Experimental investigation of the physical mechanisms governing the spread of wildfires

Frédéric Morandini, Xavier Silvani

► To cite this version:

Frédéric Morandini, Xavier Silvani. Experimental investigation of the physical mechanisms governing the spread of wildfires. *International Journal of Wildland Fire*, 2010, 19, pp.570-582. 10.1071/WF08113 . hal-00591022

HAL Id: hal-00591022

<https://hal.science/hal-00591022>

Submitted on 6 May 2011

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Experimental investigation of the physical mechanisms governing the spread of wildfires

Frédéric Morandini and Xavier Silvani*

Laboratoire Sciences Pour l'Environnement, U.M.R. C.N.R.S. 6134,
Université de Corse, campus Grimaldi, 20250 Corte, France.

* Corresponding author. Telephone: +33 495 450 243; fax: +33 495 453 326;
email: frederic.morandini@univ-corse.fr

Abstract

One of the objectives of the present study is to gain a deeper understanding of the heat transfer mechanisms that control the spread of wildfires. Five experimental fires were conducted in the field across on plots of living vegetation. The lengths of the ignition lines were set in the range of 20–30 m to reproduce wildfire front conditions as closely as possible. The experiments were performed under various vegetation properties, wind conditions and plot topography to highlight different fire spread behaviours. This study focused on characterising heat transfer ahead of the flame front. The temperature and heat flux were measured at the top of the vegetation as the fire spread. The results showed the existence of two different fire spread regimes that were either dominated by radiation or governed by mixed radiant-convective heat transfer. For plume-dominated fires, the flow strongly responds to the great buoyancy forces generated by the fire; this guides the fire plume upward. For wind-driven fires, the flow is governed by inertial forces due to the wind, and the fire plume is greatly tilted towards unburned vegetation. The correlations of the temperature (ahead of the flame front) and wind velocity fluctuations change according to the fire regime. The longitudinal distributions of the radiant heat flux ahead of the fire front are also discussed. The data showed that neither the convective Froude number nor the Nelson convection

number—used in the literature to predict fire spread regimes—reflect the observed behaviour of wind-driven fires.

Keywords: wildfires; field experiments; temperature; heat transfer; radiation.

Introduction

Experimental fires have been widely used in fire research to further our understanding of the complex mechanisms governing the behaviour of fires. A large number of experiments have been carried out at the laboratory scale to study fires propagating across fuel beds (Dupuy 1995, Mendes-Lopes *et al.* 2003, Viegas *et al.* 2004). These reduced-scale experiments allow the observation of the main features encountered in wildfires and even some specific behaviour such as eruptive fire (Viegas 2006). However, fire is a scale-dependent process (Pitts 1991), and studying a fire as it spreads under full-scale conditions appears more relevant than across small fuel beds. Indeed, flame front properties (height, irradiance, etc.) and the resulting heat transfer mechanisms in the laboratory are not of the same order of magnitude as those in the field. In a previous work (Silvani and Morandini 2009), a comparison of radiation levels impinging ahead of flame fronts, with heights in the range of 0.3–6 m, exhibited significant differences. Therefore, real-scale fire experiments that are representative of most of the physical processes involved in wildfires are needed to gain a deeper understanding of how they spread and to establish useful safety distances for fire managers. To this end, measuring devices dedicated to wildfire applications must be developed, since instrumentation in the field has raised logistical problems that need to be overcome.

Some experimental fires were conducted on a large scale (Cheney *et al.* 1993, Cheney and Gould 1995, Fernandes 2001, Carrega 2002, Viegas *et al.* 2002, Bilgili and Saglam 2003, De

Luis *et al.* 2004, Vega *et al.* 2006). However, these studies only provided observations or measurements of the macroscopic characteristics of the flame front (rate of spread, flame length, flame tilt angle, residence time, etc.). Temperature and heat fluxes were measured less frequently (Packam and Pompe 1971, Gould *et al.* 1997, Butler 2003, Stocks *et al.* 2004, Butler *et al.* 2004, Cohen 2004, Silvani *et al.* 2005, Santoni *et al.* 2006, Morandini *et al.* 2006, Silvani and Morandini 2009). The data available in the related literature are summarised in Table 1.

Such measurements, obtained on a large scale, are also needed to improve and validate physical-based modelling of wildfires (Morvan and Dupuy 2004, Linn and Cunningham 2005, Porterie *et al.* 2005a, Mell *et al.* 2007). Caution should be exercised when predicting fire spread with models or sub-models developed from and/or validated against laboratory experiments, since these formulations can be misleading when applied to large-scale fire scenarios. For instance, if thermal degradation of the vegetative fuel is modelled by laws established for low heating rates or low masses of the samples, i.e. conditions which are not representative of the mechanisms involved in wildfire spread, extrapolation to a larger scale is prone to errors. Measurements obtained from large-scale experiments are also expected to provide some guidance or validate predictions of fire safety zones (Butler and Cohen 1998, Dupuy and Morvan 2005, Kaiss *et al.* 2007) and wildland urban interface dimensioning (Cohen 2004, Consalvi *et al.* 2005, Porterie *et al.* 2005b). Some of these modelling approaches (Butler and Cohen 1998, Cohen 2004, Kaiss *et al.* 2007, Zarate *et al.* 2008) are based on purely radiative models in which the role of convection is neglected—an approach that may not be correct. Indeed, previously proposed physics-based models of fire spread under wind-blown conditions (Pagni and Peterson 1973, Porterie *et al.* 2000, Morvan and Dupuy 2004, Mell *et al.* 2007, Morvan *et al.* 2009) predicted the existence of a significant convective flux on top of the fuel layer in some configurations.

