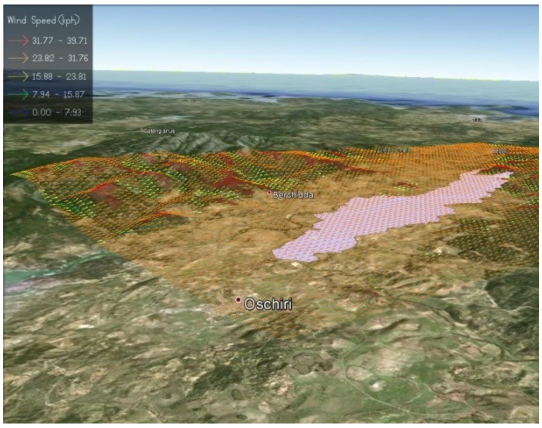

Modelling Fire Behaviour and Risk

Eds. Donatella Spano,
Valentina Bacciu,
Michele Salis,
Costantino Sirca

Supported by PROTERINA-C
Project EU Italia-Francia Marittimo
2007-2013 Programme

Proterina

MARITTIMO - IT FR - MARITIME
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Università di Sassari –
Dipartimento di
Scienze della Natura e
del Territorio
(DIPNET)

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Supported by PROTERINA-C Project:
A forecast and prevention system for climate change impacts on risk variability for wildlands and urban areas
(EU Italia-Francia Marittimo
2007-2013 Programme)

Proterina C

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Editors

Donatella Spano   Valentina Bacciu   Michele Salis   Costantino Sirca

Department of Science for Nature and Environmental Resources (DipNeT),
University of Sassari, Italy;
Euro-Mediterranean Center for Climate Changes (CMCC), IAFENT Division,
Sassari, Italy

Università di Sassari –
Dipartimento di
Scienze della Natura e
del Territorio
(DIPNET)

Centro Euro-Mediterraneo
per i Cambiamenti Climatici

ISBN
978-88-904409-7-7

Printed by
Nuova StampaColor
S.r.l. Industria Grafica
Zona Industriale
Muros 07030 Muros
(Sassari, Italy)

Graphic Design and Layout
Valentina Bacciu and
Michele Salis

Cover Photo by
Sandro Tedde
www.sandrotedde.com

May, 2012

Supported by

PROTERINA-C Project
EU Italia-Francia
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Proterina

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Under the patronage of

Università di Sassari –
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«*Dixerat ille, et iam per moenia clarior ignis*
auditur, propiusque aestus incendia volvunt.
"ergo age, care pater, cervici imponere nostrae;
ipse subibo umeris nec me labor iste gravabit;
quo res cumque cadent, unum et commune periclum,
una salus ambobus erit." »

Publius Vergilius Maro
Aeneis, Liber II, vv 705-710

«*He spoke; and higher o'er the blazing walls*
leaped the loud fire, while ever nearer drew
the rolling surges of tumultuous flame.
"Haste, father, on these bending shoulders climb!
This back is ready, and the burden light;
one peril smites us both, whate'er befall;
one rescue both shall find." »

Publius Vergilius Maro
Aeneid, Book II, vv 705-710
Theodore C. Williams, trans., 1910

CONTENTS

FOREWORD

It is my pleasure to present this volume that collects most of the papers delivered at the International Conference on Fire Behaviour and Risk, which held in Alghero (Sardinia, Italy) in October 2011. The Conference was organized in the framework of the European Project Proterina-C, Italia-Francia Marittimo Programme, co-sponsored by the Global Fire Monitoring Center (GFMC), an action of the UN International Strategy for Disaster Reduction (UN-ISDR), under the patronage of University of Sassari, the Euro-Mediterranean Centre for Climate Change (CMCC), the Regional Administration of Sardinia, and the Province Administration of Sassari. The Project involved three cross-border regions (Sardinia, Corsica, Liguria), which face similar several environmental issues, among which fire is one of the main concerns, especially in the Mediterranean Basin.

Fire is a complex phenomenon caused mainly by human activities, and we are still learning how to bind and fight fires. The purpose for this volume is to present key main results of the project activities and to review the most relevant research results from other countries. In addition, the volume represents a step ahead in disseminating recent and relevant scientific results and advances in forest fire research.

The relationship between humans and fire can be traced to the origin of our civilization. Since ancient times, fire has been considered as a sacred and powerful element. In the Greek mythology, fire could be used only by Gods. When Prometheus stole a spark from the Olympus and gave it to mankind, humans gained warmth and light. Caves were no longer dark and life became safer.

However, *fire is a good servant, but a bad master*. It has to be kept under control. Once it is out of control, it has the ability to take away lives and destroy property. In Sardinia, we have dramatically experienced that a small number of fires with extreme behaviour can account for the widest impacts on forest ecosystems and for the hugest damage to properties, along with loss of human lives.

It is, therefore, critical that the continuous progress in knowledge on fire drivers and causes, together with the advancements in technologies and modeling approaches and the awareness of population and politicians about the risk associated, are the keystones and the scientific bases for the prevention and management activities in order to reduce the risk associated with fires.

This volume gathers the contributions of the prominent researchers to scientific and operational knowledge of wildland fires at international level. It is a comprehensive source of information in answering the demands from international, national, and local Institutions, which expect improvements in knowledge, innovation, and operational tools to face the wildfire issue and support the planning fuel management and urban development.

The University of Sassari is grateful to the research group of the Department of Nature and Environmental Sciences for promoting and conducting outstanding research and teaching activities in the field of fire research. I would recall the involvement in the EU cooperative FUME (*Forest fire under climate, social and economic changes in Europe, the Mediterranean and other fire-affected areas of the world*), which is currently the most important European project with more than 35 partners. The projects funded by the Sardinia

Administration to deal with this serious concern should also be mentioned. Also, I would highlight the Course on Fire Behaviour Analyst, started in 2009, that provides extensive training to the officers of the Sardinian Forest Service; the imminent startup of the International Master PIROS on Planning, Prevention and Control of Wildland Fires in the Mediterranean Area. A particular note should be made about the upcoming International Summer School on Fire Risk Prevention and Assessment in Mediterranean Areas that will be held in Alghero in June 2012.

