Infrared imagery on wildfire research. Some examples of sound capabilities and applications

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***Abstract*—. Wildfire infrared monitoring is nowadays applied to different problems related to fire prevention, fire suppression and fire behaviour analysis. In terms of research, infrared thermography offers unique capabilities although it is constantly challenging the scientific community to develop sound process imagery methodologies in order to obtain valuable and reliable information about fire phenomena. In this paper we show some infrared thermography applications that we have recently developed to provide solutions on fuel mapping, fire behaviour analysis, fire suppression and fire effects assessment. We highlight the advantages and drawbacks of all of them and present future problems that can be tackled with this type of fire monitoring techniques.**

***Keywords*— infrared thermography, fuel mapping, fire behaviour, rate of spread, aerial suppression.**

I. INTRODUCTION

The contributions that are being done from the research community worldwide concerning the study of wildfires are diverse and can be grouped into different topics, all of them aiming at mitigating the unintended consequences of forest fires. These topics are briefly described below:

- Fire prevention, which includes among others the works to improve fire detection systems and to obtain accurate maps of fuel and fire risk, the fire weather study for the early detection of thunderstorms, the analysis of trends in climate and fire regimes and the study of the relationship between environmental conditions and the physiological state of forest fuels.
- Fire management, which includes all the works that aim at increasing and improving the information available for decision making during the management of a fire in an emergency, i.e. the development of software for the simulation of fires or the optimization of resources allocation during the emergency, or studies of prescribed burning as a management tool.
- Fire effects, an area related mainly to ecology which includes the works devoted to study the ability of the affected ecosystems to regenerate after the fire or the degree of impact that fire causes on wildlife.
- Fire security, an area devoted primarily to seek improvements in the extinction techniques, but also in the safety of people and goods exposed to flames.
- Fire behaviour, which is a basic research topic with the specific objective of understanding the spread of fire as a physicochemical phenomenon, and developing models for predicting fire behaviour to be included in the simulation tools used in fire management.

During these last decades, there has been an increased activity in the wildfire research community to develop methods based on infrared (IR) sensors in order to provide diverse solutions within the mentioned topics. For instance, airborne IR cameras have been used for early fire detection [1], to locate and study the fire perimeter evolution, to construct rate of spread maps [2], to identify eventual spot fires and to study aerial suppression effectiveness [3, 4]. Furthermore, remote sensing products based on IR sensors are applied to study fire effects and develop fuel maps [5]. However, due among other reasons to a severe reality of a climate change scenario, the wildfire problem is becoming more complex in all its different facets, hence needing more efforts and innovative solutions coming from non-intrusive sensors that can provide reliable imagery to be processed so to obtain valuable information for an efficient fire management.

In this paper some of the infrared thermography applications on wildfire research that we have recently developed are presented. They basically encompass fuel characterization, fire behaviour analysis and fire suppression assessment. Further steps towards covering other wildfire topics as well as improving the existing procedures are also put forward.

II. MATERIALS AND METHODS

The applications that we show in this paper have all been developed using an IR camera (AGEMA Thermovison 570-Pro, FLIR Systems) operating in the long wavelength infrared (LWIR) range of the spectrum (7.5 – 13 μm), also known as Thermal Infrared (TIR) range. The camera is equipped with a frame grabber to control and store sequences of IR images (240 x 320 pixels) from a laptop computer at a rate of 5 fps. Every IR image is treated as a 240 x 320 cells temperatures matrix which is represented by a colour map gradient. In all the applications a standard video camera (visual spectrum) has also been used together with the IR camera in order to have a visual evidence of the monitored phenomena.

Three different experimental scenarios are the framework of the developed procedures reported in this paper. Firstly, laboratory fires performed in CERTEC for basic fire dynamics research purposes. In this type of tests we used straw or pine needles as fuel beds. The experiments were monitored with both the IR and the video camera, standing on an elevated platform from which a whole view of the experimental set-up was obtained.

The second fire scenario used to develop IR applications for wildfire research has been the fire experiments performed in Ngarkat Conservation Park (CP) in the south-east of South Australia in March 2008 (Fig. 1). They were part of a project conducted by the Australia's National Science Agency, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the South Australian Department of Environment and Heritage. The main objectives of the project were to investigate fire behaviour in malle-heath fuels [6] and compare the effectiveness of different aerially applied fire suppressants [7]. The imagery captured during the experiments was all airborne. The cameras were positioned in an observing helicopter on top of a fixed tripod and hand-held operated.

