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Effect of Wind and Slope When Scaling the Forest Fires Rate of Spread of Laboratory Experiments

Yolanda Pérez, Elsa Pastor, Alba Àgueda and Eulalia Planas, Center for Technological Risk Studies (CERTEC), Universitat Politècnica de Catalunya, Avinguda Diagonal, 647, 08028 Barcelona, Spain*

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Abstract. This paper uses the scaling laws obtained from a *Froude Modeling* perspective to analyze the variations experienced in the rate of spread of wind-aided and up-slope laboratory fires when changing the size of a scale model. The results have shown that the rate of spread scaling law is no longer verified when working at laboratory scale in steep slopes and high wind speed conditions. The paper also provides a framework for scaling and scale issues in forest fire research.

Keywords: Changing scale, Dimensional analysis, Scaling laws, Forest fires behaviour

1. Introduction

Forest fires research has been focused on predicting fire behaviour and extrapolating these predictions to time and space scales appropriate to management decision making [1]. Different approaches have been used in order to study forest fires behaviour. Experimentation, either in the lab or field, has played an important role in fire research, although laboratory and field data cannot be compared without taking into account the differences between both scales [2]. Ideally, processes should be observed at the scale they occur, but this is not always feasible. Often the interest lies in large-scale processes but only small-scale data are available. However, some processes occur at a range of scales. This permits to observe them at different scales giving an insight into the mechanisms that control these processes [3].

Dimensional analysis is a powerful technique for dealing with complex physical problems because it is a simplification modeling process by which the number of variables used to describe a system is reduced to a fewer number of non-dimensional quantities called π groups. Furthermore, dimensional analysis is normally associated to scale analysis studies, as scaling laws, i.e. expressions describing the relations between the characteristic variables of the phenomenon at different scales, can be obtained by comparing π groups, according to the similarity principle.

* Correspondence should be addressed to: Eulalia Planas, E-mail: Eulalia.planas@upc.edu

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Thus, scaling laws are the rules that must be followed to construct an experimental model or to design experimental tests. Then, prediction models can be developed against the experimental data obtained in these experimental models or tests.

If dimensional analysis is strictly applied to forest fires modeling, more than thirty π groups can be obtained [4]. So, it is not possible to fulfill all the derived scaling laws simultaneously and therefore complete scaling is not possible. But a partial scaling is feasible by omitting some π groups in accordance with certain physically based hypotheses [5]. So, even though some of the phenomena that are expected to occur are not properly scaled, partial scaling techniques have demonstrated their potential to produce good results and a better understanding on diverse fire phenomena [3].

Different strategies for modeling can be carried out depending on the considered hypotheses. The most common strategy used in fire modeling is called *Froude Modeling*; this is the scale model works in the same ambient conditions than the full-scale phenomenon does.

In a previous study [6], scaling laws obtained by applying a *Froude Modeling* approach were deduced for the propagation of a basic flames front, i.e. in absence of wind and slope. Although the results obtained in the laboratory tests developed in that work were encouraging to validate the scaling laws, the absence of wind and/or slope is a situation unlikely to occur in a field scenario. The study of wind-aided and up-slope fires has always been of great interest due to their potential to develop extremely high rates of energy release, spreading at high velocities; and damaging natural and human resources.

In this work, the scaling laws obtained from a *Froude Modeling* perspective have been used to analyze the variations experienced in the rate of spread (R) of wind-aided and up-slope fires when changing the size of a scale model—a natural fuel bed, in the lab. Therefore, the aim of this work is to investigate when and why, the scaling laws cease to be applicable as the size of the scale model changes.

2. Dimensional Analysis and Scaling Laws

The systematic methods by which dimensional analysis should be carried out for any physical problem are presented in many standard texts (i.e. [7–9]). In this study, in order to obtain the groups needed to completely define the system, the π-Buckingham theorem has been used. More detailed information on the procedure for the selection of variables needed to develop the analysis and the resulting π groups can be found at [6]. Herein the list of variables used in the analysis is shown in Table 1. A part from these variables, some universal constants were also considered to calculate the π groups, as the acceleration due to the gravity.

The π groups, obtained by applying the π-Buckingham theorem, depend on the basic core of variables selected to compute them. Nevertheless, the π groups can be combined or rearranged to get some known dimensionless groups or other friendly forms with a straight physical meaning.