Fire spread results from the interaction of many processes: heat and mass transfer, thermal degradation of the combustible material and reactions in gaseous and solid phases. Understanding the heat transfer mechanisms governing fire propagation across vegetative fuels is thus of great interest in fire research and forest management. Fire grows and spreads across vegetative fuels by direct burning, which results from impingement of the flame on combustible materials, and from heat transfer towards the unburned fuel by means of radiation and/or convection (combustion products). Environmental factors such as wind, topography and vegetation type can affect the rate and direction of heat transfer and resulting fire spread. These parameters can be controlled in small-scale experiments in the laboratory. However, the slope, fuel and particularly wind are hardly controllable when conducting fire experiments in the field, i.e. under conditions close to those encountered in wildfires. The variability of these conditions in the open explains the drastic changes in fire dynamics which are responsible for many firefighter casualties during interventions. The most significant effects are observed in the flame front properties and dynamics. The volume of reacting gases, amount of heat release and the span of incident radiation can increase by several orders of magnitude during fire spread; even for a given set of ambient conditions, the fire front can propagate within a wide range of spread rates (Viegas 2006). This is the main reason why it is difficult to extrapolate fire spread mechanisms from the laboratory to the field. Data collection in the field is thus the best alternative for understanding the fire spread processes and for validating or improving models. These considerations are the main motivation for developing new measurement devices capable of collecting data in the field during fire spread.

Materials and methods

Fire experiments procedure

Five experimental fires were conducted in the Mediterranean region (south of France) across plots of shrublands. The fires were lit along the windward edge of the plots using a petrol torch. The lengths of the ignition lines were 20–30 m to replicate wildfire conditions. The orientation of the plot was chosen according to the main prevailing wind direction to ensure wind-aided fire spread conditions. A detailed description of the plot characteristics and environmental conditions are provided in Table 2. The experiments were conducted under various vegetation properties, wind conditions and plot topography, but the focus of this study was on characterising the heat transfer ahead of the flame front.

Plots and fuel properties

Plots with vegetative fuel as homogeneous as possible and high vegetation cover (coverage > 95%) were chosen for the fire experiments. The basic properties of the vegetation were measured and are provided in Table 2. The dominant species were *Syrmatium glabrum*, *Arbutus unedo*, *Genista lobelia*, *Erica arborea* and *Asphodelus albus*. Before the fire experiments, the total fuel load (dead and live fuel from litter and canopy) and vegetation height were measured from three sample areas of 1 m² in size. Samples were taken close to the experimental plots so that the vegetation cover would not be modified. Fuel moisture content was obtained from three samples of the most abundant species. Samples were oven-dried at 60°C for 24 h, and the fuel moisture was expressed as a percentage of the dried weight (Allgöwer *et al.* 2006). The amount of fuel removed by the fire, i.e. the fuel consumption, was expressed as the ratio of the amount of char remaining after the fire, over the three 1 m² sample areas, to the fuel load.

Measurement devices

The heat flux and gas temperature during the fire spread experiments were measured by an intrusive sensor system capable of resisting the fire (Silvani and Morandini 2009). The device consists of two heat flux gauges and a thermocouple fixed to a steel support facing the approaching fire front. It is designed to be fast and easy to set up (less than 30 min) with the possibility to be deployed in forest fires. The inside of the device was coated with a 4-cm thick layer of insulating material (ceramic felt); the inside temperature never exceeded 70°C during the experiments. In every case, the measurements were made close to the top of the vegetation using different supporting rods. A photograph of this device is shown in Fig. 1.

The gas temperature was measured using a K-type thermocouple with a 250- μm -diameter grounded junction. This configuration was chosen to guarantee a good compromise between accuracy and resistance; fine wire thermocouples are less affected by radiation effects and have a faster response (Cox and Chitty 1985), which allows the rapid fluctuations of the gas temperature to be recorded with good accuracy. The response time of the thermocouples used in this study was less than 0.2 s. Each thermocouple was covered with a ceramic insulator and inserted in a 10-cm-long stainless steel tube, leaving the junction to protrude from the device. These devices provided information on the flame residence time and peak temperature.

The total and radiant heat fluxes emitted from the flame front during the fire spread were measured with Medtherm transducers (16H and 64 Series). A sapphire window attachment was added to the radiant heat flux transducer to eliminate the convective heat being transferred to the sensing area. These transducers were calibrated by the manufacturer to 0–200 kW m^{-2} and had a response time of less than 0.25 s, which provided accurate measurements for an approaching fire front. The transducers were oriented towards the flame front and had a view angle of 150°. A thermocouple recorded the body temperature of the gauge.

152 Thermocouples and heat flux gauges were plugged into a power-supplied data logger
153 buried 0.3 m under the ground surface to protect it from the fire. Extension cables insulated
154 by a Teflon coating, a layer of ceramic and an outer layer of aluminium connected the sensors
155 to the underground data logger by passing through the steel tube of the support carrying the
156 sensors. This configuration was chosen to allow the use of short extension cables (1.5 m) to
157 reduce the measurement errors. The transducers signals were recorded at a sampling rate of 1
158 Hz. This sampling frequency matched the response time of the sensors used.

159 The wind, which can be highly variable in the open, is one of the most significant variables
160 influencing fire spread (Cheney *et al.* 1993). The wind velocity and direction were recorded
161 using a two-dimensional ultrasonic anemometer 2.5 m above the ground surface to reflect the
162 average wind acting on the fire front. The anemometer was located on the downwind edge of
163 the vegetation plot to minimise the influence of the fire on the wind measurements.
164 Furthermore, such a location protected the ultrasonic transducers from smoke and large-
165 diameter firebrands generated by the fire which can affect sonic measurements. The wind data
166 were recorded using another (synchronised) data logger at a sampling rate of 1 Hz.