Moreover, the University of Sassari supports International Programs promoting exchange and sharing of knowledge between our researchers and other reputable research centers worldwide. Some of the authors who contributed to this volume participated in the Visiting Program in the past years, and many other researchers are expressing their interest to further their research in Sardinia.

On this basis, the University of Sassari represents and will represent in the future a point of reference for the wildfire issue, with several initiatives ranging from local scale to Euro-Mediterranean areas.

Attilio Mastino

President of the University of Sassari

INTRODUCTION

The Mediterranean basin ecosystems are exceptionally sensitive and vulnerable to anthropogenic disturbances, and fire is one of the most significant threats for the Mediterranean forested areas. Over the last three decades, forest fires have showed an increase in both occurrence and number of extreme fire seasons. Moreover, a growing number of fires threats the wildland-urban interface, with a high potential risk for safety and damage for villages, tourist resorts, and other human activities. Therefore, the development of fire management policies is required to reduce the wildland and wildland-urban interface fire risk by applying methods and models for planning the operational phases of fire management. In the Mediterranean countries, considerable knowledge, several tools, and adapted methodologies typical for each country were developed to help in improving the efficiency of forest fire prevention and suppression systems. Some of these tools are efficient and should be shared with others.

In this framework, the Project PROTERINA-C aimed to focus on the interplay between climate changes and risks, providing common tools to prevent and reduce the negative effects of climate variability on risk conditions.

Key elements of the Project were the training programs for local governments and the information campaigns for the population facing fire risks. The Project aims at expanding the fire prevention culture, from communication and education programs to scientific results sharing. In this context, the International Conference on Fire Behaviour and Risk (an initiative of the Proterina-C Project held in Alghero in 2011) represented a relevant milestone in sharing scientific results, information, and experiences among Mediterranean and extra-Mediterranean countries and contributing to the enrichment of forest fire knowledge, prevention, and suppression.

This volume, titled “Modelling Fire Behaviour and Risk”, which collects the works presented during the International Conference, the Department of Science for Nature and Environmental Resources (DipNeT), is a step forward in the dissemination of relevant scientific results and advances in forest fire research. The volume illustrates the contribution of researchers to scientific and operational knowledge of wildland fire, with particular attention paid to fire behaviour and risk modelling, relationships between climate change and fires, and fire risk impacts at wildland-urban interface.

The report is organized in four sections, reflecting the main theme related to a better understanding of fire behaviour and risk modelling. The first section is focused on the theme of the relationship between Vegetation and Fire, emphasizing that an accurate knowledge and comprehensive description of fuel characteristics and conditions are critical matters in fire prevention, fire danger, and fire behaviour understanding. The second section, “Climate and Fire”, presents an investigation and analysis of weather and climate conditions that influence forest fires and directly affect fire ignition, spread, and severity. Finally, the last two sections deal with the modelling of fire behaviour, risks, and impacts on the wildland-urban interface. Several papers presenting the most recent advances in modelling techniques and fire danger forecast attest the high specialization achieved by the scientific community. In addition, the wildland-urban interface becomes a global issue, in particular in areas where fires coexist with human presence in dwellings and settlements.

Researches attempted to close the gaps in the research and understanding of the WUI challenges, its characterization, and extent.

We would like to thank all the authors for their interest and contribution to this volume.

Yours sincerely,

The Editors:

Donatella Spano	Valentina Bacciu	Michele Salis	Costantino Sirca
Donatella Spano	Valentina Bacciu	Michele Salis	Costantino Sirca

PROTERINA-C PROJECT

The Project Proterina-C “*A forecast and prevention system for climate change impacts on risk variability for wildlands and urban areas*” (EU Italia-Francia Marittimo 2007-2013 Programme) explores climate change impacts on wildlands and anthropic areas, with particular emphasis made on the interplay between climate changes and accompanying risks. The study areas are Sardinia, Corsica, and Liguria that are similar in terms of topography and land use. The main objective is to provide efficient tools to prevent and reduce the negative effects of climate variability on risk conditions. Another important aim of PROTERINA-C is to investigate the effects of climate on fuel characteristics. Fire danger and behaviour models are used to evaluate the interactions between climate changes and fires. The Project also discusses communication and education programs integrated into wildland fire management.

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EDITORS

DONATELLA SPANO

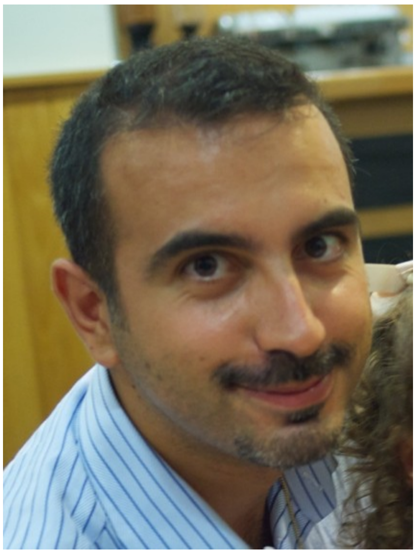
Professor at the Department of Science for Nature and Environmental Resources (DipNeT) at the University of Sassari and coordinator of the Euro-Mediterranean Center on Climate Changes (CMCC) Unit in Sassari, Italy. She is Chair of the PhD Course on Agrometeorology and Ecophysiology. Appointed to the Italian Department of Civil Protection - National Committee on Natural Hazards, subcommittee on Forest Fire. She is serving as Pro Rector of Scientific Research at the University of Sassari.
She is a biometeorogist with relevant experience on research activity on the interaction between the lower atmosphere and vegetative surfaces with emphasis on the development and refinement of micrometeorological methods for estimating evapotranspiration and CO_2 exchanges. Most recent research effort is directed towards the development and testing of wildfire risk and forecasting models and the assessment of climate change impacts on agricultural and forest ecosystems. She is involved as principle investigator in several national and international research projects and authored and co-authored more than 150 national and international scientific papers.

