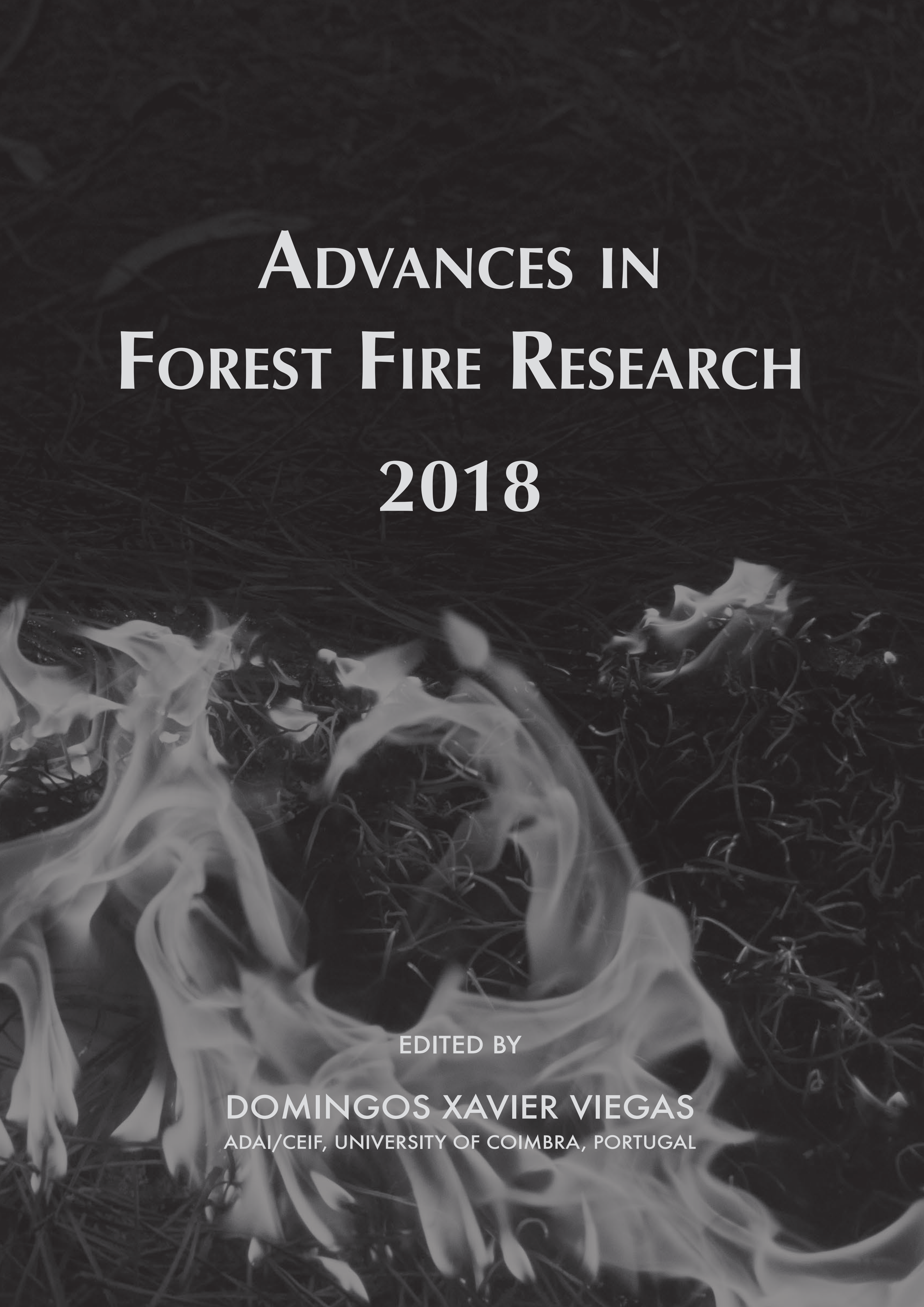

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Observations on wildfire spotting occurrence and characteristics in Greece

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Abstract

This paper presents a study on the phenomenon of spotting in some of the most common forest vegetation types in Greece, during wildfires in the 2007-2017 period. Monitoring and documenting selected wildfires during this period, noting the appearance or absence of spot fires and the prevailing conditions at the time, a database of 166 field observations was developed. The database includes information on the number of observed spot fires (Nκ), the in situ measured relative humidity (RH, %) values, the wind speed, the forest fuel type where the firebrands had landed, namely maquis, phrygana and grasses, the maximum spotting distance (Dκ, m) from the fire perimeter, the fire perimeter segment (head or flank) where the firebrands came from, and the fire type, namely surface, passive crown, active crown and plume dominated fire.