167 Finally, to obtain accurate observations of the fire spread, three digital video cameras were
168 used to record the rear, front and side views of the fire. The video recordings (25 images per
169 second) provided information on the rate of fire spread and the geometric properties of the
170 flame, i.e. the flame height and tilt angle. A virtual grid was drawn on the video images by
171 means of reference marks placed regularly every 5 m. The known positions of these marks
172 helped to relate the position and dimensions of the flame on the virtual grid to its real position
173 and dimensions on the field. The rate of spread was obtained from the slope of the curve
174 representing the fire front position versus time. About eight data points were obtained for
175 each curve by timing the arrival of the fire front head to the reference marks. A least squares
176 regression was used to fit a straight line to these points. The flame front depth was computed

from the product of the residence time and the rate of spread. The flame length and height were defined along the mean flame axis and the vertical, respectively. The flame tilt angle was defined as the angle between the terrain and the leading surface of the flame.

Results and discussion

Fire front properties and behaviour

Every experimental plot was ignited as a line fire along the windward plot edge; the fire fronts developed a curvilinear shape during their spread. Details of the environmental conditions and related fire properties are reported in Table 2. The average wind properties remained nearly constant during the experiments, and the fires reached a quasi-steady state. The steady correlation factors (R^2) for the least squares regression, which was computed to obtain the rate of spread, were in the range of 0.86–0.96. These high R^2 values are a good indicator of fire steadiness. The vegetative fuels were mostly composed of fine materials (needles, leaves and twigs) with diameters that were lower than 2 cm; consequently, the fuel consumption was very high for the set of experiments. The fireline intensity, which represents the heat released per unit time per unit length of the fire front, is defined as the product of the weight of fuel consumed (kg m^{-2}), the heat yield of the fuel (assumed to be 18 000 kJ kg^{-1} for most vegetative fuel) and the rate of spread (m s^{-1}). The measured fire intensities were in the range of 8 300–31 000 kW m^{-1} . These values are consistent with the intensities measured during the experiments across similar fuel loads (Table 1). The high intensities measured during experiments 1–3 (16 000–31 000 kW m^{-1}) can be attributed to the significant fuel load (4.1–7.4 kg m^{-2}) of particular vegetal species (*Syrmatium glabrum* and *Genista lobelia*). Fire tests conducted across these broom species, which are very inflammable, generate high intensities with fire fronts travelling very fast even under low-risk conditions (wind velocity $< 5 \text{ m s}^{-1}$,

high fuel moisture content). It should be noted that post-fire measurements were performed at least 1 h after the passage of the fire front, when the temperature had decreased to a sufficient extent to allow the safe sampling of the remaining char. During this time period, mass loss continued due to char oxidation from large-diameter materials (>2 cm) which did not participate in the spreading of the pyrolysis front; thus, the amount of fuel actually consumed within the flaming front was overestimated. Furthermore, the rate of spread was determined at the fire head or at the most advanced point of the fire front; this was because the initial straight line of ignition was observed to change to a parabolic shape when quasi-steady propagation was achieved. Both sources of errors contributed to overestimation of the fireline intensity.

Qualitative observations of the fire spread from video recordings revealed the existence of two types of fires according to the flame front properties and behaviour. Photographs of the fire spread in experiments 2 and 4 are shown in Fig. 2. In the first type of fire (experiments 1, 2 and 3), the flames stood up (flame heights were about 5 m) and the smoke plume was guided upwards to produce a nearly vertical convection column. The flow strongly responded to the heating and buoyancy forces generated by the fire (Fig. 2a), and no smoke was observed to flow ahead of the fire front. In the second type (experiments 4 and 5), the inertial forces exceeded the buoyancy forces, and the flow did not respond to heating generated by the fire. In this case, the buoyancy forces generated by the fire were weaker because of the lower fuel load. The flame front was greatly tilted forward (Fig. 2b), and the flame height was about 1.5 m. The top of the unburned vegetation layer was subjected to intermittent lapping by the flames, and the fire travelled quickly across the vegetation. The smoke flowed close to the top of the vegetation, embedding the unburned vegetation within a layer of hot gases released by combustion. In the following sections, the effects of the fire behaviour on the temperature and heat flux measurements are examined.

227

228 *Gas temperature*

229 Thermocouples are commonly used in fire research to measure gas temperatures, but they
230 often fail to measure the true gas temperature (Cox and Chitty 1985, Luo 1997, Dupuy *et al.*
231 2003, Silvani and Morandini 2009). Radiation effects that depend on the measurement
232 conditions are the most significant sources of errors. Discrepancies between the true and
233 measured gas temperatures are considered acceptable since the error range of the probes used
234 in this study is less than 10% (Silvani and Morandini 2009). The corrected temperature curves
235 are not provided here, but the effects of radiation on the thermocouple measurements must be
236 kept in mind.

237 The flame residence time for each experiment is listed in Table 2 and is defined as the time
238 during which the temperature is greater than 500°C, which corresponds to the visible flame
239 temperature (Drysdales 1985). The flame residence times did not show significant differences
240 and thus could not account for the two fire spread behaviours identified previously.

241 The temperature-time curves for the five experiments are shown in Fig. 3. The air
242 temperature measured during the fire spread showed the presence of three regions: preheating,
243 flaming and charring. These regions are delineated by two vertical dashed lines in Fig. 3,
244 using the previously defined flame temperature criteria. The measured temperatures began at
245 the ambient temperature and increased to a maximum of about 800–900°C, which is the usual
246 temperature range for burning vegetal fuels. The temperature curves show a slow trend
247 modulated by fast fluctuations. The slow trend, or the low-frequency part of the signal, is
248 related to the fire spreading, while the fluctuations are due to flame pulsations and wind gusts
249 (Morandini *et al.* 2006).

