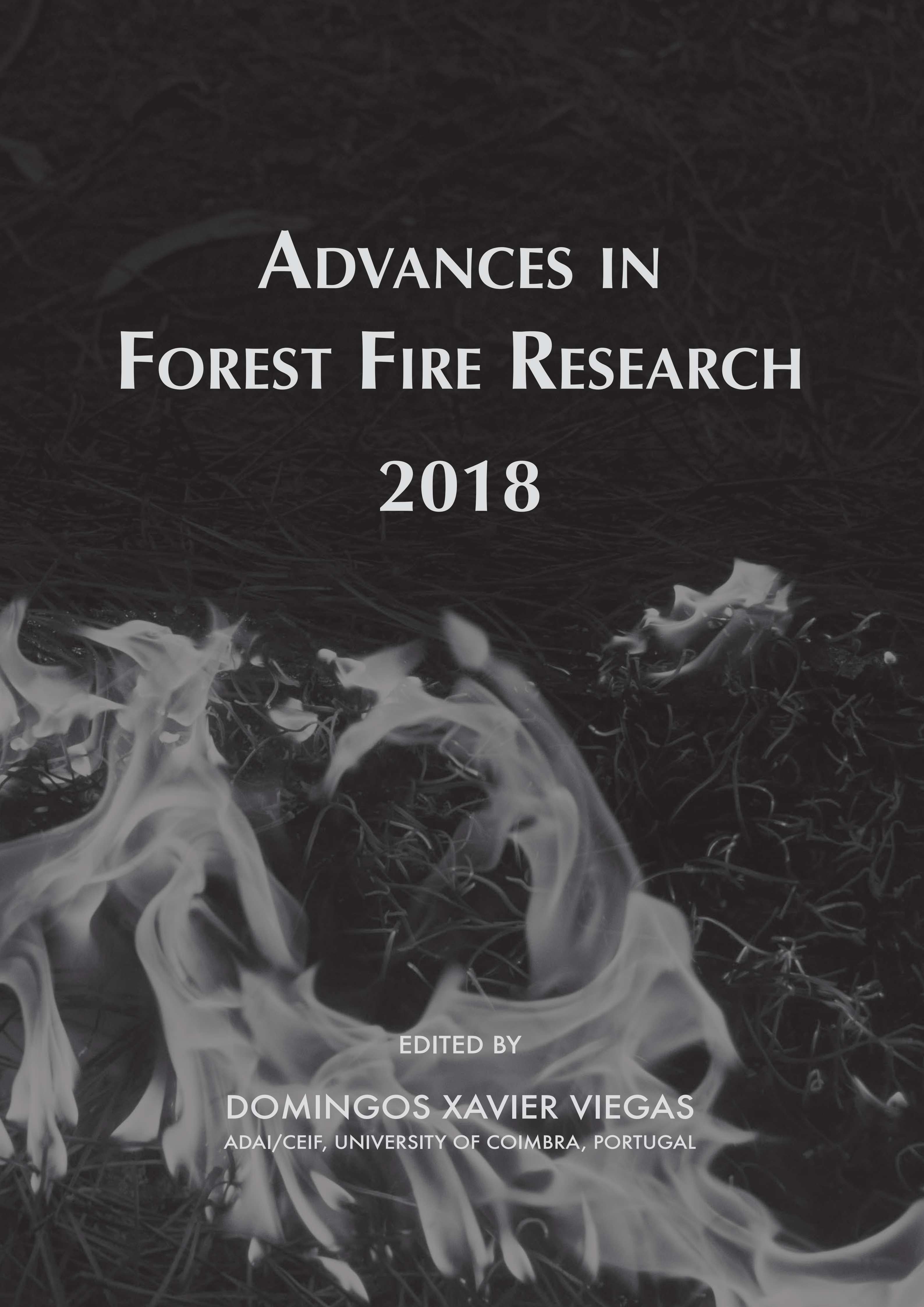

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Modelling of the rate of fire spread in heterogeneous fuel beds based on experimental data

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Abstract

195 laboratory tests were performed to analyse the effect of either slope and wind in the fire spreading in mixed fuel beds composed by one live fuel and one dead fuel – live P*inus pinaster* needles and straw were the fuels used, respectively.

Several models were built by other researchers to predict the fire spread in mixture fuel beds. Many of these models were produced using data achieved for conditions of no wind nor slope. In these tests, the effect of the airflow/wind and the effect of slope in the fire spread in mixed fuel beds was analysed. It was found that the presence of wind or slope do not clearly affect the value of the critical mass fraction xc that correspond to the minimum percentage of the dead fuel required to sustain the fire propagation.

The experimental results were modelled using exponential decay law applied to mixed fuel beds and the concept of degree of curing. These models show a good fit to the experimental results hereby presented so they can be extended to conditions of wind and slope.

In the modelling of surface forest fire spread, the prediction of the rate of spread (ROS) of a fire front, or of part of it, is the main goal that is attempted in order to be able to estimate the advance of the fire front in the course of time. It is commonly accepted that the ROS at a given section of the fire perimeter depends on the fuel bed properties, local topography and atmospheric conditions, namely air flow intensity and direction (e.g. Linn *et al.*, 2007; Cavard *et al.*, 2015). Although this concept can be challenged in several situations when the dynamic behaviour of the fire changes its environment and modifies its ROS properties (Hilton *et al.*, 2016). In this work, we shall assume, as it is commonly done, that fire spreads in a quasi-steady state and that average values of the ROS can be established and determined at least during short periods of time. This work is a follow up of previous works on ROS in heterogeneous fuel beds (Viegas et al., 2010 and 2013) performed by some of the authors of the present publication.

Keywords: combustibility, fuel mixtures, heterogeneous fuels, moisture content, rate of spread

1. Introduction

In the modelling of surface forest fire spread, the prediction of the rate of spread (ROS) of a fire front, or of part of it, is the main goal that is attempted in order to be able to estimate the advance of the fire front in the course of time. It is commonly accepted that the ROS at a given section of the fire perimeter depends on the fuel bed properties, local topography and atmospheric conditions, namely air flow intensity and direction (e.g. Linn *et al.*, 2007; Cavard *et al.*, 2015). However, this concept can be challenged in several situations when the dynamic behaviour of the fire changes its environment and modifies its ROS properties (Hilton *et al.*, 2016). In this work, we shall assume, as it is commonly done, that fire spreads in a quasi-steady state and that average values of the ROS can be established and determined at least during short periods of time. This work is a follow up of previous works on ROS in heterogeneous fuel beds (Viegas et al., 2010 and 2013) performed by some of the authors of the present publication.