The database was analyzed first by examining the correlation of RH values with Nκ for the three fuel types. An ordinal variable named Kκ was created in order to represent the following four empirical classes: a) no spotting (Nκ=0, Kκ=0), b) rare spotting (Nκ<3, Kκ=1), c) limited spotting ($3 \leq$ Nκ ≤ 9, Kκ=2) and d) profuse/massive spotting (Nκ ≥ 10, Kκ=3). At RH values higher than 46%, no spotting ignition was recorded. Massive spotting that triggered extreme fire behavior, was documented for RH values lower than 17%. The RH thresholds for spotting occurrence that were identified for the three forest fuel types on which the firebrands landed, are presented and discussed. The Dκ and the Nκ were correlated with both the fire type and the fire segment on which they were observed. Their descriptive statistics are also presented and discussed. The study confirmed the great spotting potential of the plume dominated wildfires, both in regard to spotting distance and the number of spot fires.

Keywords: Spotting, Spot fire, Forest fire, Wildfire behaviour, Firefighting, Greece

1. Introduction

Spotting ignition is one of the three significant mechanisms of wildfire spread. It can be considered as a discontinuous fire spread mechanism (Koo et al. 2010) that is synonymous with solid mass transport (Albini1979, Alexander 2009). The transport of burning fire embers outside the fire perimeter, is a cause of serious concern to firefighters because it affects fire behaviour and difficulty of control and poses a serious threat for them and for civilians.

Spotting involves the source of firebrands, how far they travel, and the probability of ignition on landing (Rothermel 1983). It is mainly caused by lofted firebrands, including burning tips of branches, cones, and pieces of bark, that fly and land beyond the main fire perimeter, but may also be caused by burning cones or pieces of wood rolling down steep slopes (Van Wagner 1988). The type of forest vegetation that is burning is important for the creation of firebrands.

The probability of ignition at the point where a firebrand lands, is a function of both firebrand size and temperature. It has been found that as firebrand size is reduced, increased temperature is required for ignition (Hadden and Scott 2011). Additionally, the probability of ignition depends on the characteristics of the dead fuels where the firebrand lands, such as fuel quantity, dimension (fineness), arrangement (compactness and continuity) and fuel moisture content (FMC, %). Atmospheric relative humidity (RH, %) affects directly the FMC of dead fuels, the effect being more dramatic and the response faster for the finer ones. Thus, significant differences in spotting may exist, depending on the forest vegetation properties. Firebrands in the flaming phase are more capable to ignite fuel beds with no air flow than the ones in the glowing phase with air flow (Ganteaume et al. 2009) while when fire danger is high, the ignition probability of flaming firebrands that land on fine fuels, approaches 100% (Ellis 2012).

A spotting distance of up to 200 meters (m) corresponds to short-range spotting and is common in high intensity wildfires, while distance values between 200 m and 1 kilometer (km) (Bushfire CRC 2009) or between 200 m and 2 km (Alexander 2009) can be considered as medium-range spotting. A spotting distance greater than 1 or 2 km, which is very common in some forest types, such as the eucalypt forests of Australia, can be considered as long-range spotting.

The number of firebrands generated and the rapidity of development of the spot fires, determine the magnitude of the phenomenon and its effect on wildfire behaviour (Ellis 2012). Spotting usually exacerbates fire suppression activities and plans, is the leading cause of loss of structures in fires in Wildland Urban Interface (WUI) areas and is a major concern regarding the safety of firefighters and the public (Alexander 2009).