To deduce the scaling laws for designing the scale model experiments the requirement of similarity must be followed (i.e. all the π groups must be identical

Table 1
List of Selected Variables Used in the Dimensional Analysis Developed

Selected variables	
Fuel bed and particles that configure fuel	*Geometry and fire behavior*
Bulk density of the bed, ρ_{ap}	Flames front length, W
Fuel bed depth, h	Flames depth, S_f
Fuel load, C	Flame height, H
Moisture content, H_s	Flame length, L_f
Fuel bed temperature, $T_s - T_a$	Rate of spread, R
Preheating length, l_s	Burning rate, V
Convective heat transfer coefficient, h_{cs}	Emissive power, E
Surface inclination, α	Flame temperature, $T_f - T_a$
Low fuel heat content, LHC	Fireline intensity, I_B
Surface area to volume ratio, σ_s	Residence time, t_r
Particle density, ρ_m	Combustion gases velocity, u_{gc}
Particle diameter, d_c	Combustion gases viscosity, μ_{gc}
Atmospheric conditions	
Relative humidity, HR	
Wind velocity, u_w	

in the scale model and the full-scale system). From a *Froude Modeling* perspective, it is not possible to retain both the Reynolds and the Froude numbers, since they lead to contradictory scaling relations. But if the scale model is large enough, it can be assumed a fully developed turbulent flow and the Reynolds number can be dropped.

Besides the hypotheses of *Froude Modeling* (the same ambient conditions), if the experiments are performed using the same fuel (i.e. vegetal species) the following variables are identical for all the scales: σ_s, d_c, ρ_m and LHC. This simplifies the number of scaling rules to keep in the experimental design.

Scaling relations resulting from *Froude Modeling* state that, among others, linear variables must scale with the characteristic length scale of the system; and velocity rates must scale with the square root of the characteristic length of the system. In this study, scaling has been performed as a function of the flames front length. So, this variable has been considered the characteristic length of the system. Flames front length is one of the more easily modifiable variable in laboratory because initially is equal to the length of the ignition line. Moreover, according to the experimental methodology used in this work, this is also equivalent to the fuel bed width. But these are not the only reasons why flames front length was selected to be the characteristic variable of the system. As observed by [2] there are some laboratory and field data which suggest that the rate of spread may depend on the fire front width.

As a result, according to the π groups computed [6] and the hypotheses considered, the following scaling laws have been obtained, where the subscript $S1$ means scale 1 and the subscript $S2$ means scale 2, in relation to the two scales that are being studied:

$$\frac{h_{S1}}{h_{S2}} = \frac{W_{S1}}{W_{S2}} \tag{1}$$

$$\frac{R_{S1}}{R_{S2}} = \frac{u_{w_{S1}}}{u_{w_{S2}}} = \left(\frac{W_{S1}}{W_{S2}}\right)^{1/2} \tag{2}$$

$$Hs_{S1} = Hs_{S2} \tag{3}$$

$$\rho_{ap_{S1}} = \rho_{ap_{S2}} \tag{4}$$

$$\alpha_{S1} = \alpha_{S2} \tag{5}$$

The previous equations present the rules that must be followed to design the experimental tests. Thus, fuel moisture content should be kept constant, as well as the fuel bed bulk density and the slope of the surface where fire is spreading. In addition, fuel bed depth must be scaled with the flames front length linearly, and wind speed must be scaled with the square root of flames front length. A part from this, Equation 2 presents the relation that must be fulfilled among the rate of spread and the flames front length and hence only after carrying out the experimentation it will be possible to validate it.

It should be noted that not all the derived scaling laws have been presented, just the ones related with the experimental design and the rate of spread.

3. Materials and Methods

The tests developed in this work have as main goal the study of wind and slope effect on forest fires spread from two different points of view: one associated to the study of changing scales and the other to study the effect of long-term forest fires retardants. This fact influenced the experimental design and methodology. Moreover, the characteristics of the experimental setups also influenced the experimental design as they limited the tests dimensions. As only the results on the study of changing scales will be presented in this paper (the results of the other study are exposed on [10]), the following paragraphs are centered on the description of the specific characteristics related to the changing scale tests.