Finally, there is a third experimental scenario that shall be used to improve and enlarge the use of IR thermography for wildfire research purposes: the experimental fires at the tropical montane cloud forests (TMCF) in the Peruvian Andes. The project behind these experiments has as main objective to model the fire behaviour and the likelihood of fire sustainability in the puna high-altitude grasslands.

The imagery captured during all the experimental work has been treated with the final aim of obtaining a package of user-friendly applications. These are basically made of algorithms and interfaces that have been implemented using MATLAB® computing software.

III. Fuel characterization

Forest fuel mapping is essential for fuel management but also to make accurate predictions of fire behaviour and fire effects [8]. Several authors have explored the use of remote sensing to generate fuel maps by processing digital images at both regional and local scale [9, 10]. Most of these applications use images taken in the near (NWIR) or medium (MWIR) infrared wavelengths.

We used LWIR thermography to explore the potential capabilities of this range of the spectrum to characterize different types of fuel strata and hence mapping fuels for fire behaviour studies [11]. We developed this study in Ngarkat CP, which holds semi-arid ecosystems where the presence of fuel gaps is an important issue to take into account when studying fire behaviour. Particularly, we wanted to detect canopies, surface fuels and fuel discontinuities following the hypothesis that every type of fuel strata should have a particular brightness TIR temperature range due mainly to differences on water content. The results of the study would have had to lead to a minimization of the fuel sampling work load that these types of experiments often involve.

Figure 2 a) illustrates the type of vegetation that is present at Ngarkat CP. It can be observed the sparse distribution of the mallee shrubs leaving uncovered gaps of sandy soil. Fig. 2 b) corresponds to a satellite image of one of the plots to be burnt. The upper part of the image has a light homogeneous canopy cover whereas in the lower part, gaps and surface fuels are more abundant.

In our study we basically compared the IR and visual images with the satellite images and contrasted the imagery information with the fuel coverage data obtained during the fuel sampling campaign. We could not clearly identify the brightness TIR temperature ranges that may determine the different elements covering the plot (Fig. 3 a)); nevertheless, we did observe significant colour thresholds in the grey scale when analysing the 3 different RGB (Red Green and Blue) layers of the images captured with the standard visual camera (Fig. 3b)). Values lower than 88 gave us canopy coverage; the range between 89 and 102 corresponded to surface fuels, whereas values greater than 103 matched with the bare soil.

TIR thermography was demonstrated to be a promising tool for fuel mapping applications, particularly in spots with light fuel coverage. However, we could not obtain reliable outcomes mainly due to a lack of replicates that could ensure the consistence of the preliminary results. Processing images from the visual spectrum gave us a better performance in this particular case.

IV. Fire behaviour

Fire behaviour is defined as the manner in which fuel ignites, flame develops, and fire spreads as determined by the interaction of fuel, weather, and topography [12]. Rate of spread (ROS) is one of the most noteworthy variables in the description of forest fire behaviour, since it is directly related to fire intensity and flame front geometry. In forest fire emergency management, knowing ROS is critical. Hence, a great deal of scientific research is dedicated to this field, which centres either on mathematical modelling or on experimental assessment for the validation of models.

Various methods can be used to experimentally assess the ROS, and their success depends on the extent to which straightforward implementation, reliability, precision, feasibility of extrapolation to other experimental scenarios and cost come together. IR thermography provides high quality ROS data, since it allows the fire front position to be detected even in those situations in which the fire spreads accompanied by thick smoke and is therefore invisible to the human eye. Moreover, it gives valuable information about the fire temperature profile and the fire intensity. However, this technique is one of the most difficult and expensive to be implemented in experiments, since it requires a robust methodology to be developed in order to process imagery as well as a considerable investment on the equipment.

In [13] we developed a new thermal image processing method for computing ROS of linear flame fronts on flat surfaces with known dimensions under laboratory conditions. The method consisted on firstly rectifying selected frames at a certain frequency using a projective geometry multiple-view technique. The correction was carried out by means of the the planar homography matrix, which was calculated with the Direct Linear Transformation (DLT) algorithm [14] and required a minimum of 4 control points located at known spots. Subsequently, the position of the flame front was determined by applying a threshold-value-searching criterion within the temperature matrix of the target surface [15]. The output of the method gave us for each point in time the position of the flame front and the most advanced flaming point with which the maximum and the mean ROS could be easily calculated (Fig. 4).