250 In the first group of experiments, the air temperature remained close to the ambient value
251 before the arrival of the fire front. The rate of the rise in air temperature from ambient to

ignition was computed from low-pass filtered signals (Silvani *et al.* 2005) and is provided in Table 2. The corresponding flame fronts (Fig. 2a) were close to the vertical, and the smoke plume was guided upward. Some peculiarities in the temperature behaviour were observed in experiment 2. The temperature suddenly dropped to 200°C for about 20 s due to the presence of discontinuities in the fuel; these resulted from animal paths that passed through the experimental plot. These discontinuities induced local extinction of the fire. The measurements made in the preheating region, which are of greater interest, were not influenced by this vegetation discontinuity. The rising temperature rate during preheating in the second group of experiments was about one-fifth lower than that in the first group. Furthermore, the increase in air temperature occurred over a longer period before flame contact (more than 100 s prior to the ignition of vegetation), and the temperature measurements showed high fluctuations. These fluctuations were higher in the second group than in the first because of the presence of the smoke plume as well as the intermittent lapping at the top of the vegetation by the flame (Fig. 2b).

Computing the correlation coefficient and related confidence intervals helps to determine if a statistical relation exists between temperature and wind velocity fluctuations. The correlation coefficient between temperature and velocity is given by:

$$r = \frac{\text{cov}(T, u)}{\sigma_T \sigma_u} \quad (1)$$

where *cov* is the covariance of temperature *T* and longitudinal wind velocity *u*, and σ is the standard deviation. The square of *r*, namely, the coefficient of determination r^2 , is used to measure the association between both variables. The coefficient of determination is the fraction of the variance in *u* that is accounted for by changes in *T* and the linear relationship between *u* and *T*. A confidence level of 95% and sample size of 100 s were chosen. As expected, the correlation between temperature and wind velocity was better in the second

group of experiments ($r^2 = 0.2$) than in the first group ($r^2 = 0.015$). In addition, a confidence level of 80% and sample size of 200 s were also tested. In the first group of experiments, the confidence interval width remained at around 0.01. In contrast, the confidence interval width increased to around 0.2 when either the confidence level increased or the sample size decreased. The r^2 statistical convergence can thus be enhanced by increasing the sampling rate. The r^2 value showed a considerable decrease when r decreased by one-tenths of its original value. Indeed, the r^2 values in the range of 0.2–0.3 coincided with r values in the range of 0.5–0.6. In contrast, r was about 0.1 when r^2 was lower than 0.05. Although the correlation between T and u is not linear, a statistical relation cannot be ignored in the second group of experiments, while it can be neglected for the first group. In other words, wind did not significantly influence heat transfer ahead of the flame front in the first group of experiments. Conversely, in the second group of experiments, coupling between wind and temperature was observed in the preheating region. Indeed, the correlation coefficient between temperature and velocity as well as the fluctuating nature of the temperature signal suggest the presence of convective heat transfer in the preheating region. In this case, the unburned vegetation was embedded into a wind-driven smoke layer (Fig. 2). However, to obtain a correct representation of the heat transfer processes governing fire spread, it was necessary to simultaneously use several sensors scattered through the vegetation plot during the experiments. The mechanisms governing heat transfer towards unburned vegetation may be different at the fire head or flanks. Numerical simulations in the presence of an ambient wind (Mell *et al.* 2007) showed that the flanks of the fire perimeter spread under conditions alternating between heading and baking fires, which influences the heat transfer processes. In general, because the information collected by a thermocouple is local in nature, it is not adequate to investigate the heat transport phenomena using single-point measurements, and

measurements of temperature distributions or integral quantities such as heat fluxes should be preferred.

Heat fluxes

The time evolution of the total and radiant heat fluxes measured during the fire spread experiments are shown in Fig. 4. The preheating, flaming and charring regions can also be observed in these curves. The heat fluxes progressively increased up to maximum values exceeding 100 kW m^{-2} when the flame was in contact with the measurement device. However, caution should be exercised in interpreting the heat flux measurements in a mixed radiant-convective environment, especially those obtained from total heat flux gauges. The calibration process consists of determining the sensitivity ($\text{kW m}^{-2} \text{ mV}^{-1}$) of the transducers in comparison to the output voltage of a known calibration source. The calibration should ideally be performed in a thermal environment similar to the one in which the gauges will be used; however, gauge calibration is usually performed using radiant sources such as a black body, furnace or radiant panel. It may not be entirely appropriate to measure the total heat flux using a Gardon gauge through radiation-based calibration in a mixed radiative-convective environment such as a fire (Bryant *et al.* 2003). The gauge sensitivity differs for radiative and convective contributions; a method to estimate measurement uncertainties from total gauges in a mixed radiative-convective environment has been proposed (Kuo and Kulkarni 1991). This method allows the total incident flux to be calculated when calibration is based only on radiative flux. Bryant *et al.* (2003) highlighted the uncertainties caused by convection when radiation is the quantity under consideration and proposed a method to calculate the incident radiant heat flux from total gauges. In both cases, the applied corrections are obtained from the thermal diffusion equation for a foil and are expressed according to the convective heat transfer coefficient or the Nusselt number, which depends on the thermophysical properties of

the fluid (density, specific heat at constant pressure, viscosity and thermal conductivity) in contact with the gauge, the velocity of the fluid, the flow regime (turbulent or laminar), the nature of convection (natural or forced convection) and the geometry of the surface of the heated gauge. The uncertainties in determining the parameters of the correction method, i.e. the convective heat transfer coefficient or the Nusselt number, make these corrections difficult to apply. A previous work (Silvani and Morandini 2009), quantified the error when following the method proposed by Kuo and Kulkarni (1991); it was determined that the total heat flux is underestimated in the flaming region.