3.1. Laboratory Setups

The experiments were conducted in the ADAI's (Associação para o Desenvolvimento da Aerodinámica Industrial) large experimental building near Lousã (Portugal). Two different setups were used for the laboratory tests (Figure 1). A combustion table (4 m × 4 m), allowing an inclination between 0° and 40° for

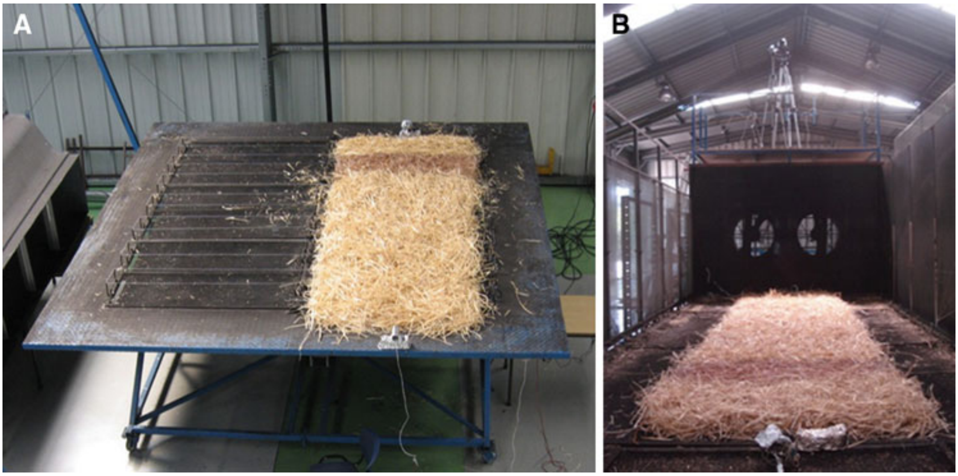

Figure 1. Images of the laboratory setups. (a) Combustion table for the tests under slope conditions, (b) combustion tunnel for the tests under wind conditions.

tests under slope conditions, and a wind tunnel (2.6 m × 8 m) which allows working within a range of wind speeds from 0.5 m/s to 5 m/s. More detailed information on these setups can be found in [11].

3.2. Experimental Design and Methodology

Three different scale models—fuel beds dimensions, were tested in the lab on different conditions of wind and slope. Thus, three different values of initial flames front length were fixed, 0.50 m, 1.00 m and 1.25 m. These values predetermined the fuel beds width as well. Each size, considered as a scale, was named W50, W100 and W125, respectively.

Given that the bulk density had to be retained (Equation 4) and normally natural fuel beds compactness increases as fuel load does, an exploratory study on forest fuel properties was carried out to opt for the proper fuel type. According to [12] wheat straw (*Triticum* sp.) was selected because, among all of the fuel species available in the laboratory for this experimentation, this fuel allows building beds preserving roughly constant the bulk density within a range large enough of fuel loads.

Once the fuel type was chosen, fuel load was established for the lower scale tests (0.30 kg/m^2), and fuel bed depth was measured (4 cm). Hence, fuel bed bulk density was obtained, too (7.5 kg/m^3). The values of fuel load for the other scales were then calculated according to Equations 1 and 4. Table 2 shows the main characteristics of the scale models or fuel beds for each scale. Fuel bed length is a variable that has not been considered in the dimensional analysis on the basis that the values used in the tests were large enough to ensure that the steady state

Table 2
Main Characteristics of the Different Scale Models

Scale	Bed width (m)	Bed depth (cm)	Fuel load (kg/m^2)	Bulk density (kg/m^3)
W50	0.50	4.0	0.30	7.5
W100	1.00	8.0	0.60	7.5
W125	1.25	10.0	0.75	7.5

would be reached. The fuel bed length varied thus from one test to another depending on the characteristics of the setup used.

Even though it was planned to perform the experiments with only one vegetal species, the fuel was supplied in wheat straw bales with a different composition in species depending on the bale. So, mainly two different wheat species were detected, whose main difference was in terms of the surface area to volume ratio (σ_s). In order to distinguish them henceforth species with a greater surface to volume ratio will be named *wheat type* 1, and species with a lower surface to volume ratio *wheat type* 2.

It is important to remark that it was also impossible to fulfill the scaling law described in Equation 3. Wheat straw bales were stored in the lab in normal ambient conditions. So, fuel moisture content varied with ambient conditions to achieve an equilibrium state. This fact should be cautiously considered when analyzing the data obtained from the experimentation.

