Vegetation flammability and ignition potential at road-forest interfaces (southern France)

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Abstract

While most wildfire ignition points are aggregated at the vicinity of roads due to human-caused ignitions (Prométhée database), the probability of ignition and initial fire propagation at the interface between road and woodlands have rarely been studied. Vegetation at these interfaces includes dead fuels (litter) and live fuels (grasses and shrubs) which present specific features influencing ignition probability: composition, annual growth cycle, variation of moisture content. Moreover, vegetation is modified by management practices such as mowing and shrub clearing.

We present here the results of ca. 900 lab burning experiments of small (18x20 cm) undisturbed vegetation samples combining five dominant vegetation types (graminae, dicots, pine litter, pine litter+ graminae, pine litter+ graminae+ shrubs), two management practices (mowed vs. unmowed vegetation), two modes of ignition (flaming vs. glowing standard wood cube), two wind speeds (3 vs. 10 km/h), and a wide range of fuel moisture content (fresh, air-dried and oven-dried). Results indicate clear differences of flammability variables (ignition probability, time to ignition, propagation) among the five vegetation facies. The combination of ignition mode and wind speed strongly affects the probability of ignition, with contrasted ignition efficiency according to vegetation facies. It also affects the 'propagation' and 'sustainability' of fire. Fuel moisture and vegetation types relate well to fire sustainability, propagation and intensity. Multiple and logistic regression were established between ignition probability and the major causal variables of ignition.

These experimental data will help modelling fire hazard, especially by implementing a spatially-explicit simulator of fire ignition and initial propagation. The final aim is to help simulating management practices to reduce fire risk at interfaces.

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Introduction

Most studies in southern Europe indicated that locations of ignition are aggregated at the vicinity of interface between wildland areas and human activities. About 50% of fire ignition are located at the edge of roads, including all road categories (Prométhée). This is due to the high number of ignitions sources owing to human activities and human-induced hazards. The probable sources of ignition are varied: cigarettes (Alexandrian, 1995), road accidents, car exhausts, roadworks (mower or shrub-clearer engines, prescribed fires), or power lines. This can produce variable modes of ignition: glowering (cigarettes), flaming (accidents, fires) or emission of sparks (power lines, engines, car exhausts) emitting variable energy, thus displaying differential ability to ignite vegetation. However, differences in fire hazard ignition and propagation for dead and live fuels typical of road-forest interface (RFI) are poorly known in contrast with forest and wildland fuels (Valette 1990). Road-forests interfaces have specific features that may control fire ignition and initial propagation towards forests or human settlements.

In fact, dead fuels at interfaces between road networks and forests (including all wildland and woodlands areas) are poorly known in terms of composition, annual growth cycle and moisture content, and flammability (see Guijarro *et al.* 2001; Manzello *et al.* 2006). Vegetation facies at road-forest interface have specific features such as the abundance of grasses. The fuel moisture content (FMC) of grasses varies strongly according to the season and time during the day, notably because grasses at RFI are generally exposed to wind and direct solar radiation in the absence of canopy cover. Depending on their biomass and their curing rate (= percentage of dead parts), grasses can promote high flammability and propagation rates (Cheney *et al.* 1998), much higher than those common for forest litter fuels. Mixings of grasses and dead wildland fuels (litter, twigs, and leaves) and native or planted shrubs are also common. These mixings have a high spatial heterogeneity that may affect fire ignition and propagation. In addition, interface fuels are often modified by management practices for fire prevention, road traffic, or landscaping. In particular, grass-dominated fuels are periodically mowed and shrubs are cleared to limit fire propagation.

In this paper we aim at assessing the flammability (ignition probability and 'sustainability') of small undisturbed samples representative of the main vegetation facies at RNI, to build a predictive model of ignition including the main probable causal factors (vegetation type, fuel treatment, FMC, wind, ignition source). Our main hypothesis is that ignition probability is a complex and specific combination of these factors. Fuel treatment is hypothesized efficient to reduce ignition hazard, and the presence of litter is hypothesized to increase considerably ignition and 'sustainability' (*sensu* Anderson 1970).

Materials and methods

Sample plan and field data collection

In the field, combinations of vegetation facies and management practices entail a large range of cases of fuels. To select representative types, we investigated the variability of vegetation types along road-forest interfaces on calcareous soils. We focused on byways and state ways (ca. 30 km) around Aix-en-Provence, southern France. This resulted in the selection of five major types of vegetation facies constituting the main part of surface: graminae, dicots, pine litter, mixing of pine litter+ graminae, mixing of pine litter+ graminae+ shrubs (Table 1).