Almost 200 experimental tests were carried out aiming at the determination of the ROS in heterogenous fuel beds composed by two different fuels – one fuel of higher combustibility (e.g, dead fuel) and other fuel of lower combustibility (e.g., live fuel). The concept of degree of curing (Anderson et al., 2005) of the fuel bed was considered. Properties such as the fuel moisture content, the slope and the air flow velocity were used as independent variables. The effect of the mentioned properties on the ROS was evaluated for sequences of tests in which the fraction x of the higher combustibility fuel was varied from a fuel bed uniquely composed by the higher combustibility fuel ($x=1$) to a fuel bed composed by the larger fraction of lower combustibility fuel $(1-x)$ from which the combustion was no longer sustained. This threshold of x below which fire stops spreading was designated by critical mass fraction x_c. The fuels used in this work were straw and dead and live *Pinus pinaster* needles. Tests were performed for a range of airflow velocity from 0 to 4m.s^{-1} and slope up to 40º.

The experimental results were modelled following the same approach of Viegas et al. (2013) and it was found that the exponential decay law can be used with reasonable accuracy to estimate the ROS of a fire front for the range of the parameters analyzed.

2. Methodology

The fuel beds were composed by straw or by a mixture of straw and live *Pinus pinaster* needles. The straw was obtained directly from the producer and thus it was collected during the later Spring or during the Summer, much time before the experiments. Regarding the pine needles, several branches of diversified pine trees were collected in the field in Lousã-Coimbra no more than two days before the experiments. In the day of the experiments the needles were detached from the pine branches. The storage of the straw, the pine branches and needles was made in the laboratory at a temperature around 20ºC and relative humidity of about 45%.

The fuel moisture content was determined using a moisture analyser (*A & D MX-50 resolution 0.01% Max = 51g*), previously calibrated by the gravimetric method, exposing a sample of the fuel at 105°C during 15 minutes. After the determination of the *FMC*, the amount of each fuel was weighted according the specifications of the test in order to have a total fuel load of 0.8kg.m^{-2} on a dry basis. The two amounts of fuels were mixed in a box taking care not to crumble the fuel particles and then the mixed fuels were homogeneously distributed in the combustion table. In the tests using uniquely straw the mixture was not performed and the fuel was distributed directly in the fuel bed after being weighted.

Every 20cm of the fuel bed, cotton threads were stretched transversally to the expected fire spread. This procedure aimed at the determination of the rate of spread by the elapsed time between the cut by the fire of two consecutive threads. The linear ignition was carried out using a woollen yarn soaked in a mixture of gasoline and diesel. The woollen yarn was extended in the beginning of the fuel bed, transversally to the expected fire spread, and than ignited to produce a fire front that spread to the fuel bed. In the slope effect tests, the slope was set before the ignition. In the airflow effect tests, the airflow turned on immediately after the ignition. The tests were considered finished when the fire stopped propagating, either because it reached the end of the fuel bed or because the higher fraction of live fuel, and consequently the higher value of FMC, did not allow a sustainable fire spread.

The slope effect tests were carried out in a combustion table with a dimension of 2.95x2.95m^2 allowing a variation of the slope angle in the direction of the intended fire spread. The fuel beds invariably had a dimension of 1.0m width and 2.0m length. The slope angles varied from 0º to 40º. The airflow effect tests were carried out in the wind combustion tunnel existing in the Forest Fires Studies laboratory of ADAI. The fuel beds' size was of 2.0m width and 6.0m length and the airflow velocity varied from 0m.s^{-1} to 4m.s^{-1}.

Since the tests were carried out in different days with slightly different conditions, the resulting data were harmonized aiming at a more accurate comparison. The harmonization of the results was based in the designated "reference tests" using the same methodology described in Viegas *et al.* (2013). The reference tests carried out in a combustion table of $1m^2$ area consist on tests with a fuel bed composed uniquely by $0.8kg.m^{-2}$ of straw, in the absence of wind and slope. These rate of spread in the reference tests was measured using the same methodology based on cotton threads stretched previously described. Two reference tests were performed per day of experiments – one test during the morning and other test during the afternoon. The rate of spread obtained in the slope or airflow effect tests were dimensionless dividing the basic rate of spread of a test by the rate of spread obtained in the reference test performed in the same period of the day.

In Table 1 and Table 2 the parameters of the tests are presented. The acronym "SL" in the reference is used to specify the slope effect tests and "AF" is used to indicate the airflow effect tests.

Table 1 - Parameters of the series SL on the role of slope on the rate of spread R of a linear fire line in a fuel bed composed by a mixture of live Pinus pinaster needles (LPP) and straw (ST) with different values of Fuel Moisture Content (FMC). Date is presented in the format yymmdd. The reference tests are highlighted in bold.