Regarding slope tests, Equation 5 establishes that the slope value must be constant across scales. Therefore, to study the effect of slope three experimental series were named P10, P20 and P30, where the slope was kept constant, taking values of 10°, 20° and 30°, respectively. For each series an experiment in every scale was carried out with one replica of the trial to check the reproducibility. Moreover, another extra series named control test (P0) was developed, in the same setup but without slope, in order to be able to account for the fuel moisture content effect on rate of spread when processing the data. Thus, in this case, just after or before a slope test, the corresponding control test—same scale and fuel conditions but without slope—was executed. Consequently, a total number of 36 experiments were conducted, 18 under slope conditions and 18 control tests.

Concerning wind tests, Equation 2 states that wind speed must be scaled with the square root of flames front length. Since the wind tunnel can work within a range of wind speeds from 0.5 m/s to 5 m/s, it was decided to test three wind speed values in each scale, from light to strong winds. So, three experimental series were planned, U1, U2 and U3. Wind speed values were firstly fixed for the lower scale, and then the wind speed values for the other scales were determined from Equation 2. Table 3 shows the wind speed values for every scale on the different series. For every series a test in each scale and a replica were carried out.

As in the slope tests, a series of control tests without wind (U0), were performed in the wind tunnel following the same criteria and objective than the control tests in the combustion table. Therefore, 36 experiments were carried out in the wind tunnel, 18 under wind conditions and 18 control tests.

Table 3
Wind Speeds Used for the Different Scales in the Experimental Series

Series	Wind speed for scale W50 (m/s)	Wind speed for scale W100 (m/s)	Wind speed for scale W125 (m/s)
U1	0.7	1.0	1.1
U2	1.4	2.0	2.2
U3	2.1	3.0	3.3

All the tests were filmed with a thermographic camera (*AGEMA Thermovision 570-Pro*) and two video cameras (*SONY handycam DCR-HC42E)*. Two heat flux sensors (*Medtherm 64-2-16* and *64-20T-20R*) were located at the beginning and at the end of the fuel bed. Moreover, several aluminum plates were randomly distributed under the fuel bed to collect the ashes after a test in order to obtain the consumed fuel load. Ambient conditions and fuel moisture content were measured just before the ignition.

3.3. Methodologies to Obtain the Variables

The validation of the full set of scaling laws derived from dimensional analysis requires the determination of many variables (Table 1). Some of them were obviously fixed prior to the tests according to the experimental design while others were measured during the tests. Some others could not be measured so they were estimated from values in the literature or through empirical or theoretical equations. Since here are presented the results related to the scaling law for rate of spread, only the methodologies to obtain the rate of spread and the flames front length, the characteristic variable of the system, are roughly explained.

The rate of spread was computed from the analysis of infrared images. For every image and thus every corresponding instant, the most advanced fire front position was detected and then the R was computed. More details on this methodology can be found in [13].

The analysis of the images allowed observing the evolution of the flames front profile. Initially, the flames front profile is nearly a straight line but, as it advances, it acquires a certain degree of curvature. In order to consider this variation in the flames front length an algorism was implemented with *Matlab*® software. This algorism computes for every instant the length of the flames front by processing the infrared images. For the subsequent analysis, a mean value of the flames front length for every test during the stationary state has been used.

4. Results and Discussion

In order to be consistent with the scaling laws, fuel moisture content would have had to be kept constant between scales but, as explained before, this was not possible due to the lack of controlled atmospheric conditions. This fact could increase the variability in the values of R measured during the experiments and thus hide the potential validity of the scaling law. For this reason, before the analysis of the validity of the rate of spread scaling law, the effect of fuel moisture content on the R has been studied. Moreover, the potential effect of fuel moisture content on the flames front length has also been analyzed as it could also influence the accomplishment of the scaling law.

4.1. Effect of Fuel Moisture Content on the Rate of Spread

The effect of fuel moisture content (H_s) on the rate of spread has been widely studied. In laboratory fires it has been observed that, when fuel moisture content increases flame temperatures, rate of spread, burning rate and flame length and width tend to decrease [14]. Rate of spread is not only affected by the fuel moisture content but also by other factors, for instance, the amount of available fuel and its properties. Figure 2 shows the effect of the fuel moisture content on R distinguishing the fuel species used. The experimental points in Figure 2 correspond to the control tests, i.e. those without wind and slope (series P0 and U0), for all the scales tested.