In Greece, spotting occurs often in all of its Mediterranean vegetation types, such as the Mediterranean pine forests, the evergreen shrublands (maquis), the low scrubland vegetation called phrygana and the grasslands (Athanasiou and Xanthopoulos 2013). As the fuel characteristics are important for the creation of firebrands and the characteristics of the fuel bed where firebrands land affect the probability of ignition, in addition to the FMC, the objective set for this study was to examine the occurrence and characteristics of spotting in three main fuel types in Greece, namely maquis, phrygana and grasses, especially in relation to the prevailing RH, since this affects the FMC of the dead fuels. Most of the work has been carried out as part of the Ph.D. dissertation of the first author (Athanasiou 2015).

2. Methods

Systematic observation, recording and measurements of spotting on maquis, phryganic areas and grass during the spread of wildfires, started in 2007 in Greece and continues until today. The procedure followed has been described in Athanasiou and Xanthopoulos (2010). An initial data set of 75 cases was analysed and preliminary findings were presented in 2013 (Athanasiou and Xanthopoulos 2013). Ninety-one (91) additional spotting observations that were collected during the following fire seasons, resulted in a total of 166 cases in which the phenomenon was either present or absent, presenting an opportunity for testing and extending the initial conclusions. The length of observation for each case varied from at least five minutes to almost half an hour, depending on the conditions and the potential risk.

The database that was developed, consists of 166 spotting observations (n=166) that include information about a) the number of the spot fires (Nκ), b) the in situ measured RH values, c) the wind speed at the height of 10 m ($Wind_{10m}$, km/h) and at eye level (calculating one from the other, depending on which of the two was actually measured), d) the forest fuel type where the firebrands had landed, e) the maximum spotting distance from the fire perimeter (Dκ, m), f) the fire perimeter segment (head or flank) where the firebrands came from, and g) the fire type, namely surface, passive crown, active crown and plume dominated fire during the spread of which the measurements had been conducted (Figure 1).

a. The first spot fire is recorded at 15:23:56 at a distance of 200 m

b. Two more spot fires at 15:24:04 at 80 and 110 m (while the first one at the left is growing)

c. Five more spot fires have occured at 180, 200, 230 and 240 m and some of them have already merged, two minutes and six seconds later (at 15:26:10).

d. Three more spot fires at 15:26:54 at 50 and 80 m (in total, eleven spot fires recorded, within a period of 2 minutes and 58 seconds)

e. Wildfire evolution at 15:28:10

Figure 1 - Spot fires (Nκ=11 & Dκ=240 m) recorded on a 84% slope, mainly covered by Sarcopoterium spinosum and Cistus spp. (phryganic vegetation), while a wind driven passive crown wildfire spreads through an Aleppo pine stand. Weather conditions: T=29°C, RH=43.5%, Wind speed at eye level= 15 km/h

3. Analysis

Meteorological measurements and the relative necessary information about month and time of day, fuels and topography that had been collected on site, were utilised for calculating fine (1-h) dead Fuel Moisture Content (FDFMC, %) values by using Rothermel's methodology (1983). The database was analysed first by examining the correlation of RH and FDFMC values with the Nκ for the three fuel types. An ordinal variable named Kκ was created in order to represent the following four empirical classes: a) no spotting (Nκ=0, Kκ=0), b) rare spotting (Nκ<3, Kκ=1), c) limited spotting ($3 \leq$ Nκ ≤ 9, Kκ=2) and d) profuse/massive spotting (Nκ ≥ 10, Kκ=3). The Nκ and the Dκ were also examined for correlation with both the fire type and the fire perimeter segment on which they had been observed. For the observations/records where Nκ > 1, the Dκ value was the distance of the farthest spot fire from the fire perimeter (e.g. Figure 1).

4. Results

At RH values higher than 46%, no spotting ignition was recorded. Massive spotting that triggered extreme fire behaviour, was documented for RH values lower than 17%. The RH and FDFMC thresholds for spotting occurrence that were found, for the three forest fuel types on which the firebrands landed, are reported in Table 1. The descriptive statistics of Nκ and Dκ in relation to both the fire type and the fire perimeter segment, are also presented in Table 2 and 3, respectively. Dκ values were only available for 58 of the 67 cases in which spotting was observed.