Refer.	*Day*	*FMC ST (%)*	*FMC LPP (%)*	*Slope (º)*	*x*	*R* $(cm.s^{-1})$	*Refer.*	*Day*	*FMC ST (%)*	*FMC LPP (%)*	*Slope (º)*	*x*	*R* $(cm.s^{-1})$
SL01	111003	10.13	110.08	0	1	0.93	**SL47**	111228	5.01	79.53	0	1	1.14
SL02	111003	10.13	110.08	0	0.8	0.66	SL48	111228	5.22	79.53	0	0.6	0.66
SL03	111003	10.13	110.08	0	0.6	0.40	SL49	111228	5.18	79.53	0	0.5	0.00
SL04	111003	10.13	110.08	0	0.5	0.00	SL50	111228	5.22	79.53	0	0.8	0.99
SL05	111003	10.13	110.08	0	1	0.99	**SL51**	120102	4.97	79.53	0	1	1.03
SL06	111003	10.13	110.08	0	1	0.92	SL52	120102	6.59	82.15	20	1	2.44
SL07	111011	4.82	52.44	0	1	0.53	**SL53**	120102	6.37	82.15	0	1	1.25
SL08	111011	4.82	52.44	30	1	3.31	SL54	120102	6.63	82.15	20	0.8	1.51
SL09	111011	4.82	52.44	30	0.6	0.95	SL55	120102	6.46	82.15	20	0.6	0.94
SL10	111011	4.82	52.44	30	0.4	0.00	SL56	120102	6.55	82.15	20	0.5	0.73
SL11	111011	4.82	52.44	30	0.5	1.71	**SL57**	120109	6.42	82.15	0	1	1.21
SL12	111011	4.82	52.44	30	0.8	2.24	SL58	120109	7.38	108.77	40	1	6.35
SL13	111020	4.82	52.44	0	1	0.93	**SL59**	120109	6.31	108.77	0	1	1.07
SL14	111020	13.77	143.31	20	1	1.94	SL60	120109	6.72	108.77	40	0.6	0.82
SL15	111020	13.77	143.31	0	1	0.59	SL61	120109	6.84	108.77	40	0.8	3.88
SL16	111020	13.77	143.31	20	0.8	0.45	**SL62**	120109	8.70	108.77	0	1	1.13
SL17	111128	13.77	143.31	20	0.6	0.00	SL63	120112	8.70	108.77	40	0.5	0.58
SL18	111128	21.07	60.00	20	1	1.14	SL64	120112	5.68	107.47	40	1	6.16
SL19	111128	21.07	60.00	0	1	0.55	**SL65**	120112	5.39	107.47	0	1	1.24
SL20	111128	21.07	60.00	20	0.6	0.42	SL66	120112	6.52	107.47	40	0.6	1.58
SL21	111128	21.07	60.00	20	0.7	0.40	SL67	120112	6.32	107.47	40	0.5	0.69
SL22	111128	21.07	60.00	20	0.8	0.60	SL68	120112	6.27	107.47	40	0.8	3.58
SL23	111130	21.07	60.00	0	1	0.57	SL69	120118	5.68	107.47	40	0.4	0.72
SL24	111130	16.55	105.47	30	1	1.50	SL70	120118	6.09	100.80	40	1	5.83
SL25	111130	16.55	105.47	0	1	0.54	**SL71**	120118	5.35	100.80	0	1	1.25
SL26	111130	16.55	105.47	30	0.6	0.55	SL72	120118	6.39	100.80	40	0.8	3.57
SL27	111130	16.55	105.47	30	0.8	0.00	SL73	120118	6.02	100.80	40	0.5	0.43
SL28	111212	16.55	105.47	30	0.9	0.84	SL74	120208	6.32	100.80	40	0.7	2.53
SL29	111212	6.28	52.91	0	1	0.78	SL75	120208	6.61	108.77	20	1	2.53
SL30	111212	6.08	52.91	0	1	0.86	**SL76**	120208	5.14	108.77	0	1	1.24
SL31	111212	6.71	52.91	0	0.6	0.22	SL77	120208	5.95	108.77	20	0.8	1.92
SL32	111212	6.94	52.91	0	0.6	0.00	SL78	120208	5.95	108.77	20	0.5	0.89
SL33	111212	17.51	52.91	0	1	0.51	**SL79**	120208	5.22	108.77	0	1	1.53
SL34	111215	17.51	52.91	0	0.8	0.26	SL80	120210	5.87	108.77	20	0.6	1.06
SL35	111215	8.62	73.01	20	1	1.93	SL81	120210	4.96	80.51	30	1	3.79
SL36	111215	8.22	73.01	0	1	1.06	**SL82**	120210	4.75	80.51	0	1	0.92
SL37	111215	8.54	73.01	20	0.6	0.57	SL83	120210	4.96	80.51	30	0.5	0.66

SL38	111215	8.62	73.01	20	0.7	0.93	SL84	120210	5.15	80.51	30	0.6	1.05
SL39	111215	8.98	73.01	20	0.8	0.98	**SL85**	120210	4.75	80.51	0	1	0.97
SL40	111219	8.38	73.01	0	1	1.07	SL86	120214	5.06	80.51	30	0.4	0.65
SL41	111219	5.58	94.55	30	1	3.62	**SL87**	120214	8.15	65.02	0	1	0.85
SL42	111219	5.35	94.55	0	1	1.26	SL88	120214	7.16	65.02	0	0.5	0.00
SL43	111219	5.96	94.55	30	0.7	1.91	SL89	120214	7.16	65.02	0	0.6	0.56
SL44	111219	5.77	94.55	30	0.6	0.85	SL90	120214	7.63	65.02	0	0.8	0.72
SL45	111228	5.58	94.55	30	0.5	0.77	**SL91**	120214	6.74	65.02	0	1	0.79
SL46	111228	5.39	79.53	0	1	1.16							

Table 2 - Parameters of the series AF on the role of airflow on the rate of spread R of a linear fire line in a fuel bed composed by a mixture of live Pinus pinaster needles (LPP) and straw (ST) with different values of fuel moisture content (FMC). Date is presented in the format yymmdd. The reference tests are highlighted in bold.