The experimental values shown in Figure 2 fit fairly well to the trend observed in the work of Anderson [14]. In this work Anderson developed a theoretical model for the determination of the rate of spread in conditions of no wind and no slope, considering the radiation as the main heat transfer mechanisms enhancing fire spread. From this model he obtained a theoretical curve relating rate of spread and fuel moisture content for different fuel species.

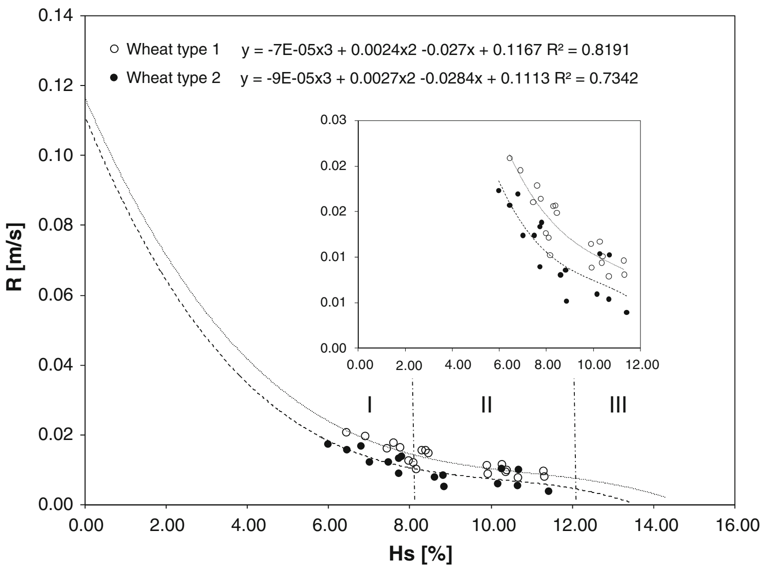

Figure 2. Rate of spread as a function of fuel moisture content for both species used.

Data on Figure 2 could be fitted to a third degree polynomial function with correlation coefficients of 0.73 and 0.82 for wheat type 2 and wheat type 1, respectively. If one observes the fitting curves, three zones of different behaviour can be distinguished: zone I with a strong slope were little changes in H_s cause great changes in R; zone II with a gentle slope and zone III in which the slope increases again but less than in zone I. The behaviour shown by the two fuels is similar although in the case of wheat type 2 the R value is always a bit lower than that of the wheat type 1, for the same fuel moisture content. This can be attributed to the fuel surface area to volume ratio—lower in the case of wheat type 2—that causes a slower water exchange between the fuel and the environment, which affects the fuel preheating and thus the rate of spread.

In the range of fuel moistures where most of the experimental points are found—between 6% and 11%—an increase of one moisture content percentage point causes a mean decrease on the rate of spread of around 13%. Nevertheless, if one distinguish between the three zones (I, II, III) shown in the graph, the decrease of the R in zone I (between 6% and 8% of fuel moisture content) is higher, approximately 20%, while in zone II it remains around 12.5%.

The effect of fuel moisture content on R distinguishing the experimental scale has also been analyzed (Figure 3), because according to the scaling laws, the amount of fuel used increases with the scale and so R does. Moreover, the increasing fuel bed depth could also influence the process of water exchange between the fuel and the environment.

From Figure 3, it can be observed that, in wheat type 1 fuel beds, small scales (W50) are slightly more affected by fuel moisture content, mainly in the lower range of fuel moistures (6% to 8%). The behaviour shown by the wheat type 2 curves, although not represented here, was similar.

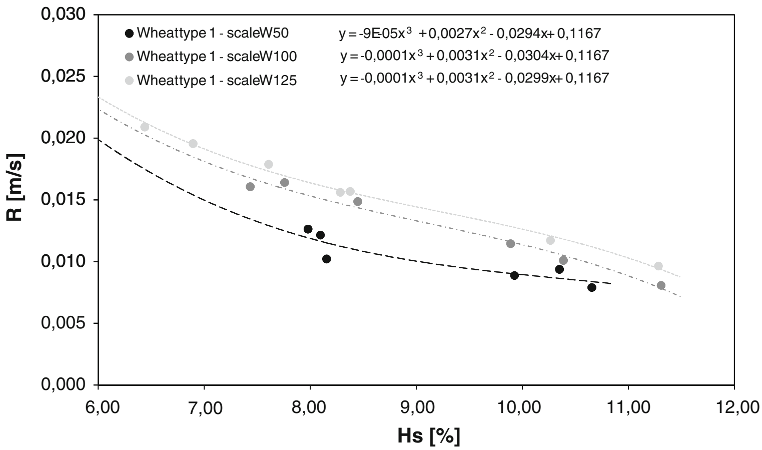

Figure 3. Rate of spread as a function of fuel moisture content for the three experimental scales used in wheat type 1 fuel beds.