We improved and extended our methodology for field applications using the data monitored in Ngarkat CP fire experiments [16]. The spatial registration of the images was undertaken by using several hot ground control points of known GPS coordinates located around the experimental plots. Following, we outlined the fire perimeter at every corrected frame (i.e. isochrone) using a brightness TIR temperature of 600 K to delimit the fire edge. Once all the isochrones were detected, the ROS map at the fire ground was obtained implementing the following steps: *i)* a linear spline interpolation was used to increase the number of points forming every isochrones; *ii)* the trajectory and mean ROS vectors between every two consecutive isochrones were calculated and *iii)* the ROS vector field was interpolated to give ROS values and directions for every pixel on the fire ground (e.g. in Fig. 5).

The methodology reported above has a remarkable potential and could be implemented in real wildfire management emergencies by improving a few non-automatic steps of the computing process.

V. Fire suppression

Fire suppression encompasses all work and activities connected with control and fire-extinguishing operations. In many fire-prone areas of the world, fire suppression is nowadays mainly based on using aerial resources that deliver chemical products (i.e. foams, water enhancers and retardants [17]. Aerial suppression is expensive and requires significant logistical support. Assessing the effectiveness of aerial suppression drops provides valuable data for determining if the cost and effort is justified. It also can be useful for reviewing and improving firefighting tactics and procedures.

We used airborne IR images captured in Ngarkat CP experiments to design a methodology that could quantitatively evaluate the drop performance during the aerial attack of a wildfire [18, 19]. Image processing encompassed several phases; *i)* georeferencing every frame taken during critical periods following the above mentioned procedure; *ii)* locating drops using temperature differentials determined immediately after drops reached the ground: the contour for each drop was outlined by using a 25% temperature gradient threshold for active fire zones (> 600 K of brightness TIR temperature), a 15% temperature gradient threshold for hot zones (i.e. areas with residual fire activity or areas preheated by the fire front proximity, with brightness TIR temperatures between 425 K and 600 K) and a 10% temperature gradient threshold for cool areas (brightness TIR temperatures between 360 K and 425 K) and *iii)* identifying the location of the fire perimeter at regular time steps in order to produce a ROS map.

The processed infrared data (e.g. in Fig. 6) could then be used to quantify the characteristics of drops and their effect on fire behaviour. The analysis of the drop area provided the dimensions of the drop footprint and the position of the drop including the distance to the fire edge, other drops and anchor points. It also provided the holding time of the drop in the case the drop experienced spotting, burnt around or burnt through breaches.

Infrared monitoring has not been comprehensively used to investigate the effectiveness of aerial suppression drops on wildland fires. The Ngarkat experiments demonstrated its potential for studying aerial suppression effectiveness. In an operational environment raw infrared footage could be used to detect drop breaches and monitor general fire behaviour and suppression effectiveness. More detailed analyses of infrared imagery could provide accurate quantification of drop placement, coverage and effects on fire behaviour. Some new airborne infrared monitoring instruments could be further developed with the type of methods that have been developed, so that they could be used to undertake drop assessments in real-time during wildfire conditions.

VI. FUTURE APPLICATIONS

In a worldwide climate change scenario, the need for reducing greenhouse gases emissions as well as to protect biodiversity has resulted in a significant increase of the interest on knowing the contribution of forest fires to total greenhouse emissions coming from tropical regions. Fires are the largest recurring natural disturbance at the Pan Amazonian region, leading to carbon and biodiversity losses, thousands of fatalities, millions of dollars in property damages, and reducing the air quality of downwind-exposed communities every year. Although fire behaviour in temperate zones has received much scientific attention, there is a big knowledge gap on fire behaviour and fire management in tropical ecosystems. TMCF are one of the most fire sensitive ecosystems in the world, and are found in montane tropical areas of South America, Africa and Asia. In the Andes, they are found at about 3,000 m at see level, sitting immediately below the highly flammable montane grasslands (puna). There is a need to characterize fuels and fire behaviour to preserve this type of ecosystems. Our next challenge is to combine IR monitoring grasslands fire experiments with satellites fire imagery in the TMCF at the Peruvian Andes, which is expected to be a fruitful solution to pick fuels combustibility in these remote areas and hence helping fire managers to establish successful fire management policies.