Table 1 - Ranges of values and thresholds of RH and FDFMC for spotting occurrence, on maquis, phrygana and grass

			n- RH – FDFMC		
RH – FDFMC	Kκ	n	Maquis	Phrygana (*Sarcopoterium spinosum*)	Grass
(15-62.5) - (4-14)	0	99	43-(15 – 62.5) – (4-14)	29-(15 - 50) – (4-12)	27-(23.8-55) – (4-11)
(15–46) - (3-11)	1	31	9-(20-38.5) – (4-11)	15-(15-46) – (3-10)	7-(16-31) – (3-6)
(14–35) - (2-9)	2	18	7-(18-33) – (4-8)	4-(34.5-35) – (6-9)	7-(14-30) – (2-7)
(13–46) - (3-8)	3	18	6-(16-21.4) – (3-7)	1-(43.5) - (8)	11-(13-46) – (3-8)
Total:		166	65	49	52

Table 2 - Descriptive statistics of Nκ, per fire type and perimeter segment for the 67 cases with spotting

	Surface (n= 22)		Passive crown (n= 21)		Active crown (wind driven) (n= 7)	Crown (plume) (n= 17)
$N_κ$	Flank (n=7)	Head (n=15)	Flank (n=7)	Head (n=14)	Head (n=7)	(n=17)
Mean value	1	2	3	5	3	21
Median	1	1	3	4	2	22
Mode	1	1	3	1	1	30
Std. Dev.	1	2	2	6	2	9
Minimum	1	1	1	1	1	5
Maximum	3	8	7	22	6	30
$Wind_{10m}$		8-30		6-111	10–26	0–27
RH	16-42	15-46	20-35	14-46	20-35	13-21
FDFMC	3-7	3-10	4-9	2-11	4-9	3-7

Table 3 - Descriptive statistics of $D_κ$, per fire type and perimeter segment (n=58)

	Surface (n= 22)		Passive crown (n= 17)		Active crown (wind-driven) (n= 7)	Crown (plume)* (n= 12)
$D_κ$ (m)	Flank (n= 7)	Head (n= 15)	Flank (n= 6)	Head (n= 11)	Head (n= 7)	(n= 12)
Mean value	51	132	71	118	229	392
Median	20	70	60	100	250	250
Mode	15	10	N/A	100	250	200
Std. Dev.	58	143	48	85	175	308
Minimum	10	5	15	20	50	150
Maximum	150	500	150	300	500	1,200
$Wind_{10m}$		8-30		6-36	10–26	0–27
RH	16-42	15-46	20-35	15-46	20-35	13-18
FDFMC	3-7	3-10	4-9	3-11	4-9	3-6

For the 67 cases in which spotting was observed, RH and FDFMC were also plotted versus Nκ (Figure 2 & 3).