Refer.	*Day*	*FMC ST (%)*	*FMC LPP (%)*	*U* ($m.s^{-1}$)	*x*	*R* ($cm.s^{-1}$)	*Refer.*	*Day*	*FMC ST (%)*	*FMC LPP (%)*	*U* ($m.s^{-1}$)	*x*	*R* ($cm.s^{-1}$)
AF001	130319	20,10	---	1	1	0,91	AF053	130626	11,10	65,50	3	0,5	0,72
AF002	130319	20,19	---	0	1	0,52	**AF054**	130626	9,40	---	0	1	0,98
AF003	130417	15,60	---	1	1	1,42	**AF055**	130626	11,10	---	0	1	1,07
AF004	130417	15,60	73,61	1	0,8	0,83	AF056	130627	10.00	94,90	3	0,4	0,00
AF005	130417	11,48	51,51	1	0,7	1,10	AF057	130627	10.00	94,90	2	0,4	0,00
AF006	130417	15,60	---	0	1	0,62	AF058	130627	9,10	112,70	2	0,8	1,20
AF007	130417	11,48	---	0	1	0,70	AF059	130627	10,20	---	2	1	2,30
AF008	130417	14,10	---	1,5	1	1,71	**AF060**	130627	10.00	---	0	1	0,83
AF009	130418	14,10	94,17	1,5	0,8	0,77	**AF061**	130627	9,29	---	0	1	0,70
AF010	130418	11,60	94,17	1,5	0,6	0,00	AF062	130703	15,70	49,25	2	0,6	0,54
AF011	130418	14,10	---	0	1	0,50	AF063	130703	11,20	101,20	2	0,5	0,68
AF012	130419	11,60	---	2	1	2,37	AF064	130703	11,40	56,49	4	0,8	3,16
AF013	130419	13,20	58,22	2	0,8	0,57	**AF065**	130703	15,70	---	0	1	0,89
AF014	130419	9,50	85,52	2	0,7	0,00	**AF066**	130703	11,20	---	0	1	0,95
AF015	130419	9,50	85,52	1,5	0,7	1,81	AF067	130705	9,80	---	4	1	6,38
AF016	130419	13,20	---	0	1	0,60	AF068	130705	8,90	81,40	4	0,6	0
AF017	130420	11,80	---	1	1	1,48	AF069	130705	9,52	88,30	4	0,7	1,33
AF018	130420	11,80	69,70	1	0,8	0,57	**AF070**	130705	9,80	---	0	1	1,24
AF019	130420	9,29	73.00	1	0,6	0,78	**AF071**	130705	9,50	---	0	1	0,93
AF020	130420	11,80	---	0	1	0,85	AF072	130709	9,70	---	4	1	3,52
AF021	130423	12,70	56,49	2	0,4	0,00	AF073	130709	10,90	93,70	4	0,8	2,81
AF022	130423	12,70	67,70	1	0,5	0,00	AF074	130709	8,90	86,90	4	0,7	1,72
AF023	130423	12,70	67,70	2	0,5	0,00	**AF075**	130709	9,70	---	0	1	1,01
AF024	130603	12,70	---	0	1	0,82	**AF076**	130709	8,90	---	0	1	1,27
AF025	130603	11,10	---	1,5	1	2,03	AF077	130716	12,80	---	3	1	2,49
AF026	130603	10,10	85,52	1,5	0,8	1,25	AF078	130716	10,90	72,70	3	0,7	1,66
AF027	130603	9,40	90,10	1,5	0,6	0,00	AF079	130716	10,90	78,50	3	0,6	0,00
AF028	130603	9,40	90,10	1,5	0,7	1,15	**AF080**	130716	12,8	---	0	1	0,63
AF029	130603	11,10	---	0	1	0,88	**AF081**	130716	10,90	---	0	1	1,10
AF030	130603	9,40	---	0	1	0,93	AF082	130717	10,80	---	1	1	1,16
AF031	130604	10.00	---	2	1	2,88	AF083	130717	10,80	94,90	1	0,8	0,79
AF032	130604	10.00	73.00	2	0,8	2,89	AF084	130717	10,80	106,10	1	0,6	0,00
AF033	130604	8,81	73.00	2	0,6	1,46	AF085	130717	10,80	106,10	4	0,6	0,00
AF034	130604	8,81	75,40	2	0,5	0,89	**AF086**	130717	10,80	---	0	1	0,89
AF035	130604	10.00	---	0	1	1,03	**AF087**	130717	10,80	---	0	1	0,90

AF036	130604	8,81	---	0	1	0,90	AF088	130718	11,50	---	4	1	3,84
AF037	130605	10,8	---	3	1	4,50	AF089	130718	10,80	---	2	1	2,34
AF038	130605	10,80	100,10	3	0,8	1,88	AF090	130718	10,10	129,80	2	0,7	0,84
AF039	130605	13,80	75,70	3	0,6	0,00	AF091	130718	12,90	67,20	2	0,6	1,00
AF040	130605	13,80	75,70	1,5	0,6	0,00	**AF092**	130718	12,90	---	0	1	0,78
AF041	130605	13,80	75,70	3	0,7	0,55	**AF093**	130718	10,10	---	0	1	1,02
AF042	130605	10,80	---	0	1	1,02	AF094	130723	12,70	73,60	3	0,6	0,00
AF043	130605	13,80	---	0	1	0,80	AF095	130723	12,80	85,80	3	0,7	2,45
AF044	130612	11,10	---	2	1	2,29	AF096	130723	11,60	---	3	1	4,81
AF045	130612	13,20	106,60	2	0,8	1,24	AF097	130723	11,60	---	1	1	1,34
AF046	130612	13,20	86,50	2	0,6	0,00	**AF098**	130723	12,70	---	0	1	0,84
AF047	130612	13,20	108,30	2	0,7	0,80	AF099	130725	13,80	---	1	1	0,70
AF048	130612	11,10	---	0	1	0,67	AF100	130725	13,80	84,50	1	0,7	0,00
AF049	130612	13,20	---	0	1	0,83	AF101	130725	9,40	82,80	1	0,75	0,73
AF050	130626	9,40	---	3	1	4,48	AF102	130725	11,80	---	4	1	3,87
AF051	130626	11,10	68,60	3	0,8	2,27	**AF103**	130725	13,80	---	0	1	0,82
AF052	130626	11,10	65,50	3	0,6	1,26	**AF104**	130725	9,40	---	0	1	0,85

3. Results and discussion

3.1. Rate of spread and critical mass fraction

In this section, the rate of spread will be analysed considering it in the dimensional or dimensionless form. In Figure 1 the rate of spread R directly obtained from the experiments as a function of the percentage of straw x in the mixture of the fuels is presented for the series of airflow effect tests (Figure 1a) and for the slope effect tests (Figure 1b). The lines in the plots correspond to the linear tendency curves for each class of airflow velocity or slope demonstrating the effect of the airflow velocity and slope in the rate of spread. The tendency lines also allow the analysis of the critical mass fraction x_c i.e., the fraction of the fuel with lower combustibility (straw) from which the combustion is no longer sustained – the final part of this section will be dedicated to the analysis of x_c.