VALENTINA BACCIU

Junior Researcher at the Euro-Mediterranean Center on Climate Changes (CMCC) Unit in Sassari, Italy. She received her PhD degree in Agrometeorology and Ecophysiology of Agricultural and Natural Ecosystems from the University of Sassari with a dissertation in *Maquis fuel model development to support spatially explicit fire modeling applications*.

She actively contributed to several European, National and Regional projects within the DipNet and CMCC, and authored and co-authored national and international scientific papers. Her most recent research includes (1) the analysis of the relationship between weather/climate and fire, (2) the description and mapping of fuel characteristics from extrinsic and intrinsic point of view, (3) the investigation of first order fire effect modeling approaches.

MICHELE SALIS



Assistant Researcher at the University of Sassari, and Junior Researcher at the Euro-Mediterranean Center on Climate Changes (CMCC), IAFENT Division of Sassari, Italy. He received his PhD degree in Agrometeorology and Ecophysiology of Agricultural and Natural Ecosystems on February 2008 at the University of Sassari, with a dissertation on "Fire behaviour simulation in Mediterranean areas using FARSITE".

He is actively involved in several European, National and Regional projects within DIPNET and CMCC.

He participated to several international workshops and Conferences and he is author and co-author of international scientific papers. He participated as lecturer to National and International Courses. Visiting Researcher at the USDA Forest Service in summer 2010. His research focuses on (1) fire behaviour and risk modelling, (2) evaluation of the impacts of future climate changes on fires in Mediterranean areas, (3) analysis and modeling of historical fires.

COSTANTINO SIRCA

Researcher at the University of Sassari (Italy), and collaborator of the Euro-Mediterranean Centre for Climate Change (CMCC). PhD on Agrometeorology. His main research fields are related to: a) fire danger modeling in the Mediterranean areas; b) fire-weather relationship; c) fuel moisture modeling; ecophysiology of Mediterranean vegetation, especially under water stress; d) ecosystems water status assessment using micrometeorological techniques.

He is involved in several national and international research projects, and has experience in international courses. He is coauthor of more than 70 contributes in peer rewieved journals, conferences, national and international meetings abstracts and papers.

Photo © Sandro Tedde, *Sardinian Forest*, 2011. Sant'Antonio di Macomer, Italy.

VEGETATION AND FIRES

Fuel types and potential fire behaviour in Sardinia and Corsica islands: a pilot study

Duce P.[1], Pellizzaro G.[1], Arca B.[1], Bacciu V.[2,3], Salis M.[2,3], Spano D.[2,3], Santoni P.A.[4], Barboni T.[4], Leroy V.[4], Cancellieri D.[4], Leoni E.[4], Ferrat L.[4], Perez Y.[4]

[1]National Research Council of Italy, Institute of Biometeorology (CNR-IBIMET), Sassari, Italy; [2]Department of Science of Nature and Environmental Resources (DipNet), University of Sassari, Italy; [3]Euro-Mediterranean Center for Climate Changes, IAFENT Division, Sassari, Italy; [4]SPE UMR 6134 CNRS – University of Corsica Corte, France

p.duce@ibimet.cnr.it, vbacciu@uniss.it, santoni@univ-corse.fr

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Abstract

One of the goals of the EU PROTERINA-C project (Programme Italy-France Maritime 2007-2013) is to evaluate the fire danger in Mediterranean areas and characterize the vegetation parameters involved in the combustion process. Therefore, specific project activities were focused on i) identifying and describing the different fuel types mainly affected by fire occurrence in Sardinia and Corsica islands and ii) developing custom fuel models for Mediterranean vegetation. In the first part of the work, field sampling sites were randomly located on selected vegetation types historically affected by fires in Sardinia and Corsica islands. The following variables were collected: live and dead fuel load, depth of the fuel layer, plant cover. In the second part of the work, a cluster analysis algorithm was used to identify fuel types by grouping fuel variables collected in the field. A set of custom fuel models was then developed. Finally, the potential fire behaviour for every custom fuel model was calculated by Behave Plus fire behaviour prediction system using two different weather scenarios typical of summer conditions.

Keywords: Proterina-C, fuel characteristics, potential fire behaviour, custom fuel models

1. INTRODUCTION

An accurate knowledge and comprehensive description of fuel characteristics and conditions has shown to be a critical matter in fire danger description (Deeming et al. 1977), and fire effects prediction (e.g. Reinhardt et al. 1997). Knowledge of natural fuel loads (biomass weights) and species composition is also critical for improving current fire prevention and fire behaviour modeling programs (Tian et al. 2005). During the last decade, considerable effort has been devoted to fuel characterization (e.g. Dimitrakopoulos 2002; Keane et al. 2001; Sandberg et al. 2001, Fernandes et al. 2006). Several fuel type classifications have been developed and are currently employed by different forest management services around the world (e.g. NFDR, Deeming et al. 1977; ICONA 1990; FCCS, Ottmar et al. 2007). However, in several European countries, for example in France and Italy, the systematic analysis of vegetation characteristics related to fire behaviour and risk is still a relevant issues that need to be addressed.

This study is a comprehensive, collaborative effort conducted under Proterina-C Project to identify and describe the different fuel types mainly affected by fire occurrence in Sardinia and Corsica islands and provide a set of fuel models for the main Mediterranean maquis associations.