VII. CONCLUDING REMARKS

IR monitoring is currently applied to wildfire management for prevention, suppression and ecological purposes. During these last decades, there has been an increased activity in the wildfire research community to develop methods based on IR sensors in order to provide better fire management solutions. It still is a challenging work, since the fire problem is getting more complex due among other reasons to a severe scenario of climate change. We have shown recently developed applications that provide solutions which improve fuels characterization, fire behaviour mapping and analysis, and aerial fire suppression effectiveness evaluation. In general terms they have shown successful results and have significant potential to be implemented in real fire management operations. On-going research devoted to assess fuels combustibility with IR technology in tropical fire-prone regions has also been presented and put forward.

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VIII. ILLUSTRATIONS, GRAPHS, AND PHOTOGRAPHS

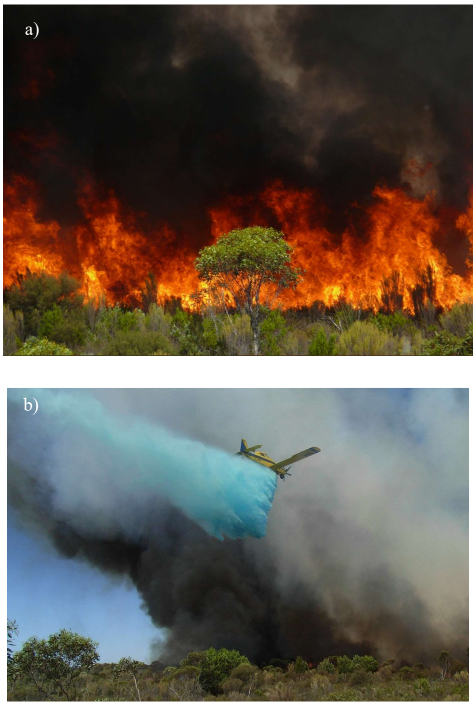


Fig.1.a) Experimental fire in Ngarkat CP. b) Foam drop during the aerial suppression experiments at Ngarkat CP (Photos by M.G. Cruz, CSIRO Ecosystem Sciences and CSIRO Climate Adaptation Flagship).

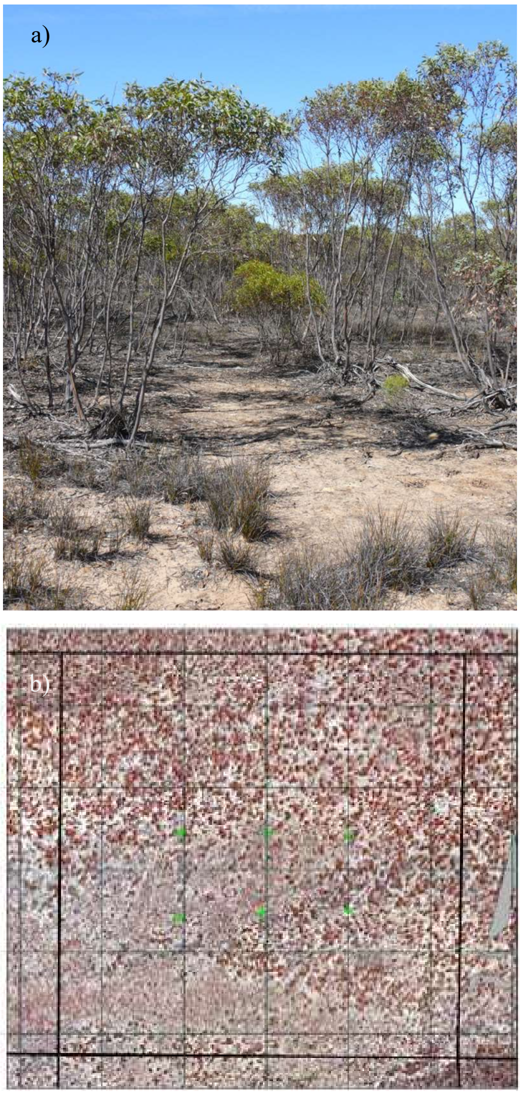
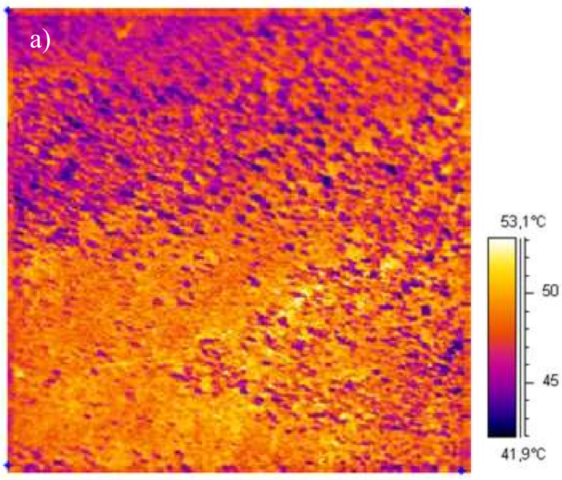