(a) **(b)**

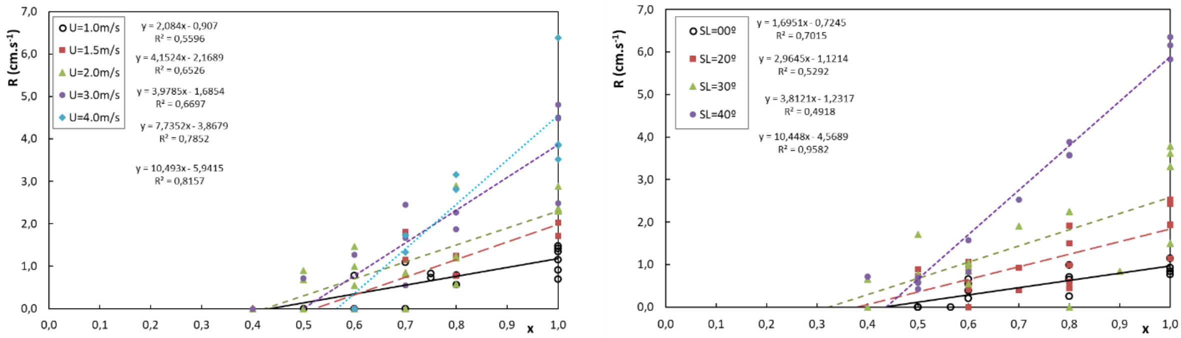

Figure 1 - Rate of spread (R) of the fire front as a function of the mass fraction (x) of the dead fuel (straw): a) airflow effect tests; b) slope effect tests.

The dimensionless rate of spread *R´* presented in Figure 2 is determined by the quotient between the basic rate of spread obtained in the ordinary tests (airflow or slope effect tests) and the rate of spread obtained in the reference tests (Equation 1), providing harmonized results allowing a more accurate data analysis.

$$R' = R/R0 \qquad [Eq.\ 1]$$

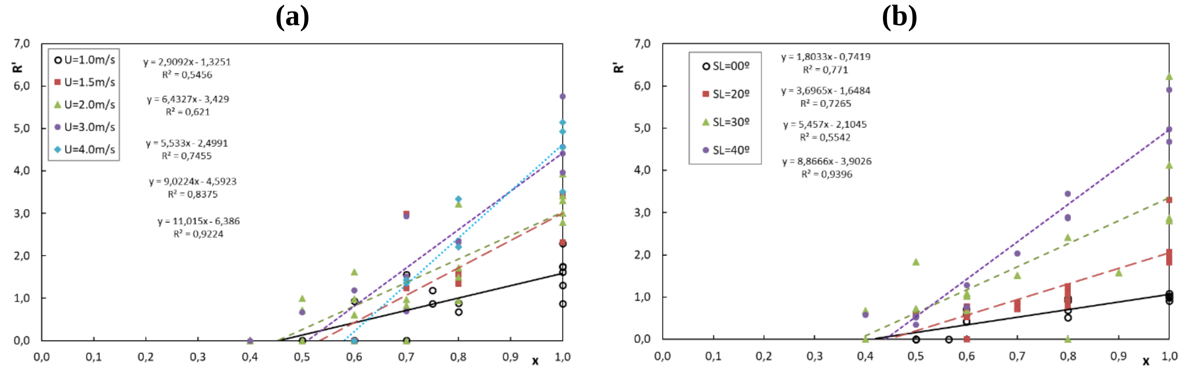

Figure 2 - Non-Dimensional rate of spread (R/R_0) of the fire front as a function of the mass fraction (x) of the dead fuel (straw): a) airflow effect tests; b) slope effect tests.

In Figure 3, the normalized rate of spread R'' is presented. R'' is determined by the quotient between the basic rate of spread R and the rate of spread R_1 obtained in tests with fuel beds uniquely composed by straw ($x=1$) with the same conditions of slope or airflow velocity (Equation 2). Theoretically all the lines should intercept the point ($R''=1$, $x=1$) but that was not observed due to the deviations in the results that led to a correlation coefficient $r^2 \neq 1$.

$$R''=R/R_1 \qquad [Eq.\ 2]$$

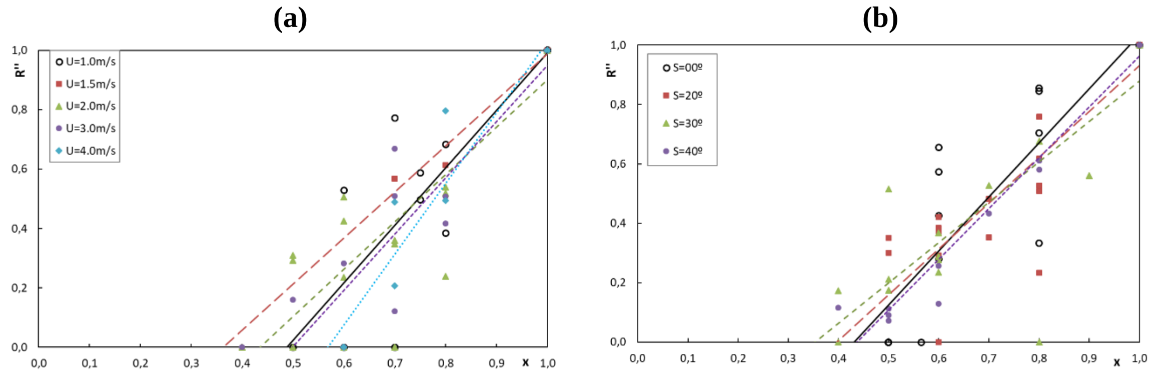

Figure 3 - Normalized rate of spread (R) of the fire front as a function of the mass fraction (x) of the dead fuel (straw): a) airflow effect tests; b) slope effect tests.

The values presented in Table 3 are referred to the tendency lines showed in. Figure 1 to Figure 3. The right side of the table is referred to the critical mass factor x_c analysed by two perspectives. The x_c *(linear)* corresponds to the interception of the tendency line in the x-axis for $y=0$. One value of x_c was obtained for each form of the rate of spread (R, R' and R''). The *xc (experimental)* is based on the direct experimental results considering the range of x_c for which the fire propagation was not sustained ($R=0 m.s^{-1}$) and tests with x immediately above for which the fire propagation was observed ($R>0 m.s^{-1}$).