2. MATERIAL AND METHODS

Experimental activities were performed in 12 experimental sites, 4 in south-east Corsica island (France) and 8 in western Sardinia island (Italy) (Figure 1). All sites are characterized by different types of Mediterranean shrub community, as reported in Table 1. The climate along the coast line of both regions is sub-arid with a remarkable water deficit from May to September.

Figure 1. Study areas and experimental sites in Sardinia and Corsica

Fuel characteristics were determined on five 2x2 m sampling plots along a transect in each test site. In Letia site (Corsica), which is characterized by a high homogeneity of vegetation, measurements were carried out only on two plots. Therefore, the analysis included a set of 57 plots. Each plot was ideally partitioned into 16 quadrants and the height of the prevailing plant species was measured on each quadrant. Plant cover and dominant species were also surveyed and sketched on a "plot description" form. The images were analysed using AutoCAD map 2002 (Autodesk Inc., San Rafael CA, USA) to calculate the area covered by each species. All plant material inside each plot was clipped at the ground line, divided into biomass and necromass, and weighed. Litter was sampled by dividing the plot in four quadrats and collecting a sample from each quadrat using a 0.13 m x 0.13 m sampling frame. In laboratory all shrub parts were separated into size classes by diameter: 0 to 0.6 cm (fine fuels), 0.6 to 2.5 cm (medium branches), and 2.5 to 7.5 cm (thick branches) (Roussopoulos and Loomis 1979; Martin et al. 1981; Brown 1982). The size classes we used correspond to the 1h, 10h, and 100h time-lag fuel categories described in literature (Deeming et al. 1972). Each sample was weighed and a sub-sample (about 20% of total weight) was oven dried at 100°C until constant weight, in order to measure the dry weight. The surface volume ratio (SAV) of live fuel was also measured for the following species: *Arbutus unedo, Cistus monspeliensis, Genista salzmannii, Olea oleaster, Phyllirea angustifolia, Pinus pinaster, Pistacia lentiscus,* and *Erica arborea.*

Hierarchical cluster analysis using Euclidean distances and Ward's method was used to identify homogeneous fuel type groups, (e.g. McCune and Grace 2002; Poulos et al. 2007). Cluster analysis was performed by SYSTAT 13 statistical software package. The average property values of all the plots classified into the same cluster were assigned to each homogeneous fuel type group. Then, the ANOVA and LSD post-hoc tests were performed to test statistical differences in fuel bed characteristics across the groups. Experimental data grouped according to fuel types were also generalized adapting the methodology proposed by Burgan and Rothermel (1984) and used in BehavePlus 3.0 (Andrews et al. 2005), and custom fuel models describing maquis vegetation were developed.

As suggested by Burgan and Rothermel (1984), the depth of the fuel layer was set equal to 70% of the maximum depth. Moisture of extinction values we used derive from observations made on Mediterranean maquis by several authors. In addition, the standard values proposed by Anderson (1982), Pyne et al. (1996) and Scott and Burgan (2005) were used for the fuel heat content. Live SAV values were obtained comparing experimental data with data from literature.

BehavePlus 3.0 (Andrews et al. 2005) was run to evaluate the potential fire behaviour using as input data the fuel variable values of each custom fuel model. The fire behaviour simulations were performed by setting two different fuel moisture content scenarios (dry and wet). Wet scenario represents fuel moisture content typical of a medium summer season in Sardinia and Corsica, whereas for dry scenario, fuel moisture condition typical of extreme weather summer conditions were used (Table 2). The simulations were performed assuming burning wind speed at 15 km h^{-1}. All fire behaviour simulations were referred to horizontal terrain.

Table 1. Dominant species and average vegetation height by site

Site	Code	Dominant species	Average height (m)
La Corte 1	S-LC1	*Myrtus communis, Pistacia lentiscus*	1.0
La Corte 2	S-LC2	*Pistacia lentiscus, Herbaceous*	0.7
La Corte 3	S-LC3	*Myrtus communis, Chamaerops humilis*	1.0
Porto Palmas	S-PP	*Cistus salvifolius, Calicotome spinosa*	0.8
Rumanedda	S-RU	*Myrtus communis, Pistacia lentiscus*	1.2
Monte Doglia 1	S-MD1	*Cistus monspeliensis, Chamaerops humilis*	0.5
Monte Doglia 2	S-MD2	*Cistus monspeliensis, Chamaerops humilis*	1.0
Monte Forte	S-MF	*Arbutus unedo, Erica arborea*	2.4
Favonia	C-FA	*Cistus monspeliensis*	1.0
Letia	C-LE	*Genista salzmannii*	>0.5
Bonifacio	C-BO	*Mediterranean shrubs*	1.5
Vallée du Cavu	C-VC	*Heterogeneous understorey of Pinus pinaster (Erica arborea, Arbutus unedo)*	3.0

Table 2. Summer moderate and extreme conditions for fuel moisture used for fire behaviour simulations

Burning condition	Fuel moisture (%)				
	1-hr	10-hr	100-hr	Live herbaceous	Live shrubs
wet	12	13	14	60	80
dry	6	7	8	30	60

3. RESULTS AND CONCLUSIONS

Cluster analysis allowed to identify four different fuel types. As derived from the ANOVA and LSD post-hoc tests, the four fuel types differ mainly in live fine shrub load, litter load, cover percentage and height (Figure 2).

Fuel type I differs significantly from the other fuel types for both the lowest height and cover percentage. It shows a fuel load lower than the other fuel types, especially in term of live fuel and litter. It is characterized by a high proportion of live fine load (foliage and twig smaller than 0.6 cm) over total fuel load (50%); the dead fine fuel component contributes for the 14% of the total shrub fuel load. Fuel type II is characterized by a taller and denser structure than type I. In particular, the height of fuel bed and the amount of live fine load show to be significantly different from the other fuel types, whereas litter load and cover percentage values are intermediate between fuel type I and III.