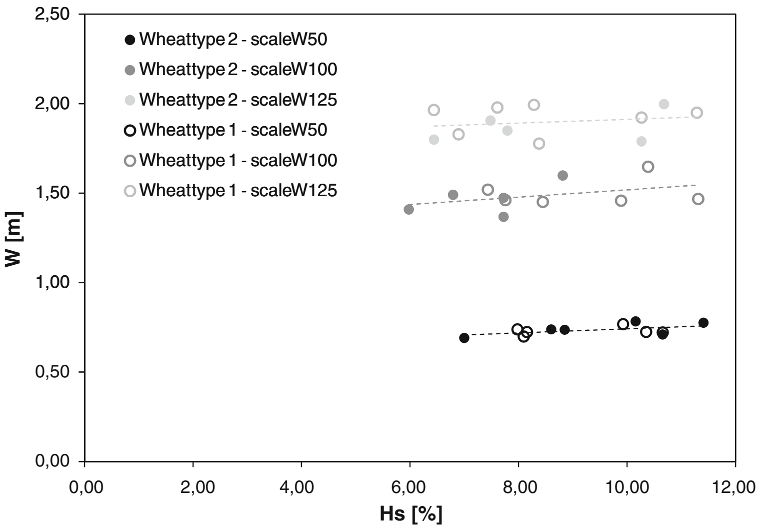

Figure 4. Flames front length as a function of fuel moisture content, distinguishing between the three scales (W50, W100 and W125) and the two fuels used.

In this study, the flames front length has been taken as the characteristic length for the scaling process. It is thus important to know whether the fuel moisture content or the type of fuel has some influence on this parameter. In the literature there are very few references concerning this subject. For instance, [15] observed that the effective flames front length was independent of the fuel moisture content in experimental tests conducted at field scale. Here the same conclusion can be extracted from the laboratory test, as it can be observed in Figure 4, together with the fact that there are not significant differences between the two fuels used with regard to the effect of moisture content on the flames front length.

As a conclusion for this section it can be said that, when discussing the rate of spread scaling law, care has to be taken with the fuel moisture content. This is especially important in the range of moistures between 6% and 8% as it can cause changes on R of around 20%, which can be even marked for the lower scales (W50). It was not possible to carry out the same analysis for the wind and slope tests due to the limitations on the available data. Nevertheless, similar results should be expected.

4.2. Validation of the Rate of Spread Scaling Law

According to Equation 2 the rate of spread scales to the square root of the flames front length (W). In this section the effect of wind and slope on the performance of the rate of spread scaling law is analyzed.

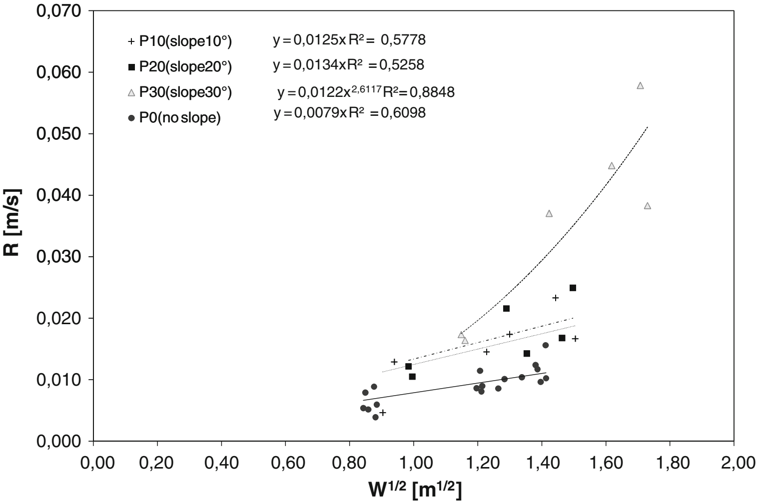

Figure 5. Rate of spread as a function of the square root of the flames front length for the series with slope (10°, 20° and 30°) and including control tests (0° slope).