Vegetation sampling was operated over a large period when fires were susceptible to be ignited along roads, i.e. from April to October, 2006. We replicated sampling on the same sites to keep similar site conditions and vegetation facies. We collected 18x20 cm undisturbed vegetation samples, to take into account the real fuel structure. In fact, fuel microstructure is hypothesized to affect flammability, especially for heterogeneous mixings that associate grasses and shrubs. In practice, we used a metallic template to delimit each sample, and a solid and 20-cm large trowel to extract the whole vegetation sample. Each sample was numbered and directly put into an aluminium tub to prevent any damage. The characteristics of vegetation facies such as biomass, height and covering (Table *) were assessed using additional 50x50 cm samples. For the 'fresh' modality of fuel moisture, which corresponds to the real moisture content at the date of sampling, we used additional 18x20 cm samples. Fresh samples were put in plastic bags then rapidly weighted. Afterwards, they were oven-dried for two days at 60°C to get the dry weight.

Experimental schedule

The objective of our experimental schedule was to study the effects of the main probable causal variables of ignition and flammability for the five dominant vegetation types Thus, the schedule for flammability experiments comprised:

- five vegetation types: (i) graminae grasses; (ii) dicots grasses; (iii) pine (*Pinus halepensis*) litter; (iv) pine litter + graminae grasses; and (v) pine litter+ graminae+ shrubs (*Quercus coccifera*);
- two management modes: unmanaged vegetation and mowed/shrub cleared facies, with the exception of pure pine (*Pinus halepensis*) litter that is unmanaged;
- two ignition modes (flaming vs. glowing), which were chosen to mimic the two main real modes of ignition. We used a standardized pine cube (1.9 x 1.9 x 1.0 cm) following a standardized procedure described by Guijarro *et al.* (2001). To obtain a glowing cube, the cube was put on an epiradiator until the extinction of flame (about 70 seconds). The flaming cube was ignited with the epiradiator then left out and rapidly put on the sample still flaming at a standard time of 45 seconds after ignition;
- three levels of fuel moisture content (FMC): (i) real 'fresh' values from the field gained by a periodic collection along the summer season; (ii) air-dried values gained by letting the samples at room equilibrium moisture content for 2 days; and (iii) oven-dried values gained by oven-drying the samples for two days at 60°C;
- two wind speeds: (i) 'low wind' (ca. 3 km/h ~ 1 m/s); and (ii) 'strong wind' (ca. 10 km/h ~ 2.9 m/s). Wind was generated by a domestic fan and controlled by periodic measurements at the centre of the sample with an anemometer (accuracy ± 0.1 km/h)

Flammability experiments

Flammability experiments were conducted at the Cemagref Aix-en-Provence facility. Air temperature and humidity were measured all over the burning experiment, at the beginning of each experiment. These covariables were assumed to have a nil effect since the duration of each experiment is insufficient to entail significant changes in the fuel moisture content of burnt samples. We tested this effect, which was proven nil ($p > 0.05$, LSD test). Experimental modalities corresponded to a combination of one vegetation facies, one management mode, one FMC value and one wind speed. Each modality was repeated 10 to 30 times. In total, we burned 896 samples. As the main objective was to assess the probability of ignition on a large number of replicates, only three major variables describing ignitability and sustainability (*sensu* Anderson 1970) were assessed:

- the time to ignition is the time between the dropping of the cube and the eventual beginning of litter flaming (in seconds). The wood cube was put glowing or flaming at the centre of the sample, and if a flame appeared within 3 minutes, the test was considered as positive and classed as 'ignition';
- the flaming duration is the time with visible fire propagation by flames or glowing (in seconds). The flame sustainability or the presence of smoldering were noted;

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- the number of sides reached by the fire. We noted if fire propagation had reached the left, right, forward and backward sides of the sample.

The probability of ignition (i.e. ignition success in %) was computed as the ratio between the number of trials for one litter type and the number of successful ignitions. Ignition was considered successful when a flame appeared during the experiment and maintained during at least ten seconds.

Data Analysis

Flammability data were analysed using different analysis methods. Comparisons between different vegetation facies and treatments were operated using analysis of variance (ANOVA), and a general linear model (GLM) was used to assess the importance of isolated or combined variables. For the ignition data which are bimodal (i.e. 0= no ignition and 1= ignition) a logistic model was used. We tested the effects of variables with a chi-squared goodness of fit test.