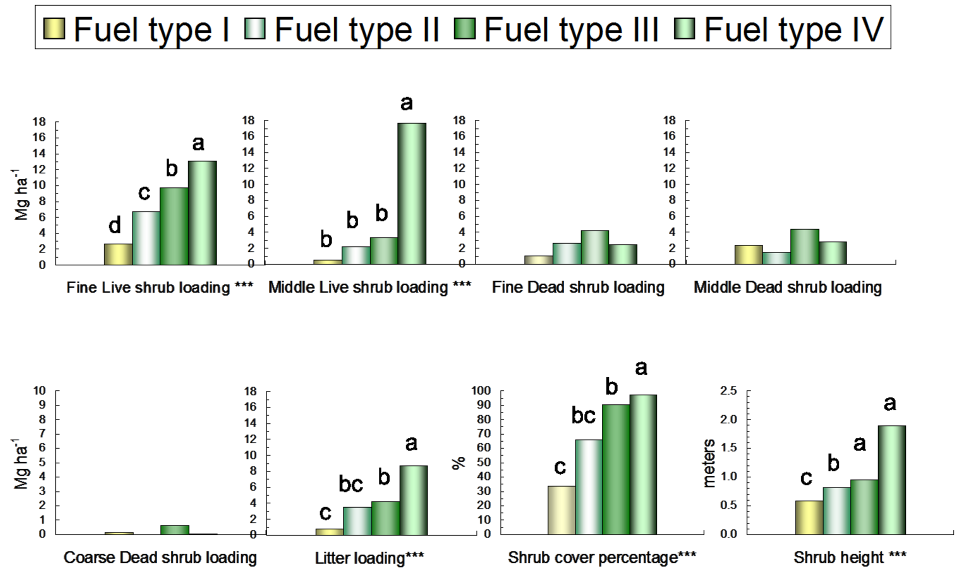

*Figure 2. Mean values and significant differences of fuel bed variables among fuel types obtained from the hierarchical cluster analysis. *** indicates significant differences level (P<0.001) between fuel models according to ANOVA. Different letters indicate significant differences (p< 0.05) by LSD post hoc test.*

Fuel variable values of fuel type III are significantly different in height, amount of live fine load and cover percentage when compared to the other fuel types. In this case, live fine load contributes for about the 40% of the total shrub fuel load. Fuel type IV is representative of a mature and high maquis. The properties that characterize fuel type IV from the other three groups are the closed canopy, the fuel bed depth and the amount of live fuel load. It shows the highest amount of middle live fuel load. Live fuel contributes for about the 70% of total shrub fuel load.

Four custom fuel models (CFM) of Mediterranean shrubs were then developed (Table 3). CFM I describes a low and sparse shrubland fuel complex, CMF II is representative of a low and dense shrubland fuel complex, CFM III represents a shrubland fuel complex of medium height and dense cover and, finally, CFM IV illustrates a high and closed shrubland fuel complex.

The outputs from fire behaviour simulation (Surface rate of spread, Fireline intensity, Flame length, and Heat per unit area) indicate that all CFMs had a more severe fire behaviour in dry conditions. In particular, CFM IV had the most severe fire potential in both extreme and moderate weather condition (Figure 3). This behaviour is mainly due to the higher amount of fine fuel loading than the others CFMs. The CFM I, which describes a low and sparse shrubland fuel complex, presents the lowest fire danger in both weather conditions due to the very low fuel load. This pattern is especially evident for CFM IV. In this fuel model, live fuel contributes for about the 45% of total load and can be considered the primary contributor to that high value of fire rate of spread. Extreme weather conditions strongly affect moisture content of live fine fuel in most Mediterranean shrubs. In these situations live fuel component becomes really dry and, therefore, more favorable for ignition and propagation.

Table 3. Custom fuel model parameters. LH: live herbaceous; LS: live shrub; SAV: surface area to volume ratio; ME: moisture of extinction.

	Fuel loading (Mg ha^{-1})									
Fuel model	1 hr	10 hr	100 hr	LH	LS	1hr SAV	Live SAV	Fuel bed depth (m)	ME (%)	Heat content (kJ kg^{-1})
CFM I	3.29	3.27	0.16	0.33	2.65	2460	4418	0.70	25	18622
CFM II	6.39	2.48	0.00	0.07	6.72		3573	0.91		
CFM III	8.65	5.40	0.64	0.41	9.76		4464	1.02		
CFM IV	11.50	4.42	0.06	0.06	13.04		5539	1.75		

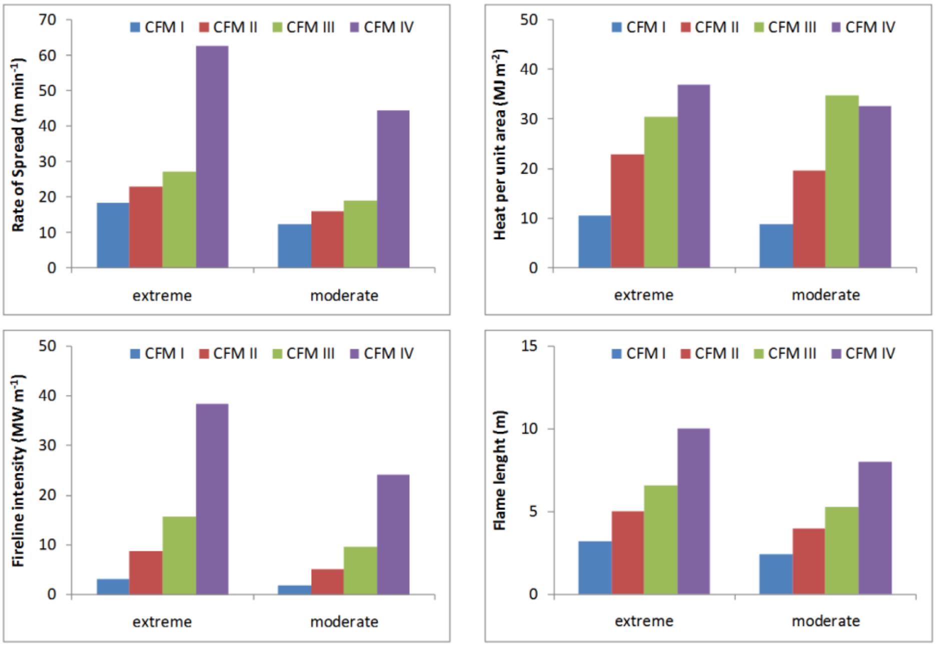

Figure 3. Fire behaviour simulation output (Rate of spread, Fireline intensity, Flame length, and Heat per unit area) for the four custom fuel models