In order to study the effect of slope on the rate of spread scaling law, the results obtained in the series P0, P10, P20 and P30 (i.e. 0°, 10°, 20° and 30° slope tests) have been plotted in Figure 5.

It can be observed that series P0, P10 and P20 have a linear tendency and thus follow the scaling law in the range of scales of this work while series P30 does not, which actually is in better agreement with a power trend.

Between the series P10 and P20 it seems that there are almost no differences. This is an effect that can be caused by the fuel moisture content. Series P0 and P10 have very similar mean fuel moisture contents (9.7% and 9.6%, respectively) which means that the existing difference between the slope of their linear regressions can be directly attributed to the difference on the slope used in these tests; whereas series P20 has a slightly higher moisture content value (10%). As explained in the previous section, this can induce a reduction in R of about 5% with respect to the value that one could expect for H_s values around 9.6%, hiding the real difference between P10 and P20 linear regressions slopes.

In the case of series P30 the mean H_s was lower (8.9%) so the R values in Figure 5 are probably around 9% higher than those expected; nevertheless this would not make any change on the curve behaviour and so the scaling law wouldn't probably be accomplished anyway. The cause of the P30 data trend can be attributed to the fuel bed length, which in this case was not large enough to ensure the steady state propagation. There is no agreement between the scientific community about if it is possible or not to attain a steady propagation for such high slopes. In case that propagation remained unsteady, the scaling law proposed in this work would no longer be applicable because the dimensional analy-

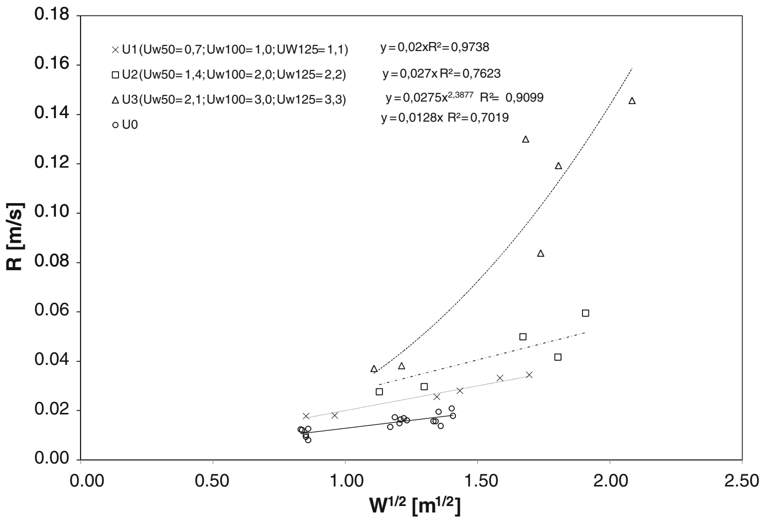

Figure 6. ***R* as a function of the square root of the flames front length, for the wind series.**

sis performed would have had to consider the rate of spread acceleration, which currently it has not. Otherwise, if steady propagation was reached, more data would be needed in order to assess if the *R* scaling law is verified under steep slope conditions.

Concerning to the effect of wind on the rate of spread scaling law, Figure 6 shows the results obtained for the four series of experiments conducted.

As it can be seen, series U0, U1 and U2 accomplish rather well the scaling law, while series U3 do not. In other words, for wind velocities higher than approximately 2.5 m/s the scaling law is no longer verified. There are diverse reasons that could explain this behaviour apart from the fact that maybe some of the hypotheses done during the scaling process are no longer applicable. One of the reasons can be the experimental setup dimensions and design, which at these high wind speeds does not allow the fire stationary state to be reached, as already happened in the steeper slope tests. Moreover, when high wind velocities are tested, the fire moves so fast that fewer points are available to obtain the mean *R* plotted in the graph, which then becomes less reliable.