Results

Overall results

The Table 2 displays the results of the flammability experiments per ignition modality. It clearly shows significant differences among modalities, with a high ignition potential for the flaming firebrand, and for the glowing firebrand with a high wind speed. In contrast, the flaming firebrand had a low ignition potential at low wind speed (Figure 1). Comparisons between the different modalities of ignition confirm these differences (Figure 2, Table 3). The Table 4 displays the effect of the different causal variables on the flammability variables for the whole database, using multiple regression models and a logistic model. It shows that most flammability parameters result from combination of several causative factors. The probability of ignition is a combination of all factors, with a clear predominance of the mode of ignition and the wind speed. The time to ignition can hardly be predicted and only depends on wind speed and vegetation facies. The flaming duration and the number of burnt sides both result from the predominant combination of the mode of ignition and the wind speed, then vegetation facies and moisture content. The variance explained by the different models (general linear model and logistic regression) ranges from one-third to about a half of the total variance, thus no predictive model can be used on this basis owing to the high standard error. The variance explained by the GLM for the time to ignition is very low.

External factors of ignition

In most of the cases, the mode of ignition acts in combination with the wind speed to explain a large part of the variance of the ignition probability (Table 4). But these variables are also predominant for the vegetation 'combustibility', i.e. flaming duration and the number of burnt sides. The Figures 1 to 3 clearly show that a flaming firebrand with a low wind speed has a very low potential of ignition. In fact, the probability of ignition is low to null, the time to ignition is long and the flaming duration is short; fire generally does not reach the border of the 18x20 cm sample. Conversely, using a flaming firebrand is very efficient even with the low wind. Ignition probability is very high, time to ignition very low, then combustion and propagation almost complete. The modality using a glowing firebrand with a strong wind entails an intermediate behaviour of fire for most of the vegetation facies.

The fuel moisture content appears secondary in our results. For the two modalities having a high ignition potential, fire ignition and propagation decrease with the increasing of FMC, but the extinction fuel moisture is not reached. It is almost reached for the grass and litter-grass mixings for the modality having a low ignition potential.

Effects of vegetation facies and management

All vegetation facies had a high and similar probability of ignition when using a flaming firebrand and low wind, irrespective of the moisture content and the fuel management practice (Figure 3). The time to ignition was very low, although a bit higher for the 'litter' and mixed modalities. It logically decreased with decreasing fuel moisture but was not affected by the vegetation management. Flaming duration and the number of burnt sides were high, indicating a complete burning. They increased with decreasing moisture content. These two variables were not affected by the vegetation management. Both pure grass modalities had low a flaming duration and an almost total propagation. Pure pine litter had minimal probability of ignition, flaming duration and number of burnt sides, and maximal time to ignition. Mixed litter-grass vegetation burned almost all the times, completely and fast. Mixings with shrubs had lower burning duration and number of burnt sides.

The combination of a glowing firebrand and a low wind speed resulted in a low ignition potential for most of the vegetation types except pure litter and grass-litter mixings, whatever the moisture content and the vegetation management. In grass-litter mixings, grass mowing decreased the flaming duration. Propagation within vegetation was very limited for all the samples that burned.

Applying a strong wind on the glowing firebrand strongly increased the probability of ignition for all the vegetation facies. Ignition was maximal in litter-grass mixings, minimal in dicots grasses, and intermediate in litter-grass-shrub mixings. It was favoured by grass mowing and shrub-clearing. Time to ignition was low for grass and grass-litter mixings, and maximal in grass-litter-shrub mixings. Strikingly, it was often lower when vegetation was mowed or shrub-cleared. Flaming duration was long for most of the vegetation types, minimal for grasses, maximal for litter, and intermediate for mixings. The number of burnt sides highly varied according to the vegetation facies. Three or four sides were burnt in vegetation mixings for low moisture (i.e. oven-dried) values, especially when the grass was mown and shrubs cleared.