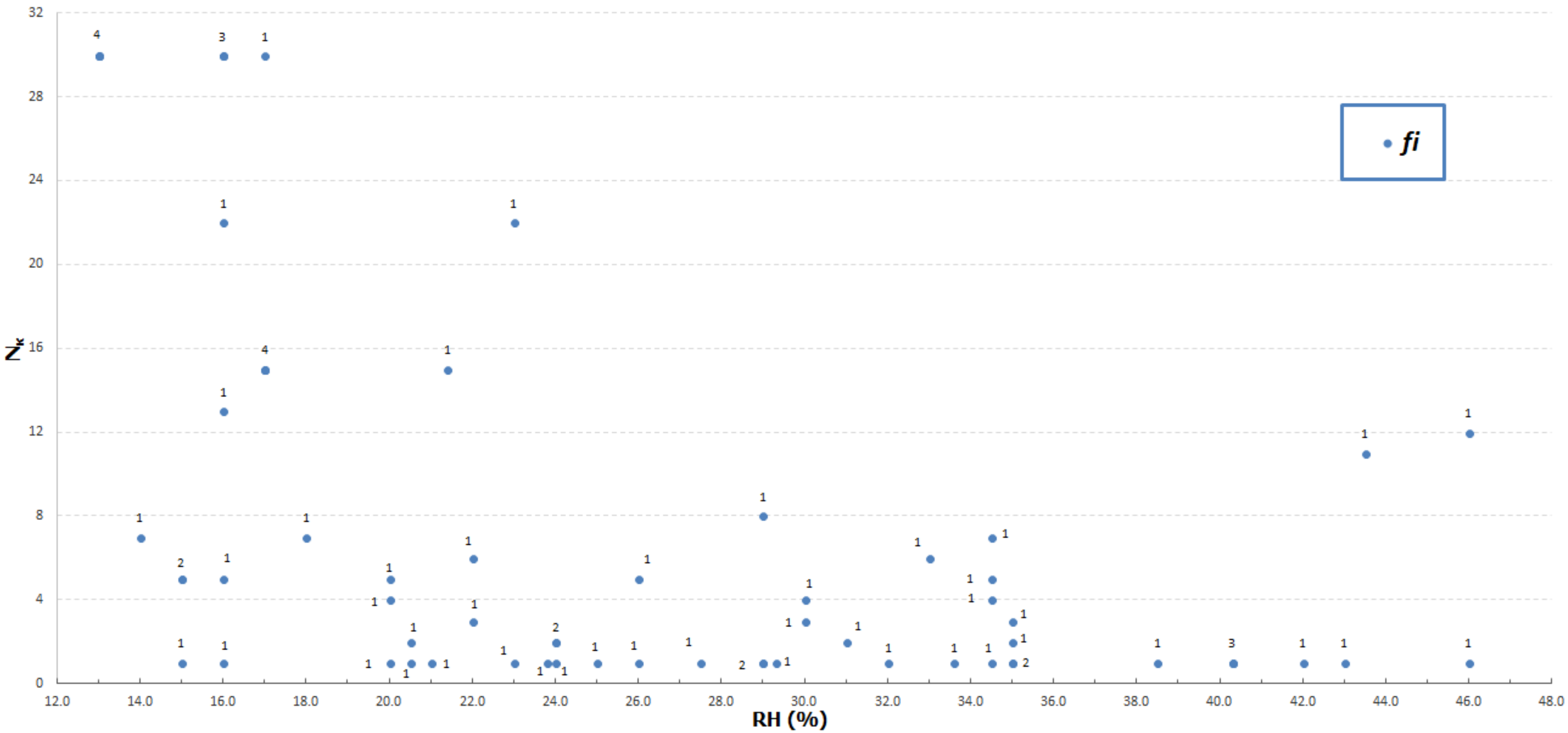

Figure 2 - Plot of RH and Nκ for the 67 records with spotting (fi: absolute frequency)