The radiation heat flux transducers are not subject to such uncertainties since the window attachment eliminates convection. Nevertheless, these gauges may suffer from deposition of soot on the sapphire window attachment. The use of gas purging eliminates soot deposition, but this is not easy to implement in the field. To clarify the deposition of soot on the radiometer window, a preliminary study was conducted in the laboratory using fires from a forest fuel burner (Appendix 1). The results showed that the deposition of soot on the gauge window can be considered negligible when the radiometer is only exposed to smoke, but flame contact with the gauge leads to the deposition of a significant quantity of soot on the window. For this reason, the radiation heat flux gauges underestimate radiation inside sooty flames; thus, only the measurements ahead of the fire front are considered in the following sections.

Using two different gauge types allows the qualitative partitioning of the convective and radiative processes in the preheating region. When the total and radiation heat fluxes coincide, heat transfer ahead of the fire front is dominated by radiation, and gauges provide accurate quantitative measurements. Conversely, greater discrepancies between the two signals indicate preheating due to mixed radiant-convective heat transfer. By integrating the heat flux curves ahead of the flame front, the differences between radiation and total heat fluxes can be

evaluated in the preheating region. In the first group of experiments, these differences were lower than 10%, so radiation could be considered as the dominant heat transfer process ahead of the fire front. In the second group of experiments, the measurements revealed the non-negligible contribution of convective preheating for the unburned fuel, but the heat flux levels were lower. The difference between the radiation and total heat fluxes was as great as 50% (experiment 4). These results confirm the existence of a convective component ahead of the flame front. The significant role of convective heat transport in the overall thermal balance ahead of the flame front is related to the stronger correlation between fluctuating temperature and wind velocity fields. This study did not focus on the quantitative measurement of the convective exchange between the hot gas stream and vegetation. Aside from the previously mentioned problems of radiation-based calibration for total heat flux gauges in a mixed environment, the convective heat transfer coefficient of the transducer was different from that of the fuel particles. The geometric properties (shape and orientation) and thermal conductivity of the fuel particles should be taken into account to estimate convective heating from the viewpoint of the vegetation. Furthermore, the vertical velocity profile within the vegetation has significant effects on advection, and convective heating varies within the fuel layer. For instance, quantitative measurements of the convection above the vegetation can be performed by determining the temperature and velocity fields using thermocouples and particle image velocimetry, respectively.

Heat transfer mechanisms governing fire spread

The different heat transfer processes ahead of the fire front that are observed between the two groups of experiments are influenced by changes in the fire plume properties and affect the time needed for the unburned vegetation to ignite. The time during which the unburned vegetation is exposed to a radiation heat flux greater than 13 kW m^{-2} is provided in Table 2

for the set of experiments. This threshold value corresponds to the minimum radiation heat flux needed to ignite volatile matter from the vegetative fuels by a pilot flame (Drysdale, 1985). The exposure time to radiation was significantly longer in the first group of experiments than in the second group. These results show that in the first group of experiments, the preheating mechanisms ahead of the fire front were governed by radiation.

The longitudinal variation in the radiation heat flux impinging upon the unburned vegetation is shown in Fig. 5. The data were deduced from flux-time measurements considering a steady rate of fire spread. The flux-time signals were first filtered before time-to-space transformation with a Butterworth filter to eliminate high signal frequencies (Silvani *et al.* 2005). This process allowed a better representation of the mean spatial distribution for radiation impinging ahead of the fire front. The distance to the fire front was estimated by multiplying the time to ignition by the rate of spread for each experiment. The spatial distribution of the heat fluxes ahead of the flame front confirmed the existence of two fire spread processes. In the first group of experiments, radiation ahead of the flame front presented some characteristic length scales or impact distances (lengths across which radiation level was greater than the threshold of 13 kW m^{-2}) of about three times the flame height. Thermal radiation is a long-range process and is usually considered as the dominant mode of heat transfer, which determines the growth and spread of large-scale fires (Sacadura 2005). Incident radiation plays a significant role in the thermal degradation of the fuel through processes such as water evaporation and fuel pyrolysis. Heat flux measurements were performed above the vegetation; therefore, they are related to the energy impinging on the top of the fuel layer, i.e. the incident radiation. The typical absorptivity of vegetation in the Mediterranean region, which depends on fuel properties (spectral, shape, orientation and moisture content), is around 0.9 with reference to the radiation emitted by a black body at 1000°C (Monod *et al.* 2009). The top of the vegetation absorbed most of the thermal radiation

measured by the transducers. The radiation mean path length within the vegetation was smaller, as was the radiation penetrating inside the fuel layer.

For experiments 1–3, the measurements showed significant radiation levels up to 10 m from the fire front (Fig. 5). The thermal degradation of the vegetative fuel due to radiant heating began several meters ahead of the flame front. It is argued that the fire spreading scenario, which involves ignition of the mixture formed by these combustible gases and by the oxidiser located ahead of the flame front, is most commonly observed in wildland fires. Most safety criteria (fuel breaks or wildland-urban interfaces) are based on a radiation-dominated fire spread (Butler and Cohen 1998, Cohen 2004, Zarate *et al.* 2008). However, the present heat flux measurements indicate the existence of a different scenario. In the second group of experiments, the radiation level ahead of the flame front was lower than 13 kW m^{-2} (Fig. 5); this value is too low for sustained pyrolysis of the vegetative fuel to occur. In this case, the fire spread by convection heating, which is related to the intermittent licking of the top of the unburned vegetation by the flame. Physics-based models developed in previous studies (Morvan and Dupuy 2004, Linn and Cunningham 2005, Morvan *et al.* 2009) predicted a change in the fire spread regime dominated by either radiation or convection under low or high wind conditions, respectively. This change in the fire spread regime is usually predicted using the convective Froude number F_c (Clark *et al.* 1996) or the convection number N_c (Nelson 1993). These dimensionless numbers represent the ratio of the inertial forces induced by wind flow and the buoyancy forces generated by combustion. The convective Froude number and convection number are given by:

$$F_c = \sqrt{\frac{(u - r)^2}{g \frac{\Delta \theta}{\theta_a} \ell}} \quad (2)$$

$$N_c = \frac{2 g I}{\rho C_p \theta_a (u - r)^3} \quad (3)$$

where u stands for the average wind velocity (m s^{-1}), r is the rate of fire spread (m s^{-1}), g is the acceleration due to gravity (m s^{-2}), $\Delta\theta$ is the difference between the temperatures of the hot gases and the surroundings, θ_a is the temperature of the surroundings (K), I is the fireline intensity (kW m^{-1}), ρ is the air density (1.2 kg m^{-3}) and C_p is the specific heat of dry air at constant pressure ($1.005 \text{ kJ kg}^{-1} \text{ K}^{-1}$). The variable ℓ (m) is a characteristic length scale of the flame front which is representative of buoyancy forces generated by the fire, i.e. the flame's length, L , depth, D or height, H .

In numerical simulations (Pagni and Peterson 1973, Clark *et al.* 1996, Morvan and Dupuy 2004, Morvan 2006), researchers suggested that $F_c^2 < 1$ (resp. $N_c > 1$) indicates a plume-dominated fire, while $F_c^2 > 1$ (resp. $N_c < 1$) indicates a wind-driven fire. In this study, the convective Froude and convection numbers (Table 2) were lower than 0.4 and greater than 14, respectively. These results therefore confirm the conclusions of Sullivan's analysis of grassland fires (Sullivan 2007). Neither dimensionless number reflects the observed behaviour of wind-driven fires at the field scale and both numbers seem more appropriate for quantifying academic fire spread scenarios such as laboratory-scale experiments or numerical simulations. The wind-driven fire spread regime, in which the contribution of convection becomes significant due to contact of the fire plume with unburned vegetation, should be taken into account when managing safety zones. Simulation results (Porterie *et al.* 2005b, Morvan 2006) also pointed out that convection cannot be neglected in predicting fire safety zones when plume impingement occurs. Morvan and Dupuy (2004) clarified that for wind-driven fires, radiation and convective heat transfer initially have the same order of magnitude; however, fire propagation is subsequently controlled by convective heat transfer, which can represent up to 70% of the energy received by the solid fuel. The existence of such a regime, which is favoured by a low fuel load (generating less buoyancy forces) on steep slopes and under wind-aided conditions, suggests that the dimensioning of fuel breaks in vegetal cover

may not be appropriate if it is based only on a purely radiative evaluation of the impact distance.

Conclusion

The heat transfer mechanisms ahead of a flame front were investigated in the field to further our understanding of how wildfires spread. Within the range of experimental configurations considered (wind velocities $< 5 \text{ m s}^{-1}$), the collected data indicated the existence of two fire spread regimes. The first regime, which occurs for higher fuel loads, is plume-dominated. In this case, the flow strongly responds to the great buoyancy forces generated by the fire: flames and smoke plume are guided upward. Radiation is the dominant heat transfer mechanism ahead of the fire front. The second regime, which occurs for lower fuel loads, is wind-driven. In this case, the flow is governed by inertial forces due to wind: flames and smokes travel close to the top of the vegetation. Preheating of the unburned fuel occurs due to mixed radiant-convective heat transfer. The flame front spreads quickly by direct contact with unburned fuel. Within the range of experimental conditions considered in this study, it was found that the Clark's convective Froude number and Nelson's convection number, which are used in numerical studies to predict the fire spread regime, did not reflect the observed behaviour of the wind-driven fires in the field. The complexity of the turbulent wind flow modified by the fire needs further investigation to assess the role of convective heat transfer in greater detail. Convection can endanger fuel break efficiency or firefighter safety if these distances are determined according to radiation only.

Acknowledgements

This work was financially supported by the Corsica region. Experiments 2–5 would not have been possible without the assistance of the French forestry, agriculture and firefighting services (Forestiers Sapeurs, Office National des Forêts, Direction Départementale de l'Agriculture et de la Forêt, Service Départemental d'Incendie et de Secours). We also thank our colleagues from CEREN (Centre d'Etude et de Recherche de l'Entente) for having invited us to their experimental campaign (experiment 1).

References

- Allgöwer B, Calogine D, Camia A, Cuiñas P, Fernandes P, Francesetti A, Hernando C, Koetz B, Koutsias N, Lindberg N, Marzano R, Molina D, Morsdorf F, Ribeiro Lm, Rigolot E, Séro-Guillaume O (2006) Methods for Wildland Fuel Description and Modelling: A State of the Art. Deliverable D–02–06 EUFIRELAB. <http://eufirelab.org>.
- Bilgili E, Saglam B (2003) Fire behavior in maquis fuels in Turkey. *Forest Ecology and Management* **184**, 201–207.
- Bryant RA, Womeldorf CA, Johnsson EL, Ohlemiller T (2003) Radiative Heat Flux Measurement Uncertainty. *Fire and Materials* **27**, 209–222.
- Butler BW (2003) Field measurements of radiant energy transfer in fuel scale wind driven crown fires. *6th ASME–JSME Thermal Engineering Joint Conference*, 16–20.
- Butler BW, Cohen J, Latham DJ, Schuette RD, Sopko P, Shannon KS, Jiminez D, Bradshaw LS (2004) Measurement of radiant emissive power and temperatures in crown fires. *Canadian Journal of Forest Research* **34**, 1577–1587.
- Butler BW, Cohen JD (1998) Firefighter Safety Zones: A Theoretical Model Based on Radiative Heating. *International Journal of Wildland Fire* **8**, 73–77.
- Butler BW, Finney MA, Andrews PL, Albini FA (2004) A radiation-driven model for crown fire spread. *Canadian Journal of Forest Research* **34**, 1588–1599.