4. ACKOWLEDGEMENT

This work has been partially carried out within the project PROTERINA-C (*A system for the forecast and the prevention of the impact of the variability of the climatic conditions on* *the risk for the natural and urbanized environment*), funded by the EU (2009-2011), "Obiettivo 3 Italia-Francia Marittimo" program.

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The potential of remote sensing measurements of canopy reflectance for the evaluation of live fuel moisture content and fire hazard mapping

Maffei C., Menenti M.

Delft University of Technology, Stevinweg 1, 2628 CN Delft, The Netherlands

c.maffei@tudelft.nl

Abstract

Many authors demonstrated the role of remote sensing in the assessment of vegetation equivalent water thickness (EWT), which is defined as the weight of leaf liquid water per unit of leaf surface. However, fire models rely on the fuel moisture content (FMC) as a measure of vegetation water. FMC is defined as the ratio of the weight of the liquid water in a leaf over the weight of dry matter, and its retrieval from remote sensing measurements might be problematic, since it does not provide specific spectral features. The aim of this research was to explore the potential of the Moderate Resolution Imaging Spectrometer (MODIS) in retrieving FMC from top of the canopy reflectance. To this purpose, a dataset of synthetic canopy spectra was constructed coupling PROSPECT and SAIL radiative transfer models. Reflectance spectra were then convolved to MODIS channels 2 (0.86 µm) and 5 (1.24 µm) spectral response functions. Results show that isolines of FMC can be identified in the plane representing MODIS measurements in channels 2 and 5. These observations allowed for the construction of a novel spectral index that is directly related to FMC. It appears that the proposed indicator is robust to all variable factors affecting canopy reflectance except leaf area index (LAI). The index explains most of the variability in FMC when LAI is large enough (R^2=0.68 when LAI>2; R^2=0.89 when LAI>4), while decreasing values of LAI enhance the effect of soil background on the observed relationship between the index and FMC, degrading it.

Keywords: Fire risk, equivalent water thickness, fuel moisture content, PROSPECT, SAIL, MODIS.

1. INTRODUCTION

Considerable economic resources are spent every year in fire detection and suppression (FAO 2007), whereas the development of advanced tools for fire prevention might have a beneficial effect on the final socio-economic and environmental costs related to the phenomenon (Riera and Mogas 2004). This outlines a clear need for a fast and reliable method to forecast fire hazard and support fire managers in the allocation of resources.

Several factors contribute to fire hazard, including the relative amount of fuels available for burning, their type and their condition, specifically moisture content (FAO 1986). Among these, fuel moisture is the most dynamic; it is also the most relevant, since it determines the forests susceptibility to fire ignition and propagation (Rothermel 1972).

A common measure of water content in leaf tissues adopted by the remote sensing community is the equivalent water thickness (EWT), which is defined as the weight of water per unit area of leaf:

$$EWT = \frac{W_f - W_d}{A} \tag{1}$$

where W_f is the weight of the fresh leaf as measured in the field, W_d is the corresponding weight of the same leaf that has been oven dried, and A is leaf area.

Various spectral indexes were proposed for the quantification of EWT from broad-band optical remote sensing reflectance measurements in the near infrared (NIR) and short-wave infrared (SWIR), such as the Moisture Stress Index (Hunt and Rock 1989), the Normalised Difference Water Index (Gao 1996), and the Global Vegetation Moisture Index (Ceccato et al. 2002), However, fire hazard and fire propagation models rely on a different measure of vegetation water (Finney 2004), the fuel moisture content (FMC), which expresses the percentage weight of water in leaf tissues over the dry leaf weight:

$$FMC = \frac{(W_f - W_d)}{W_d} \square 100 \tag{2}$$

Spectral indexes for the estimation of EWT exhibit poor performance in estimating FMC (Danson and Bowyer 2004). This is due to the fact that, as opposed to EWT, FMC does not provide specific spectral features in vegetation reflectance (Gao and Goetz 1990). To overcome this limitation, methods based on the inversion of a radiative transfer model (RTM) were proposed, but they need extensive ground measurements for the parameterisation of the retrieval strategy in order to provide accurate results (Yebra and Chuvieco 2009).

Despite the outlined limitations, a spectral index sensitive to FMC is highly desirable, in order to provide for a simple and fast measure of a biophysical property specifically used to model fire hazard. Spectral indexes have a clear advantage over radiative transfer model inversion methods (Dasgupta et al. 2007), since their simplicity allows for the near-real time processing of remote sensing data at ground reception facilities, such as those permitted by MODIS, and the fast delivery of vegetation moisture maps to local authorities.

The objectives of the research described in this article were the development of a MODIS based spectral index that would not track the outlined limitations of traditional vegetation moisture indexes, and the understanding of its potential and limitations.

2. MATERIALS AND METHODS

The Moderate Resolution Imaging Spectroradiometer (MODIS) is an Earth observation instrument on board Terra (EOS AM-1) and Aqua (EOS PM-1) NASA satellites. Each MODIS system views the entire Earth's surface on almost a daily basis, acquiring data in 36 spectral channels ranging from the optical to the thermal domains.