***Table 3** - Values the gradient "b" of the tendency line (y=a+bx) followed by the correlation coefficient r^2 between parentheses; critical mass fraction x_c deducted from the linear tendency from the figures 1-3 for no fire propagation (R/R´/R´´=0); range of x_c obtained from the experimental data considering the percentage of straw (x) when the fire front did not propagate ($R=0m\text{-}s^{-1}$) and the value of x of the immediate test with fire propagation ($R>0m\text{-}s^{-1}$).*

		b (r^2)			x_c (linear)			x_c (experimental)
		R	R´	R´´	R	R´	R´´	[R=0 ; R>0] $m.s^{-1}$
Airflow effect	$U=1.0m.s^{-1}$	2.084 (0.56)	2.909 (0.55)	1.936 (0.76)	0.4	0.5	0.5	[0.402 ; 0.348]
	$U=1.5m.s^{-1}$	4.152 (0.65)	6.433 (0.62)	1.550 (0.96)	0.5	0.5	0.4	[0.416 ; 0.330]
	$U=2.0m.s^{-1}$	3.979 (0.67)	5.533 (0.75)	1.595 (0.77)	0.4	0.5	0.4	[0.500; 0.492]
	$U=3.0m.s^{-1}$	7.735 (0.79)	9.022 (0.84)	1.894 (0.83)	0.5	0.5	0.5	[0.609 ; 0.383]
	$U=4.0m.s^{-1}$	10.493 (0.82)	11.015 (0.92)	2.385 (0.92)	0.6	0.6	0.6	[0.434 ; 0.327]
Slope effect	SL=0º	1.695 (0.70)	1.803 (0.77)	1.821 (0.79)	0.4	0.4	0.4	[0.462 ; 0.269]
	SL=20º	2.964 (0.53)	3.696 (0.73)	1.543 (0.77)	0.4	0.4	0.4	[0.656 ; 0.509]
	SL=30º	3.812 (0.49)	5.457 (0.55)	1.357 (0.70)	0.3	0.4	0.4	[0.334 ; 0.503]
	SL=40º	10.448 (0.96)	8.867 (0.94)	1.710 (0.96)	0.4	0.4	0.4	[ND ; 0.668]

ND – Non-Determined

As can be seen in the figures and table above, the increase of slope or the airflow velocity drives to higher values of the rate of spread either in the dimensional and dimensionless forms, as could be expect. This statement is most evident for values of higher values of *x*. When the percentage of straw is closer to the critical value x_c for which the fire does not spread sustainably, the variations in the slope or airflow velocity do not drive to higher deviations in the rate of spread until $x=x_c$ that by definition implies a rate of spread equal to zero. This statement gains relevance as the value of x_c is very similar, around 0.45, to all the series of tests as can be seen in Table 3 and Table 4.

***Table 4** - Average values (Av.) and Standard deviation (Sd) of the critical mass fraction values x_c obtained for the airflow effect tests and slope effect tests, considering the tendency lines of figures 1 to 3.*

	R		R´		R´´	
Airflow effect tests	0.49	0.054	0.51	0.048	0.47	0.069
Slope effect tests	0.39	0.045	0.42	0.024	0.40	0.034

These results are very similar to the values of x_c presented by Viegas *et al.* (2013) where a range of $0.3<x_c<0.5$ was found for tests with no slope and no airflow conditions. This similarity of results indicates that the critical values for fire propagation depends mainly on the fuel bed composition instead of external factor like the slope or the wind.

In Figure the range of *x* values in which x_c is included, presented in Table 4 as "x_c *(experimental)*", are analysed as a function of the fuel moisture content (dry basis) of the mixture of fuels. The arrowhead in this figure indicates the upper limit of the x_c *(experimental)* range, i.e. the values of the tests with lower *x* with fire spread sustainably.

(a) **(b)**

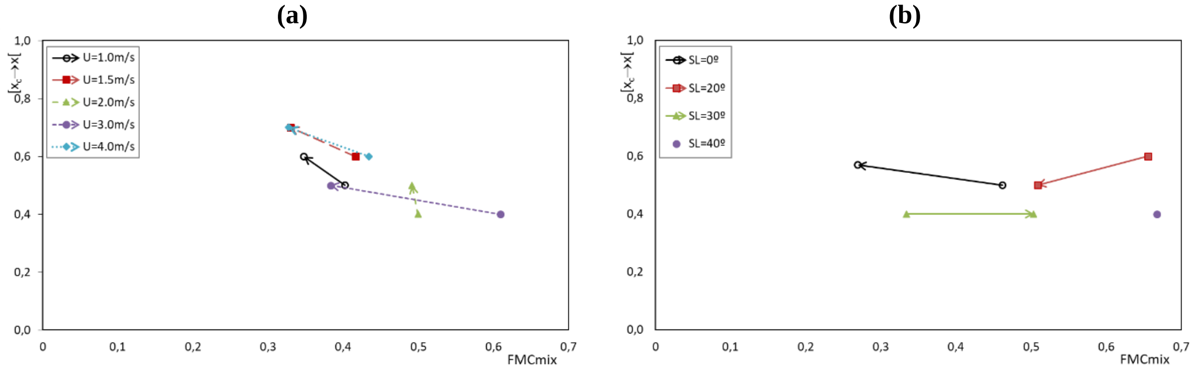

***Figure 4** - Critical mass fraction as function of the fuel moisture content of the mixture of fuels for the airflow effect tests (a) and slope effect tests (b). The arrowhead indicates the tests with $R>0m.s^{-1}$ and the arrow tail indicates the tests for which the fire propagation was not sustained ($R=0m.s^{-1}$). As mentioned in Table , the lower limit of x_c for 40º slope was not determined.*