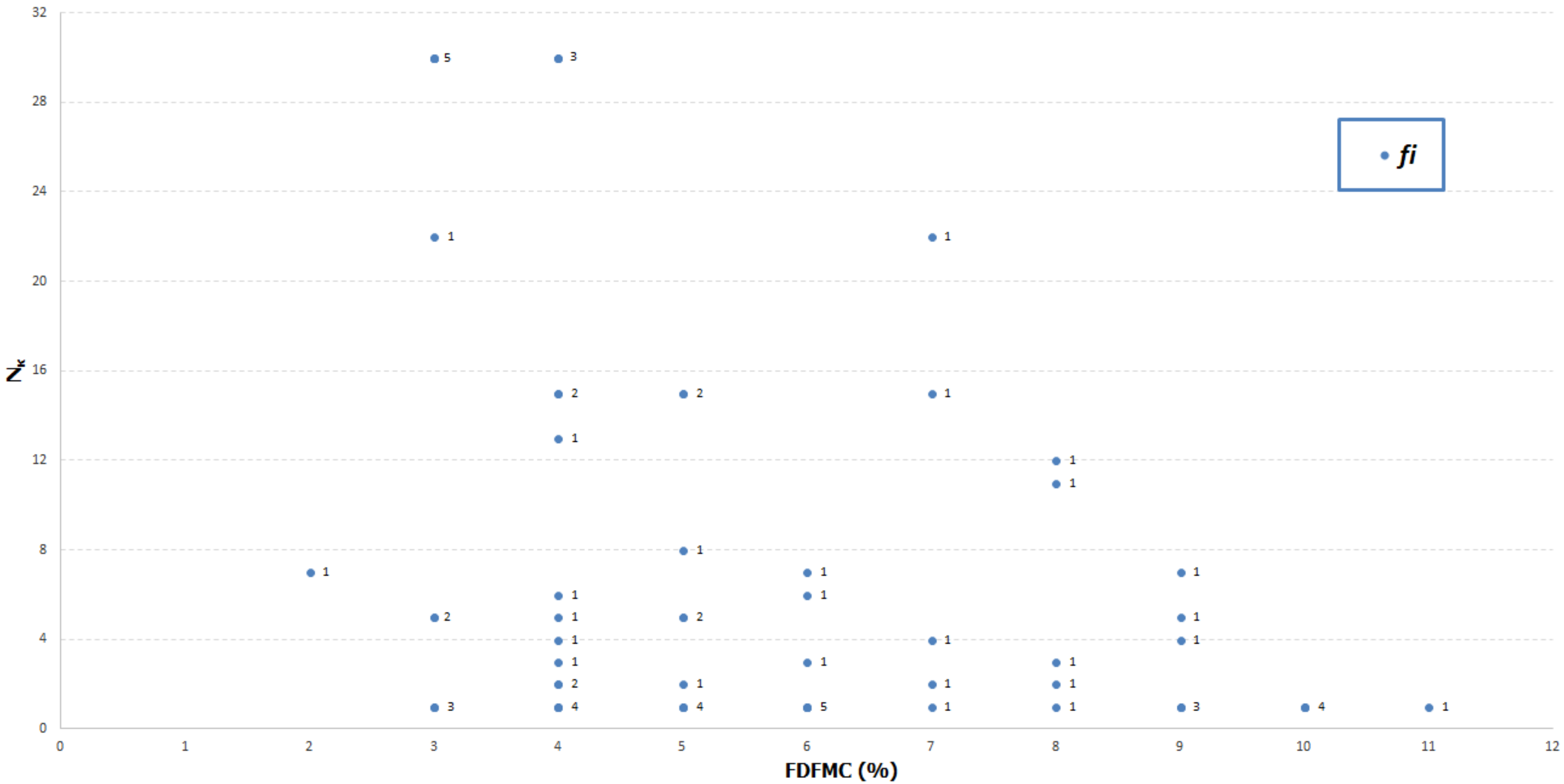

Figure 3 - Plot of FDFMC and Nκ for the 67 records with spotting (fi: absolute frequency)

5. Discussion

The maximum RH value at which spotting occurred (Nκ=1) on maquis, was 38.5% (Table 1, Figure 2) and the corresponding calculated FDFMC value was 11% (Figure 3). The RH and FDFMC thresholds were 46% and 10% (Nκ=1) for phrygana and 46% and 8% for grass (Nκ=12). Regarding phrygana, it is worth noting that there was also one observation (Figure 1) of Kκ=3 spotting class (Nκ=11), at relatively high RH and FDFMC values, 43.5% and 8% respectively. In this case, the radiation emitted against the fuel bed, from the leaning smoke column, played a crucial role in preheating the fuels including the fine dead ones (Figure 1). Moreover, regarding the previously mentioned maximum RH and FDFMC datapoint for grass, 12 spot fires were recorded on a grassland, at RH=46% (Figure 2) and FDFMC=8% (Figure 3), at a Dκ of 30 m. The fire brands originated from a torching *Pinus halepensis* tree and one of them broke into smaller ones upon landing. According to Gould et al. (2007) this is a potentially important notification, and it should be included in any future analysis if available.

