grasses Type 1	$FCR = 108.23^{(**)} – 0.468\ FMC^{(*)} – 0.939\ BD$	0.523	0.031
Grasses Type 2	$FCR = 85.94 – 1.019\ FMC + 6.923\ BD$	0.000	0.642

3.2.1 *Litters*

In litters, both FMC and BD, for the ranges considered, produced in general a significant effect on the rate of spread of the fire (Table 3.b) and on the maximum and mean flame height (Tables 3.d and 3.e). The coefficients are negative, so these parameters increase when either, moisture content and bulk density of the fuel decrease. Nevertheless, the effect of BD was not signitificant in the tests done for the *Quercus faginea* litter. The adjusted R^2 values of the equations for coniferous species were higher than the values for the equations for hardwood. This is probably due to the fact that needles originate more homogeneous fuel beds than leaves.

On the contrary, neither FMC nor BD had, as a general rule, a meaningful effect on the time to ignition of fuel beds (Table 3.a). However, this result is not in contradiction with classical bibliography (Trabaud, 1976; Valette, 1988; Hernando, 1989…) that highlights an increase in the time to ignition of forest fuel derived from an increase in moisture content of the fuel. The difference is connected to the test method used in this work. In fact, in the studies previously mentioned, flammability is determined through a calorific focus on which the vegetation, arranged in 1 g samples, is laid, and where a pilot flame allows a more regular ignition of the gases, whereas, for the present study, the heat source selected to initiate the fuel ignition is an ignited piece of wood and the fuel is composed of a continuous stratum. Nonetheless, when the effect of independent variables was significant, its influence was positive, so that time to ignition increases as either, FMC and BD, increase.

Exceptions apart, a significant effect of independent variables on the rate of combustion (Table 3.c) or on the fuel consumption ratio (Table 3.f) have not been established. However, in the cases on which the effect of these variables was significant, its influence was negative, as it was in the rate of spread and flame height. Therefore, both RoS and RoC are positively correlated, with correlation coefficients that vary between 0.550 and 0.902.

3.2.2 *Grasses*

Although as previously reported, denser grasses (Type 1) revealed lower TIB and while the values of RoS and RoC, FH, MFH, FCR as well as IF proved to be higher than those obtained for less dense grasses (Type 2), for each grass type, bulk density did not have a significant effect on the parameters considered to analyse its flammability.

4 CONCLUSIONS

From the study accomplished, and taking into account the previously stated considerations regarding methods of the tests and selected ranges of variables, the following conclusions may be underlined:

- Grasses show lower times to ignition, higher rates of spread and of combustion as well as higher flame heights than litters, even with higher values of fuel moisture, facts that imply a higher flammability.
- Between the two types of grasses, that with higher density and horizontal continuity presents a higher flammability.
- Among litters, those belonging to the species of *Pinus* genus and the *Ulex europaeus* litter, reveal higher flammability than hardwood litter.
- Among hardwood, *Eucalyptus globulus* litter has intermediate characteristics, with high ignition frequency and high flame height, along with relatively low times to ignition and rates of spread.
- On the whole, an increase of moisture content and of bulk density of litters implies an increase of the time to ignition and a decrease of the rates of spread and of combustion, of the flame height and of the fuel consumption ratio.
- From the point of view of preventive silviculture, the high flammability of *Ulex europaeus* bed fuel, derived from the process of brushing out with grinding, makes it necessary to advise against the habit of leaving these residues on the ground to protect and fertilize it.

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