497 Carrega P (2002) Relationships between wind speed and the R.O.S. of a fire front in field
 498 conditions: an experimental example from the Landes forest, France. *In Proceedings of the*
 499 *4th International Conference on Forest Fire Research, 2002.*

500 Cheney NP, Gould JS (1995) Fire Growth in Grassland Fuels. *International Journal of*
 501 *Wildland Fire* **5**, 237–247.

502 Cheney NP, Gould JS, Catchpole WR (1993) The influence of fuel, weather and fire shape
 503 variables on fire–spread in grasslands. *International Journal of Wildland Fire* **3**, 31–44.

504 Clark TL, Jenkins MA, Coen JL, Packham DR (1996) A Coupled Atmosphere–Fire Model:
 505 Role of the Convective Froude Number and Dynamic Fingering at the Fireline.
 506 *International Journal of Wildland Fire* **6**, 177–190.

507 Cohen JD (2004) Relating flame radiation to home ignition using modeling and experimental
 508 crown fires. *Canadian Journal of Forest Research* **34**, 1616–1626.

509 Consalvi JL, Porterie B, Nicolas S, Loraud JC, Kaiss A (2005) Modeling Thermal Impact of
 510 Wildland Fires on Structures. Part II: Radiative Impact of a Fire Front. *Numerical Heat*
 511 *Transfer Part A: Applications* **47**, 491–503.

512 Cox G, Chitty R (1985) Some source–dependent effects of unbounded fires. *Combustion and*
 513 *Flame* **60**, 219–232.

514 Cox G, Chitty R (1985) Some source–dependent effects of unbounded fires. *Combustion and*
 515 *Flame* **60**, 219–232.

516 De Luis M, Baeza M, Raventos J, Gonzalez–Hidalgo J (2004) Fuel characteristics and fire
 517 behaviour in mature Mediterranean gorse shrublands. *International Journal of Wildland*
 518 *Fire* **13**, 79–87.

519 Drysdale D (1985). An introduction to fire dynamics, Wiley–Interscience, New York.

520 Dupuy JL (1995) Slope and fuel load effects on fire behavior: laboratory experiments in pine
 521 needles fuel beds. *International Journal of Wildland Fire* **5**, 153–164.

522 Dupuy JL, Maréchal J, Morvan D (2003) Fires from a cylindrical forest fuel burner:
 523 combustion dynamics and flame properties. *Combustion and Flame* **135**, 65–76.
 524 Dupuy JL, Morvan D. (2005). Numerical study of a crown fire spreading toward a fuel break
 525 using a multiphase physical model. *International Journal of Wildland fire*, **14**, 141–151.
 526 Fernandes PM (2001) Fire spread prediction in shrub fuels in Portugal. *Forest Ecology and*
 527 *Management* **144**, 67–74.
 528 Gould JS, Knight I, Sullivan AL (1997) Physical modelling of leaf scorch height from
 529 prescribed fires in young Eucalyptus sieberi regrowth forests in Southeastern Australia.
 530 *International Journal of Wildland Fire* **7**, 7–20.
 531 Kaiss A, Zekri L, Zekri N, Porterie B, Clerc JP, Picard C (2007) Fuelbreak efficiency for
 532 wildland fire prevention. *C. R. Physique* **8**, 462–468.
 533 Kuo CH, Kulkarni AK (1991) Analysis of heat flux measurement by circular foil gages in a
 534 mixed convection/radiation environment. *Journal of Heat Transfer* **113**, 1037–1040.
 535 Linn R, Cunningham P (2005) Numerical simulations of grass fires using a coupled
 536 atmosphere–fire model: Basic fire behavior and dependence on wind speed. *Journal of*
 537 *Geophysical Research* **110**, 1–19.
 538 Luo M (1997) Effects of Radiation on Temperature Measurement in a Fire Environment.
 539 *Journal of Fire Sciences* **15**, 443–461
 540 Mell W, Jenkins MA, Gould J, Cheney P (2007) A Physics Based Approach to Modeling
 541 Grassland Fires. *International Journal of Wildland Fire* **16**, 1–22.
 542 Mendes–Lopes J, Ventura J, Amaral J (2003) Flame characteristics, temperature–time curves,
 543 and rate of spread in fires propagating in a bed of Pinus pinaster needles. *International*
 544 *Journal of Wildland Fire* **12**, 67–84.
 545 Monod B, Collin A, Parent G, Boulet P (2009) Infrared radiative properties of vegetation
 546 involved in forest fires. *Fire Safety Journal* **44**, 88–95.

547 Morandini F, Silvani X, Rossi L, Santoni PA, Simeoni A, Balbi JH, Rossi JL, Marcelli T
 548 (2006) Fire spread experiment across Mediterranean shrub: Influence of wind on flame
 549 front properties. *Fire Safety Journal* **4**, 229–235.

550 Morandini F, Silvani X, Rossi L, Santoni PA, Simeoni A, Balbi JH, Rossi JL and Marcelli T
 551 (2006) Fire spread experiment across Mediterranean shrub: Influence of wind on flame
 552 front properties. *Fire Safety Journal* **41**, 229–235.

553 Morvan D (2006) A numerical study of flame geometry and potential for crown fire initiation
 554 for a wildfire propagating through shrub fuel. *International Journal of Wildland Fire* **16**,
 555 511–518.

556 Morvan D, Dupuy JL (2004) Modelling the propagation of a wildfire through a Mediterranean
 557 shrub using a multiphase formulation. *Combustion and Flame* **138**, 199–200.

558 Morvan D, Meradji S, Accary G (2009) Physical modelling of fire spread in grasslands. *Fire*
 559 *Safety Journal* **44**, 50–61.