Simulated top of the canopy (TOC) reflectance data were produced coupling PROSPECT and SAIL models. PROSPECT (Jacquemoud and Baret 1990) is an RTM that simulates spectral reflectance and transmittance of plant leaves. Four parameters are required: chlorophyll a+b concentration C_{ab} (in μg/cm^2), EWT (in g/cm^2), dry matter content (DMC, in g/cm^2), and a leaf structural parameter N. With this model a wide range of leaf spectra can be simulated, corresponding to a variety of physiological conditions. Leaf reflectance and transmittance were scaled to TOC reflectance by using SAIL model (Verhoef 1984), which requires information on leaf area index (LAI), average leaf angle (ALA), hot-spot size, background spectrum, and on view and illumination geometry.

To simulate TOC reflectance, input parameters to PROSPECT and SAIL models were chosen from random uniform distributions, as specified in Table 1; the only exception was the hot-spot size, which was kept constant. A total of 1000 spectra were produced, 100 for each of the FMC values between 50 and 500% in steps of 50%. In order to simulate the values of FMC in the specified steps, for each value of FMC, EWT was first randomly chosen according to ranges in Table 1; the corresponding DMC value was then computed accordingly. The couple of values EWT + DMC was actually retained only if the calculated DMC was within the ranges in Table 1, otherwise a new couple of values was iteratively generated until the given constraints were met.

Table 1. Values of the parameters adopted to run PROSPECT and SAIL; observation geometry is set accordingly to MODIS specifications with random view angle along the scan line.

PROSPECT parameters		SAIL parameters	
N	1 - 3	LAI	0.5 - 7
C_{ab} (µg/cm^2)	20 - 60	ALA	45 - 75
EWT (g/cm^2)	0.01 - 0.07	Hot-spot size	0.001
DMC (g/cm^2)	0.004 - 0.04	Soil spectrum	Dark to medium
		Sun zenith angle (deg)	40 - 60

All produced TOC reflectance spectra were converted to MODIS reflectance basing on channels' spectral response functions (Xiong et al. 2006). Vegetation moisture is the main source of variability in the SWIR (Ceccato et al. 2001; Danson and Bowyer 2004). Three MODIS channels are in this spectral range, centred at 1.24 µm (channel 5), 1.64 µm (channel 6) and 2.13 µm (channel 7). Spectral indexes of vegetation moisture usually rely on NIR reflectance as well (e.g. MODIS channel 2, centred at 0.86 µm), using it as a normalising factor (Gao 1996; Ceccato et al. 2002). In this research only channels 2 and 5 were taken into consideration for the development of the spectral index.

The construction of the spectral index followed the theory and methodologies introduced by Verstraete and Pinty (1996). Basically, the simulated dataset was first analysed in the Cartesian plane whose axes are MODIS reflectance channels 2 and 5. Isolines of FMC were then identified and characterised along with disturbing factors. This finally led to the definition of a new spectral index whose variation corresponds to a displacement in the spectral plane that is perpendicular to isolines of FMC, in order to maximise its sensitivity.

3. RESULTS

A preliminary analysis was performed on the graph representing simulated data points on a Cartesian plane whose axes are MODIS reflectance in channels 2 and 5 (Figure 1). The adopted ranges of PROSPECT and SAIL parameters imply considerable variability in simulated reflectance values. In order to facilitate visual inspection, only a subset of simulated data were plotted, specifically points with FMC values of 50, 200 and 500%.

Points with different values of FMC clearly overlap; nevertheless, there is evidence of separability. For each group of points with the same value of FMC, the observed dispersion appears to depart from a dense alignment of points towards lower values of reflectance in channel 2 and higher in channel 5.

Figure 2 shows a subset of the points in Figure 1, characterised by a simulated value of LAI greater than 4. It appears that when vegetation cover is dense, points with the same value of FMC align on a straight line with little variability. This clearly hints at the existence of isolines of FMC, at least in conditions of dense vegetation cover.

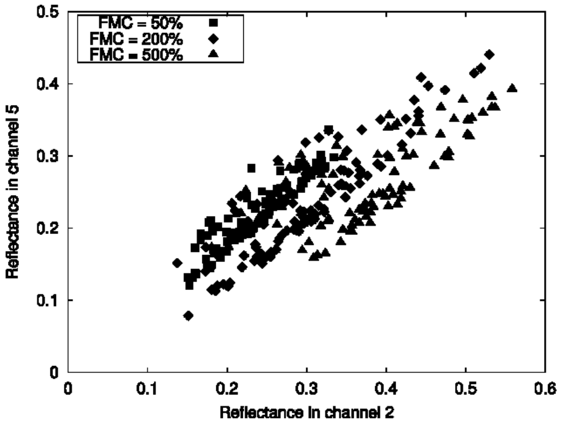

Figure 1. Distribution of simulated data points in the channel 5 vs channel 2 plane.

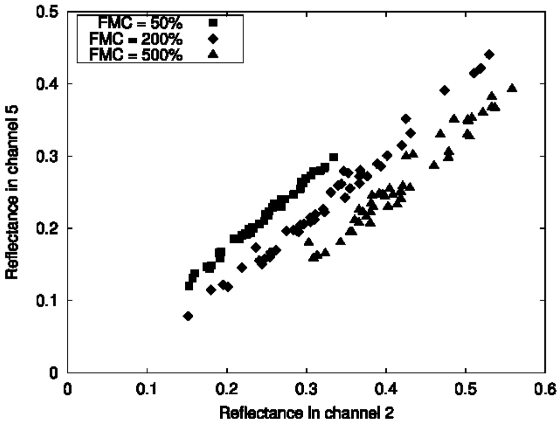

Figure 2. Distribution of simulated data points the channel 5 vs channel 2 plane. Only points corresponding to LAI>4 were plotted.