In order to study the validity of the *R* scaling law in a wider range of flames front lengths, Figure 7 shows together data of the control tests (U0), data obtained in a test performed in a larger combustion table (fuel bed width of 2.5 m, W250) and data already published in [6] which covered the scales from W25 to W100 (fuel bed widths 0.25, 0.50 and 1.0 m). All these tests were designed following the scaling laws here presented. As it can be seen, data are in good agreement with the *R* scaling law (R^2 = 0.869). The point corresponding to the test W250 seems to be more deviated from the regression line than the rest of the data points. The fuel moisture content on test W250 was 6.5% whereas the mean

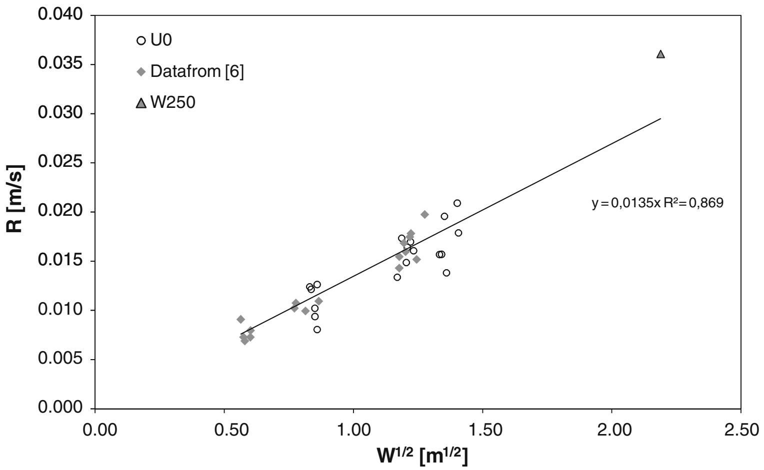

Figure 7. ***R*** **as a function of the square root of the flames front length for tests under no wind and no slope conditions.**

fuel moisture content for the rest of data was 7.6%. If correlation equations derived from the analysis of fuel moisture content effect on R (Figure 3) are considered, the rate of spread associated with a H_s value of 7.6% would be around 20% lower than the one associated with a H_s value of 6.5%. A difference of 17% is obtained between the R value measured for W250 and the value of R predicted by using the regression line shown in Figure 7. Thus, it can be stated that the deviation observed for the data point W250 is due to the fuel moisture content effect on R.

5. Discussion on the Use of Scale Analysis

Scale analysis has been used here in order to study the effect of wind and slope on the rate of spread. Scale models have been built according to the scaling laws, but also taking into account the fuel bed characteristics—load, depth, bulk density, and vegetal species—that are generally used in forest fires laboratory experimentation.

This has allowed obtaining interesting results such as that the failure to keep H_s constant does not introduce large deviations to the rate of spread scaling law but it causes some noise in the R values which, if possible, it is preferable to avoid. Moreover, fires with neither slope nor wind can be scaled in a wide range of fuel bed widths (from 0.25 m to 2.5 m). This means that it is not necessary to make experiments with large fuel beds as the same information regarding R will be obtained from smaller beds. In the case of wind and slope tests, results show that the scaling laws cease to be applicable for the steepest slope (30°) and to the higher winds (>2.5 m/s). The main causes of the scaling law failure have been already discussed but to summarize, it can be said that care has to be taken with the setup, as small facilities may not be suitable to work in these situations.

If one wants to use scaling laws to design reduced scale models of fires in field scenarios (i.e. prescribed burnings, experimental tests in the field, etc.), there are some other important aspects that have to be borne in mind. Firstly, it should be highlighted that the scaling laws here presented have a definite limit of applicability since neither the geometric descriptors of the fuel bed nor the rate of spread cannot increase indefinitely as the scaling law suggests. To somehow avoid this problem the properties of the scale model have to be defined starting from a large scenario previously characterized. Moreover, another interesting issue is how the wind has to be scaled between field scenarios and lab tests; issues like the wind profile, the measurement height or the potential effect of the fuel bed depth have to be taken into account as they can led to undesirable scaling effects. Furthermore, wind tunnels usually work within a range from 0.5 m/s to 6 m/s, but we should question whether it is necessary to work with such high wind velocities. For instance, working in the laboratory with fires of 1 m flames front length and wind velocities of 3 m/s (which is rather normal) would amount for a fire of 100 m flames front length, according to the scaling law, to have wind velocities of 30 m/s (108 km/h). Therefore, more work has still to be done in order to clarify all these aspects.

6. Conclusions

This study highlights the need for multiscale analysis in order to adequately characterize and monitor forest fires and provides insights into rate of spread scaling patterns under wind and slope conditions. The results obtained are promising but more efforts have to be done in this field, mainly on scaling fires in field scenarios.

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