Discussion

Our results confirmed that the fuel ignition results from complex interactions between the ignition potential coming from the mode of ignition and external factors (especially wind), and the characteristics of vegetation itself such as composition, physical characteristics and moisture content (Anderson 1970; Dimitrakopoulos 2001; Guijarro *et al.* 2001). We hypothesize that this is especially true for mixings typical of road-wildland interfaces, which combine dead and live fuels. Live fuels exhibit varying biomass, bulk density and moisture content during the season of fire risk owing to their phenology and to the meteorological events (Cheney *et al.* 1998). A striking result is that FMC plays a secondary role in our data whereas this is generally the first explanative variable in studies of wildland fuel flammability (Guijarro *et al.* 2001). This is likely due to the fact that most vegetation facies studied here set below the fuel moisture of extinction. The air- and oven-dried modalities that correspond to high or severe summer drought conditions are logically capable of ignition and fire propagation if the ignition mode is efficient enough. Even the 'fresh' modality is generally below the moisture of extinction, because water stress is high for grasses and dead fuels in the study area. This threshold has been estimated to about 16 to 30% for a large range of pine litters (de Groot *et al.* 2005). According to the wind speed, literature indicates values ranging from 20 to 28% for dead grass (de Groot *et al.* 2005). Fire can spread in live grass at moisture contents reaching about 150% (as shown by Marsden-Smedley and Catchpole 1995 for Tasmanian buttongrass). Complementary experiments on fresh or moisturized fuels on a larger range of fuel moisture would help establishing this extinction threshold for our fuels.

A major finding is that grass mowing and shrub-clearing do not efficiently reduce the probability of ignition and fire propagation for the two contrasted modalities having a low- and a high- ignition potential. At low potential, ignition success is too small and no statistically significant difference can be observed. In contrast, at high potential, vegetation facies ignite and burn in a similar way whatever

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the vegetation management (i.e., grass mowing and shrub-clearing vs. no management practice). The modality having a medium ignition potential (low wind and glowing firebrand) displays marked results. Ignitability and fire propagation tend to be higher in mown grasses and shrub-cleared facies than in unmanaged vegetation. Cautiousness is necessary before extrapolating this counter-intuitive result. Both grass facies have very low ignition probability when unmown, and much higher values when mown. This is likely to be due to two effects. Firstly, grass mowing during the dry summer season creates high amounts of continuous dead fuel that ignite easily when using a glowing firebrand. This mode of ignition necessitates a large contact surface with the fuel and a long time to ignite. Secondly, wind speed is strongly reduced in unmown grass facies, thus reducing the ignition potential of the firebrand. Moreover, the area of contact between the small firebrand and the grass is very low when the grass is vertically erected and loosely packed.

The combination of the mode of ignition and wind speed plays the predominant role in ignition but also in fire propagation and consumibility. The importance of the mode of ignition throughout the whole time of burning can be explained by the fact that samples are small, and that the initial mode of ignition (glowing vs. flaming) propagates through the whole sample.

In total, three main groups of vegetation typical of wildland-road interfaces can be distinguished according to their flammability. Grasses have a high ignitability, a rapid propagation and a high level of consumption. Most grasses ignite easily, experience rapid fire propagation (see Cheney *et al.* 1998; de Groot *et al.* 2005), and burn completely. This is due to a large part of very fine particles, and it is especially true with a flaming firebrand. In contrast, pine litter is dense and compact. It ignites much slower, and has a low and incomplete smoldering consumption (see Frandsen 1997). Mixings have an intermediate behaviour. The presence of litter in grass and shrub-grass mixings increases the time to ignition but also increases the probability of ignition, the duration and the completeness of burning when the mode of ignition is a glowing firebrand.

Building robust and precise models to predict the flammability of these vegetation types along the growth and fire season implies complementary experiments, especially for live fuels. A wider range of fuel moisture and biomass values would help building this model. The influence of grass mowing and shrub-clearing would be improved in such models.

Table 1—*Main characteristics of the vegetation types used for the flammability experiments*