560 Nelson R. (1993) Power of a Fire – a Thermodynamic Analysis. *International Journal of*
 561 *Wildland Fire* **3**, 131–138.

562 Packam DR, Pompe A (1971) Radiation temperatures of forest fires. *Australian Forest*
 563 *Research* **5**, 1–8.

564 Pagni PJ and Peterson TG (1973) Flame spread through porous fuels. In *Proceedings of the*
 565 *14th Symposium (Int) on Combustion* pp. 1099–1107. The Combustion Institute. Pittsburgh.

566 Pitts WM (1991) Wind effects on fire, *Progress in Energy and Combustion Sciences* **17**, 83–
 567 134.

568 Porterie B, Consalvi JL, Kaiss A, Loraud JC (2005a) Predicting wildland fire behavior and
 569 emissions using a fine-scale physical model. *Numerical Heat Transfer Part A:*
 570 *Applications* **47**, 571–591.

571 Porterie B, Morvan D, Loraud JC, Larini M (2000) Firespread through fuel beds : Modelling
 572 of wind-aided fires and induced hydrodynamics. *Physics of Fluids* **12**, 1762–1782.

573 Porterie B, Nicolas N, Consalvi JL, Loraud JC, Giroud F, Picard C (2005b) Modeling
 574 Thermal Impact of Wildland Fires on Structures. Part I: Radiative and Convective
 575 Components of Flames Representative of Vegetation Fires. *Numerical Heat Transfer Part*
 576 *A: Applications* **47**, 471–489.

577 Sacadura JF (2005) Radiative transfer in fire safety science. *Journal of Quantitative*
 578 *Spectroscopy and Radiative Transfer* **93**, 5–24.

579 Santoni PA, Simeoni A, Rossi JL, Bosseur F, Morandini F, Silvani X, Balbi JH, Cancellieri
 580 D, Rossi L (2006) Instrumentation of wildland fire: Characterisation of a fire spreading
 581 through a Mediterranean shrub. *Fire Safety Journal* **41**, 171–184.

582 Silvani X, Morandini F (2009) Fire spread experiments in the field: temperature and heat flux
 583 measurements. *Fire Safety Journal*, **44**, 279–285.

584 Silvani X, Rossi L, Morandini F (2005) The measurements of integral scales in free wildland
 585 fires. *Proc 4th Mediterranean Combustion Symposium*, Lisbon.

586 Stocks BJ, Alexander ME, Lanoville RA (2004) Overview of the International Crown Fire
 587 Modelling Experiment. *Canadian Journal of Forest Research* **34**, 1543–1547.

588 Sullivan AL (2007) Convective Froude number and Byram's energy criterion of Australian
 589 experimental grassland fires. *Proceedings of the Combustion Institute*, 2557–2564.

590 Vega JA, Fernandes P, Cuiñas P, Fontúrbel MT, Pérez JR and Loureiro C (2006) Fire spread
 591 analysis of early summer field experiments in shrubland fuel types of northwestern Iberia.
 592 *In Proceeding of the 5th International Conference on Forest Fire Research*.

593 Viegas DX (2004) Slope and wind effects on fire propagation. *International Journal of*
 594 *Wildland Fire* **13**, 143–156.

- Viegas DX (2006) Parametric study of an eruptive fire behaviour model *International Journal of Wildland Fire* **15**, 169–177
- Viegas DX, Cruz MG, Ribeiro LM, Silva AJ, Ollero A, Arrue B, Dios R, Gómez–Rodríguez F, Merino L, Miranda AI, Santos P (2002) Gestosa Fire Spread Experiments. *In Proceedings of the 4th International Conference on Forest Fire Research*.
- Viegas DX, Palheiro PM, Pita LP, Ribeiro LM, Cruz MG, Ollero A, Arrue B, Dios R (2006) Analysis of fire behaviour in Mediterranean shrubs: Gestosa Fire Spread Experiments. *In Proceeding of the 5th International Conference on Forest Fire Research*.
- Zarate L, Arnaldos J, Casal J (2008) Establishing safety distances for wildland fires. *Fire Safety Journal* **43**, 565–575.

Appendix 1

A preliminary study of the deposition of soot on the radiometer window was conducted in the laboratory using two radiation heat flux transducers with sapphire windows and fires from a forest fuel burner. The burner was made from a 50-cm-diameter basket filled with 500 g of forest fuel (*Pinus pinaster* needles) and ignited using alcohol. Prior to each fire test, both radiometers were exposed to a radiant source of about 60 kW/m² in order to check the good agreement (Table A). In the first test, one radiometer was exposed to a smoke plume about 50 cm above the flame for 200 s. After exposure, the measurements of the heat flux gauge exposed to smoke were compared to those of the soot-free reference radiometer. In the second test, the radiometer was exposed to the flame for 60 s, and the measurements obtained were compared with those of the reference radiometer. The attenuation of the gauge reading after smoke exposure was not significant. These results confirm that the deposition of soot on the gauge window can be considered as negligible when the transducer is only exposed to smoke

620 (in the preheating region, for instance). This is due to the well-ventilated nature of the flame
621 in the open in contrast with fire in an enclosure. In contrast, flame contact with the gauge
622 deposited a significant quantity of soot on the window. In this case, the attenuation measured
623 during this test was about 25%; therefore, radiation measurement in the flaming region could
624 no longer be considered. When the radiometer is used in a hostile flame environment,
625 nitrogen purging is used to prevent soot deposition in order to keep the radiation transmitting
626 window clean. The purge system requires the use of an inert gas which flows ahead of the
627 window to prevent soot from depositing on it. Another alternative is the use of ellipsoidal
628 radiometers with gas purging to prevent soot from entering its cavity.