Fig. 2.a) Mallee shrublands in Ngarkat CP. b) Satellite image of one of the plots (J) to be burnt in Ngarkat CP experiments (Source: CSIRO).



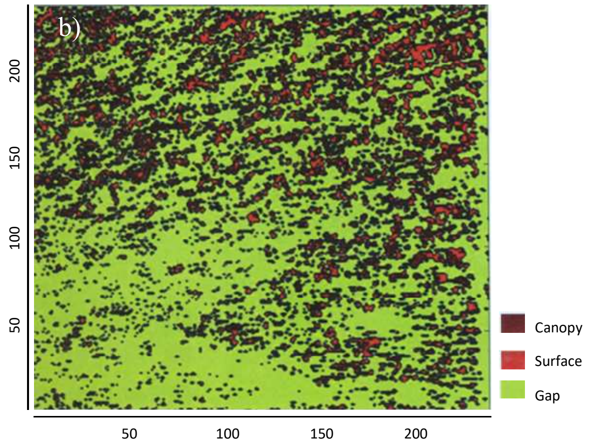
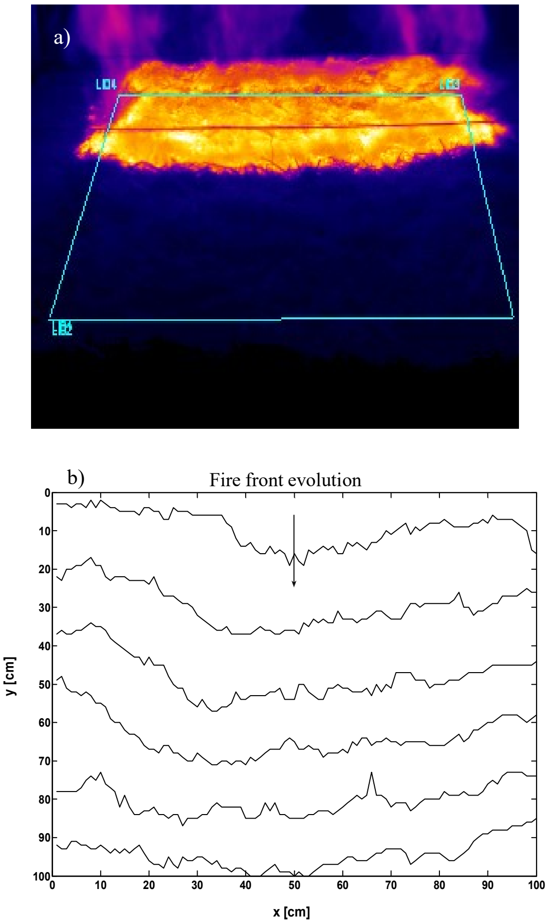


Fig. 3.a) IR image of plot J (brightness TIR temperature scale). b) Segmented G layer of an RGB image of plot J (axis are in m).



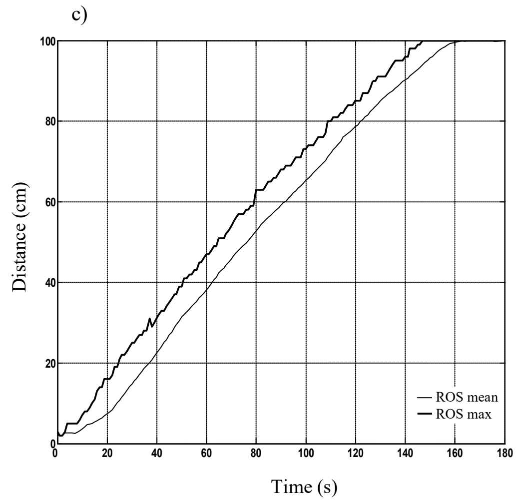


Fig. 4. a) Raw IR image of a laboratory straw fire. b) Fire front evolution obtained from processed imagery of the experiment. The arrow shows the direction of fire spread. c) Plot of maximum ROS and mean ROS of the experiment.