As could be expected, the decrease from x to x_c drives to a higher values of *FMC* as the mass percentage of the dry fuel (straw) decreases relatively to the live fuel (live pine needles). In the slope effect tests, that was not so obvious with two tests $SL=30^o$ with $x=0.4$ presenting surprising results – the test with $FMC=0.50$ led to a sustained fire propagation and the test with $FMC=0.33$ did not sustained the fire spread. A different result occurs also for $SL=20^o$ with a sustained combustion verified for $x=0.5$, while the value of $x=x_c=0.6$ was obtained for other experiments – this case was not so surprising as the *FMC* value was much lower in the tests with sustained combustion. All these results show the high importance that the *FMC* have in the definition of the critical mass value. However, the consistency of the x_c range resulting from the large number of tests performed and the many other tests presented by Viegas *et al.* (2013), for different values of *FMC*, show that the *FMC* is not the only factor affecting this parameter. The composition of the fuel bed with dead and alive fuels also have an important role in the fire propagation that can be explained by the different chemical composition of the fuels with different release of flammable volatile organic compounds during the burning. The presence of live fuels in relation to the dead fuels is associated to the degree of curing that will be analysed in the next section.

3.2. Degree of curing

The dimensionless normalized rate of spread R´´ was analysed as a function of the degree of curing C (%) defined by Luke and McArthur (1978) and Cheney and Sullivan (1997, 2008) as the percentage of vegetation in grasslands that present physical damages or variations in colour related to its natural green state. Hereby, the degree of curing is highly dependent on the percentage of straw in the mixed fuel bed. This analysis is presented in Figure where the dotted line represents the experimental results obtained by Barber (1990), which was also used as a comparison term in Viegas et al. (2013). In this plots, two models for the determination of the degree of curing were used – the Formulation of Barber (1990) (Eq. 3) and the Formulation of Anderson (2005) (Eq. 4).

$$C(\%)=-6.295\times10^{-6}\times FMC^3+4.4\times10^{-3}\times FMC^2-1.0721\times FMC+109.6758 \qquad [Eq.\ 3]$$

$$C(\%)=90\times exp(1.0439\times10^{-3}\times FMC^{1.335})+10 \qquad [Eq.\ 4]$$

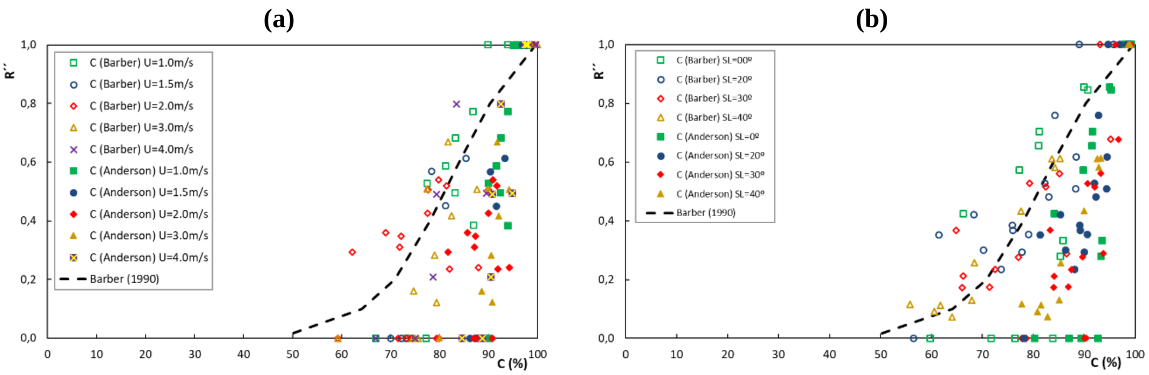

Figure 5 - Comparison between present results for dimensionless normalized rate of spread (R´´) hereby presented and those obtained by Barber (1990)(dotted line) as a function of degree of curing C(%), using the formulations proposed by Barber (Eq. 3) and Anderson et al. (2005) (Eq. 4): (a) airflow effect tests and (b) slope effect tests.

As can be observed the experimental results hereby presented and those obtained by Barber (1990) follow reasonably the same tendency. The formulation proposed by Anderson (Eq. 4) drives to values of C(%) a little larger than those determined by the Formulation of Barber (Eq. 3) which fit better to the experimental results obtained by the same author. These were the same conclusions of Viegas et al. (2013).

3.3. Exponential Decay Law

In Wilson (1990), an exponential decay model to describe the moisture content damping effect on fuel bed combustibility properties was proposed (Eq. 5 and Eq. 6) with ξ as the parameter to be analysed and FMC* a reference value of the fuel bed moisture content. In Viegas et al. (2013) the parameter ξ was the basic rate of spread of the mixed fuel bed with the definition presented in Eq. 7 with R*0 as a reference value of the basic rate of spread of the mixture that corresponds to a value of μ=0. In this section we will follow the same approach of Viegas et al. (2013).

$$\xi=\exp(\mu) \qquad [Eq.\ 5]$$

$$\mu=FMC/FMC^* \qquad [Eq.\ 6]$$

$$\xi=R_0/R^*_0 \qquad [Eq.\ 7]$$

The plots of Figure were used to determine the values of "*a*" and "*b*" used by Viegas et al. (2013) to apply the exponential decay law according Eq. 8. In Table **,** the summary of the fuel bed moisture content damping law parameters is presented. These parameters were used to produce the plots of Figure **.**