Vegetation type	Mowed / Shrub cleared	Composition (Main species)	Mean litter depth (cm)	Mean grass height (cm)	Cover (%)	Biomass (dry weight, g)	Fuel moisture ('Fresh') (%)
Dicot grasses (DG)	No	*Festuca* spp., *Dactylis* spp., *Lolium perenne, Lotus corniculatus, Sanguisorba minor, Plantago lanceolata*	1.0 ± 0.5	25 ± 5	80 ± 15	665 ± 40	71 ± 8
	Yes			10 ± 5		362 ± 143	25 ± 5
Graminae grasses (GG)	No	*Brachypodium* spp., *Festuca* spp., *Dactylis* spp., *Bunch*	1.0 ± 0.5	35 ± 5	80 ± 15	469 ± 143	52 ± 18
	Yes		1.0 ± 0.5	15 ± 5		241 ± 61	7 ± 1
Pine litter (L)	No	*Pinus halepensis* needles (%),	1.5 ± 0.5		90 ± 5	838 ± 209	8 ± 1
Litter + grasses (LG)	No	*Pinus halepensis* needles, oak leaves, graminae grasses	1.0 ± 0.5	35 ± 5	90 ± 5	669 ± 327	24 ± 11
	Yes		1.0 ± 0.5	15 ± 5		440 ± 156	9 ± 2
Litter + grasses + shrubs (LGS)	No	*Pinus halepensis* needles, oak leaves, shrub (*Quercus coccifera*) leaves and twigs, graminae grasses	1.0 ± 0.5	35 ± 5	90 ± 5	839 ± 196	27 ± 12
	Yes		1.0 ± 0.5	15 ± 5		727 ± 48	5 ± 7

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Table 2—*Percentage of ignition, flaming duration and number of sides reached by fire for the main modalities of ignition are combinations of a type of firebrand and a wind speed*
Values are mean ± standard errors. Different letters in a same row indicate statistically significant medians (Kruskal-Wallis test, 95%; *p*= probability value)

	Low Wind Glowing Firebrand	Low Wind Flaming Firebrand	Strong Wind Glowing Firebrand	Total/Mean	Kruskal-Wallis test
Nb samples	352	274	270	896	
Percentage of Ignition (%)	7 *a*	94 *c*	48 *b*	47	
Time to ignition (s)	6.2 ± 35.9 *a*	4.2 ± 7.8 *a*	19.5 ± 42.5 *b*	9.6 ± 33.3	281.2 (*p*=0.0)
Flaming Duration (s)	5.7 ± 24.4 *a*	54.7 ± 34.8 *b*	31.6 ± 43.2 *c*	28.5 ± 36.6	392.8 (*p*=0.0)
Number of burnt sides (n)	0.21 ± 0.04 *a*	2.73 ± 0.10 *b*	1.64 ± 0.11 *c*	1.41 ± 1.78	332.7 (*p*=0.0)

Table 3—*Comparison tests (ANOVA) between the main experimental modalities of flammability. Modalities of ignition (i.e. combinations of a type of firebrand and a wind speed) are compared by pairs.*
W= Mann-Whitney test (5%); NS= Non significant; *p*= probability value

Modality Comparisons	Percentage of Ignition (%)	Time to ignition (s)	Flaming duration (s)	Number of burnt sides (n)
Low Wind Glowing vs. Flaming Firebrand	W=43043 ; *p*=0.0	W=3357 ; *p*=0.0	NS	NS
Glowing Firebrand Low vs. Strong Wind	W=20474 ; *p*=0.0	W=-675 ; *p*=0.002	NS	W=427.5 ; *p*=0.030
Low Wind Flaming vs. Strong Wind Glowing	W=16608 ; *p*=0.0	W=14157 ; *p*=0.0	NS	W=-2039 ; *p*=0.029

Table 4—*Multiple regression analysis for the flammability variables.*
The model used was logistic for the probability of ignition (chi-square goodness of fit test). The model was a general linear model for the other variables (*P*-Value).

	Factors					Test of the model	
Flammability Variables	Vegetation Facies	Ignition Mode	Wind	Vegetation Mowing	Fuel moisture content	Test of the model	Adjusted deviance explained by the model (%)
Probability of ignition	48.5 ****	559.8 ****	164.5 ****	8.1 **	16.2 ***	0.0000 [1]	48.3
Time to ignition (s)	5.2 ***	1.0 [NS]	28.6 ****	1.9 [NS]	2.7 [NS]	0.0000 [2]	6.1
Flaming Duration (s)	23.9 ***	342.9 ****	109.2 ****	3.36 [NS]	17.7 ****	0.0000 [2]	35.5
Number burnt sides (n)	11.0 ****	493.2 ****	170.3 ****	0.8 [NS]	24.1 ****	0.0000 [2]	40.5

[1] Logistic regression (chi-squared goodness of fit); [2] general linear model (*P*-Value)

Figure 1—Percentage of ignition according to the three modalities of ignition and the three levels of fuel moisture content. Values are means