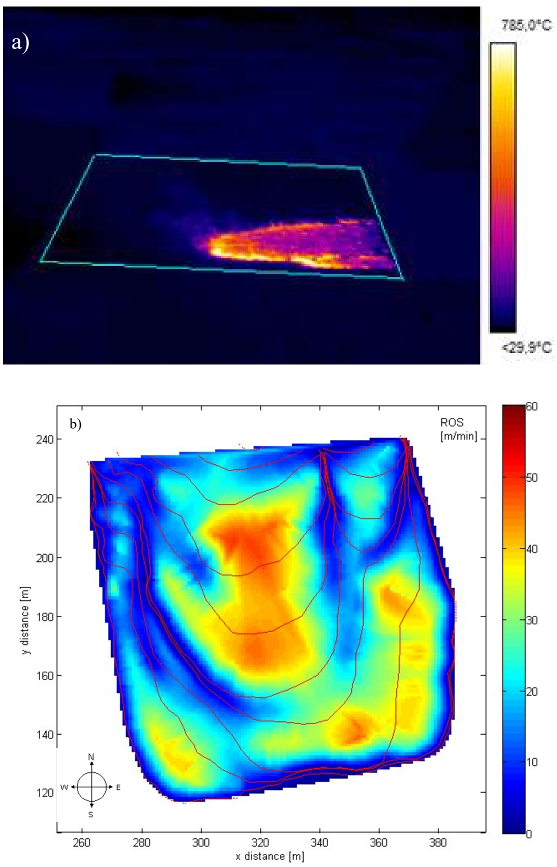


Fig. 5. a) Raw IR image of one of the plots (E) burning at Ngarkat CP (brightness TIR temperature scale). b) ROS map with outlined isochrones of plot E.

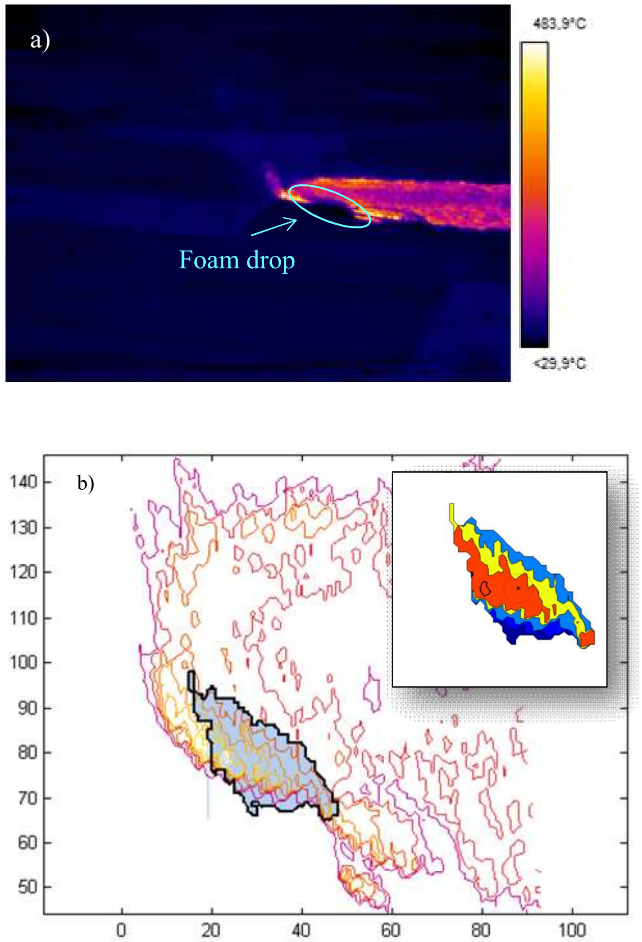


Fig 6.a) Raw IR image at an instant at which a foam drop was delivered (brightness TIR temperature scale). b) Processed IR image with the outline of the drop contour superimposed over a temperature contour field of the fireground. At the upper right corner, the drop is segmented in brightness IR temperature ranges that cover flaming zones (red), smouldering zones (yellow), hot zones either burnt or pre-hetated (light blue) and cool zones of unburned fuel (dark blue).

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