The RH versus Nκ (Figure 2) and FDFMC versus Nκ (Figure 3) plots, show that spotting tends to be rare when RH > 40% or when FDFMC > 10%. The former trend is consistent with Weir's (2004) conclusion who examined 99 prescribed fires and found that spotting occurrence was very rare when RH exceeded 40% The latter one is in general agreement with the finding of Manzello et al. (2006) that embers with mass of 0.5 gr could ignite pine needles with fuel moisture of 11% or less and with the finding of Ellis (2000) that for fine fuel moistures below 9%, flaming embers with mass between 0.7 and 1.8 gr had a 100% probability of igniting the Monterey pine litter while glowing ones had lower probabilities. With a light wind (1 m/sec) the probability of ignition was found to be about 20% at fine fuel moisture content of 9% and approximately 65% at a fine fuel moisture content of 3.5% (Ellis 2000).

The great spotting potential of the plume dominated wildfires, both in regard to the Dκ, and the Nκ, was confirmed (Table 2 & 3). Future modeling of the shed-vortex transport (Berlad and Lee 1968) and of the plumes' characteristics, may shed light into the long-distance transport aspect for this fire type. Regarding wind driven fires, $Wind_{10m}$ was not found to be a Dκ predictor, not even a poor one, for the "head spread" subset. A possible reason is because a fire brand does not always originate at the fire perimeter, so the total horizontal distance it has traveled, is not known and is not necessarily equal to Dκ (the distance between the fire perimeter and the farthest recorded spot fire). Furthermore, in addition to the ambient atmospheric conditions, the trajectories of fire brands are also affected by the tilted or vertical turbulence and currents of the convection column.

Additionally, the spot fires that were documented at the flanks of surface and passive crown fires, were not in a windless environment and there was a component of wind of unknown velocity and direction that temporarily drove them. Moreover, fire behavior is sometimes a poor predictor of spotting distance or number of spot fires: as found by Racher (2003), wildfires producing the most distant or numerous landing embers are not always those with the greater rate of spread, flame height or flame depth zone.

The analysis of the subset of 67 records of spotting occurrence did not show a strong correlation between Nκ and RH or FDFMC. Tables 1, 2 and 3 as well as Figures 2 and 3, may offer some guidelines and relative practical advice to firefighters and fire behaviour practitioners but they are not predictive tools. Number and size of embers produced by various fuel types, is essential information, in order to estimate how many embers could be carried downwind and how far downwind they will go, to determine whether spotting (Nκ and Dκ) will affect the fire rate of spread and to assess whether the spot fires will be numerous enough to merge readily. According to the field observations, the patterns of spatial distribution of spot fires vary, depending on the fire segment the firebrands originate from, the wind field and the landscape (Figure 4a & 4b).

Figure 4a - An along-wind pattern of landing embers, on grass, downwind from a surface head fire

Figure 4b - An across-wind pattern of landing embers, on phrygana beyond the flank of a surface wildfire that spreads through rough landscape

The along-wind pattern of groups of spot fires has been observed to form a roughly elliptical shape (Figure 4a) and seems to be more predictable, while the across-wind one (Figure 4b) is irregular. Although these patterns have not yet been thoroughly described, they may allow firefighters to get a feeling on what to expect, a practically useful information: those patterns may play a crucial role in the behavior as the proximity among the spot fires affects their merging rate and the overall effective rate of spread and intensity. As proposed by Gould et al. (2007), they can be studied in the field, leading to the development of empirical functions.

6. Conclusions

The findings of the work presented here is that no spotting ignition was recorded on maquis, phrygana and Mediterranean grasslands, at RH values higher than 46% and that massive spotting that triggered extreme fire behaviour, was documented for RH values lower than 17%.

The RH threshold below which a spot fire is most likely to occur seems to be close to the value of 40%. However, it was also observed that a significant number of spot fires may take place even if RH values range between 40% and 46%. The finding that this is most likely to occur on fine fuels (phrygana and grass) should be taken into consideration, in operational firefighting.

The patterns of the spatial distribution of spot fires, and their basic characteristics in head and flank fires, can be included in practical guidelines about spotting

Future work is expected to shed additional light on the issues discussed in this paper, as field data continue being collected, ultimately improving fire behaviour prediction and firefighter safety in Greece.

7. Acknowledgements

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