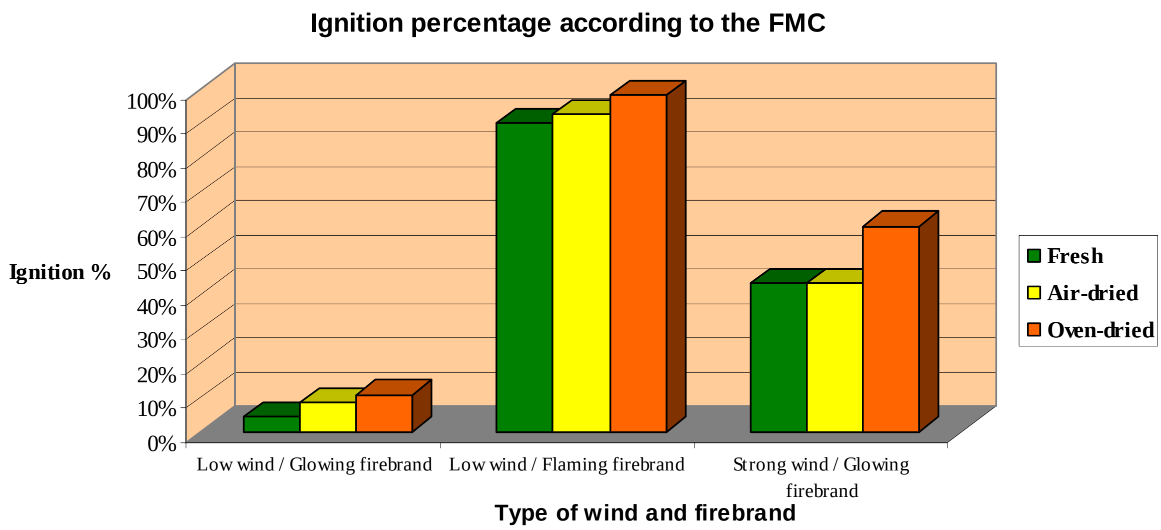

Figure 2—Percentage of ignition according to the vegetation treatments (mown grasses vs. unmown) and the three modalities of ignition. Values are means