$$R=a\times\exp(-b\times FMC_{mix}) \qquad [Eq.\ 8]$$

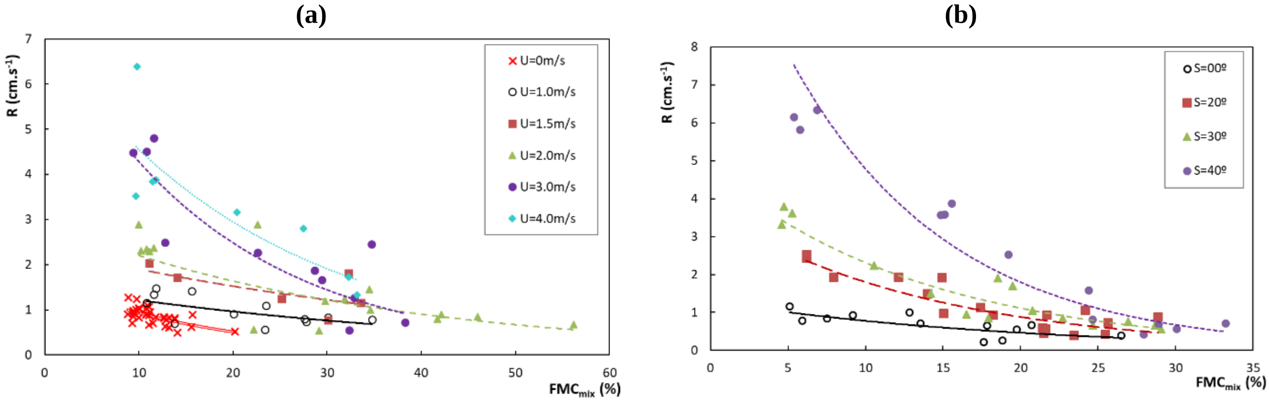

Figure 6 - Basic rate of spread (R) as a function of the fuel moisture content of the mixture of fuels for the airflow effect tests (a) and the slope effect tests (b).

Table 5 - Summary of the fuel bed moisture content damping law parameters.

Airflow effect tests					Slope effect tests				
U ($m.s^{-1}$)	a=R^*_0 ($cm.s^{-1}$)	b	r^2	FMC^*_{mix} (%)	SL (º)	a=R^*_0 ($cm.s^{-1}$)	b	r^2	FMC^*_{mix} (%)
0	1.700	0.060	0.431	16.67	0	1.303	0.052	0.434	19.23
1.0	1.533	0.023	0.378	43.48	20	3.681	0.072	0.676	13.89
1.5	2.374	0.022	0.351	45.45	30	4.812	0.073	0.868	13.70
2.0	2.968	0.030	0.543	33.33	40	12.744	0.098	0.903	10.20
3.0	7.385	0.054	0.638	18.52					
4.0	7.020	0.043	0.804	23.26					

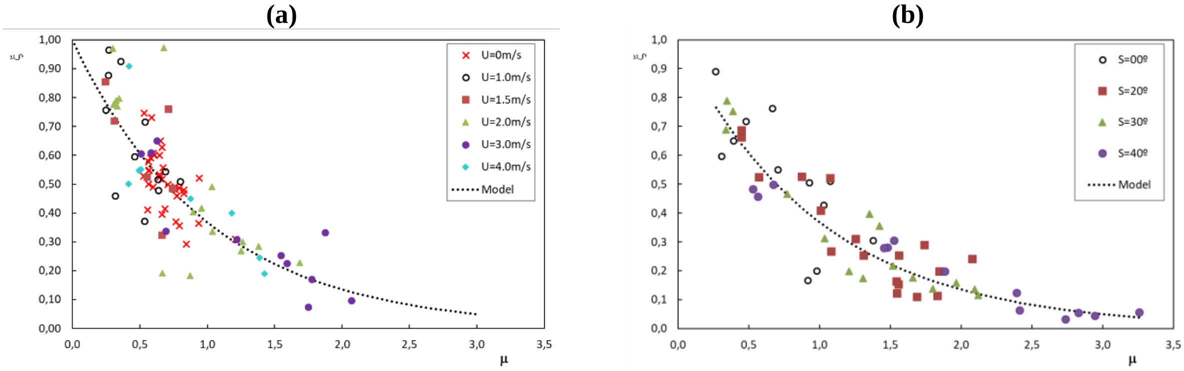

***Figure 7** - Non-dimensional rate of spread decay (ξ) of mixed fuel beds as a function of the ratio of fuel moisture contents FMC and FMC* (Eq. 6) for the airflow effect tests (a) and the slope effect tests (b). The dotted line corresponds to the model given by Eq. 5.*

As can be observed the exponential decay model fits well to the experimental results allowing a good estimation of the rate of spread in mixed fuel beds in conditions of wind or slope. It is important to highlight that the tests with no sustained fire propagation were not included in this analysis since in Viegas et al. (2013) this model is not applied for tests with $x \leq x_c$.

4. Conclusions

195 tests were carried out to analyse the effect of slope and wind in the rate of spread in mixed fuel beds composed by one live fuel (live *Pinus pinaster* needles) with higher fuel moisture content and one dead fuel (straw) with lower *FMC*. The results clearly show that the increase of the straw percentage in the mixture drives to high values of the rate of spread. As could be expected, the increase of either slope and wind/airflow also lead to higher values of the basic rate of spread *R* and for the harmonized rate of spread *R´*. The hereby designated calibrated rate of spread *R''* did not show that tendency with the results following approximated values for the same fuel bed composition (same *x*).

These experiments showed that either the slope or the wind do not have an important role in the definition of the critical mass fraction parameter x_c, from which the fire does not spread sustainably, since all the sequence of tests performed resulted in values of x_c very similar around *0.45*. These results are very consistent with the results of Viegas et al. (2013) which obtained an average value of $x_c=0.4$ for tests in mixed fuel beds with no wind and no slope.

The concept of the degree of curing *C(%)* was also analysed in this study and the formulations of Barber (1990) and Anderson (2005) were tested. Both formulations showed a good fitting to the experimental results.

The Exponential Decay Law described by Wilson (1990) and adapted by Viegas et al (2013) for mixed fuel beds was tested in these experiments with airflow and slope do not considering the tests where the fire did not propagate sustainably. A good fitting of this law to the experimental results was observed.

5. List of acronyms

a, b	Parameters of Equation 8
Av	Average
C (%)	Degree of curing in percentage
FMC	Fuel moisture content
FMC_{mix}	Fuel moisture content of the fuel bed
*FMC**	Reference value of the fuel bed moisture content in Eq. 6
LPP	Live *Pinus pinaster* needles

R	Basic rate of spread
R´	Harmonized rate of spread (Eq. 1)
R´´	Normalized rate of spread (Eq. 2)
ROS	Rate of spread
Sd	Standard deviation
SL	Slope
ST	Straw
U	Airflow velocity
x	Mass percentage of straw in the fuel bed
x_c	Critical mass value
ξ	Combustibility property in analysis
μ	Ratio between FMC and FMC*

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