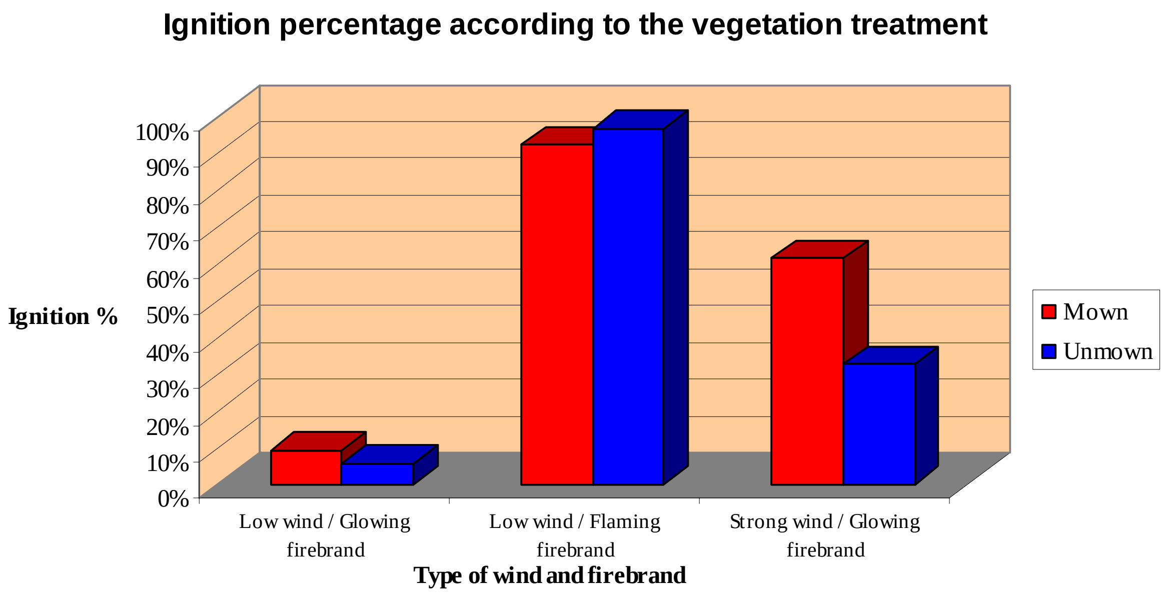

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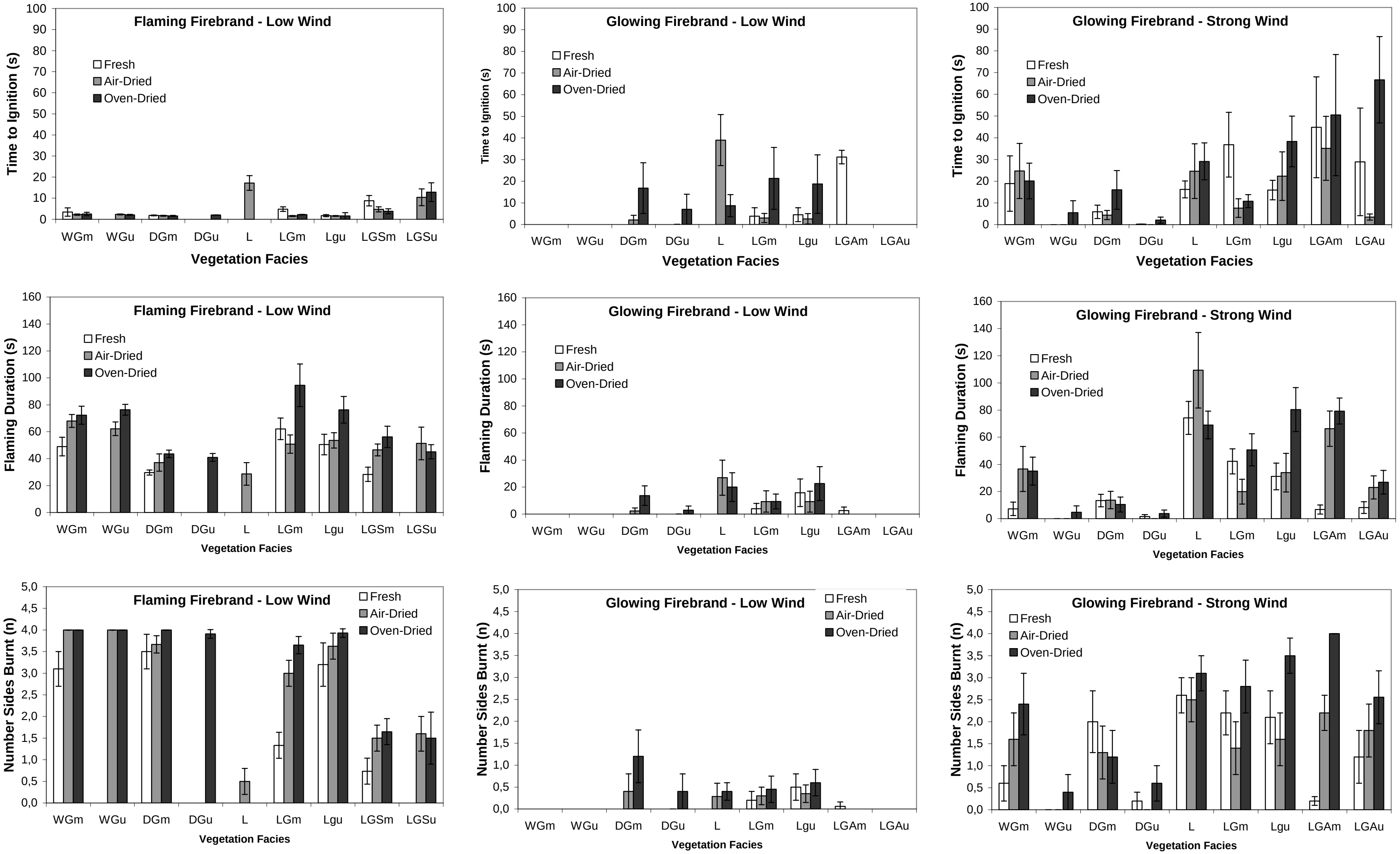
Figure 3—Time to ignition, flaming duration and number of sides burnt by fire for the different vegetation facies, the type of firebrand, the wind speed and the fuel moisture. WG: dicot grasses; DG: graminae grasses; L: pine litter; LG: litter + graminae grasses; LGS: litter + graminae grasses + shrubs. The letter ‘m’ indicates the mown and/or shrub-cleared vegetation facies, while the letter ‘u’ indicates the unmown or not cleared facies. Large vertical bars are mean values, and light lines are confidence intervals (95% LSD procedure)



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