All linear regressions of the points with the same value of FMC and LAI>4 are strong and significant ($R^2>0.96$, $p<0.0001$), and were thus identified as FMC isolines. The slopes of all isolines overlap within their 95% confidence interval, and can be considered parallel. The lines shift towards higher NIR and lower SWIR reflectance values with increasing FMC.

Basing on these findings, a new spectral index was developed, defined as the distance of the measured reflectance in MODIS channels 2 and 5 from a reference line. Such line was assumed to be that of completely dry vegetation, i.e. FMC=0%, EWT=0, and the distance was calculated perpendicularly to it. We call this the perpendicular moisture index (PMI), and we calculate it as:

$$PMI = -0.73 \cdot (R5 - 0.94 \cdot R2 - 0.028) \qquad (3)$$

where R2 and R5 are reflectance values measured in channel 2 and channel 5 respectively.

The PMI is larger for larger values of FMC. However, its predictive power is dependent on the density of vegetation cover. The observed regression equations and coefficients of determination of the PMI vs FMC relationship are reported in Table 2 for all simulates data and for the subsets with LAI>2 and LAI>4. When all data points are taken into account, a poor predictive performance is observed. The relationship becomes stronger as LAI increases.

Table 2. Regression laws of the PMI vs FMC relationship.

	Regression law	R^2
All data	PMI= -0.12+0.034*log(FMC)	0.32
LAI > 2	PMI= -0.14+0.040*log(FMC)	0.68
LAI > 4	PMI= -0.17+0.047*log(FMC)	0.89

4. DISCUSSION AND CONCLUSIONS

Vegetation moisture is the main source of variability in the SWIR (Danson and Bowyer 2004). In its contribution to vegetation reflectance, the EWT plays the role of state variable of the radiative problem. This justifies the success of some spectral indexes in retrieving this measure of vegetation moisture. However, the wildland fires research community is interested in estimates of FMC, which actually is the ratio of EWT and DMC, two independent state variables of the same radiative problem. While this has been seen as a complication in the retrieval of FMC from broad-band remote sensing measurements in the optical domain, from the theory (Verstraete and Pinty 1996) the value of an environmental variable can indeed be estimated if it results in an observable variation in vegetation reflectance.

In this article, it is shown evidence that in the plane spanned by MODIS channels 2 and 5 vegetation reflectance lies on lines of constant FMC, at least for dense covers. Lines of decreasing values of FMC shift towards lower reflectance values in channel 2 and higher in channel 5. This means that in the spectral space a point representative of the observed vegetated area is displaced when FMC changes.

This observation was used for the construction of a novel spectral index, the PMI, sensitive to FMC. The effect of extraneous factors on this relationship was investigated as well. This was needed to understand how to eventually remove the effect of the factor, or to take it into account when dealing with the specific application (Seelig et al. 2008).

The retrieved relationship between FMC and PMI is essentially affected by LAI. Good results are achievable when LAI>2, which is a typical condition in a large variety of vegetation associations in the countries facing the Mediterranean basin. With decreasing values of LAI, the accuracy in the PMI vs FMC relationship decreases. Dispersion of points away from the observed isolines is towards lower reflectance values in channel 2 and higher in channel 5. This is due to the fact that when LAI diminishes, more soil is exposed and contributes to TOC reflectance.

From a practical point of view, with decreasing values of LAI, the dispersion of points is towards isolines of lower FMC. This means that in these circumstances the PMI underestimates vegetation moisture, which is safe from the point of view of fire prevention.

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Experimental investigation into dynamics of flame temperature characteristics during burning of combustible plant materials by IR methods

Loboda E.L.[1], Reyno V.V.[2]

[1]Tomsk State University, Tomsk, 36 Lenin Prospekt; [2]Zuev Institute of Atmospheric Optics, Tomsk, 1 Academician Zuev square

Loboda@mail.tsu.ru, reyno@iao.ru

Abstract

At present, IR-cameras are commonly used to measure temperatures in laboratory and full-scale experiments. They allow obtaining a good time and space discretization, which provides an opportunity to eliminate the use of thermocouple arrays, not damaging the structure of flame during combustion of different fuels. In this contest, there are a number of specific questions related to the determination of spectral range, emissivity coefficient, and multiple changes of temperature at a point over a short period of time in the case of research in flame temperatures during combustion of vegetable fuels. In this paper, we present the results of experimental studies using thermal combustion of vegetable fuels and frequency analysis of changes in temperature in the flame. The results are obtained using a thermal imager of vegetable fuel combustion and a frequency analysis of changes in the flame temperature.

Keywords: flame temperature, IR methods, Steppe plants

1. MATERIAL AND METHODS

Experiments were conducted in laboratory and full-scale conditions. The fuels were a mixture of steppe plant materials [*Elytrigia repens* (Couch grass), *Artemisia austriaca* (Austrian wormwood), *Festuca ovina* (Fescue or Sheep's fescue grass)] typical for the Karasuk area in the Novosibirsk Area, as well as pine needle litter. For measurements, an IR JADE J530SB Camera was used, equipped with a narrow-band optical filter in the range of 2.5-2.7 μm with image recording in real time up to 170 frames per second. The high speed of the thermal imager allowed performing good time and space data discretization at the location of thermocouples. The mass of fuels was measured with an AandD EK-1200G electronic balance with an accuracy of 10^{-2} kg. The moisture content of fuels was measured with an AandD MX-50 moisture analyzer with an accuracy of 0.01%. The air temperature, relative humidity, and atmospheric pressure were controlled by a Meteoscan RST01923 weather station.

The total relative errors of parameters did not exceed $\delta w/w \cdot 100\ \% \leq 3.3\ \%$ for moisture content, $\delta m/m \cdot 100\% \leq 1{,}2\ \%$ for mass, $\delta P_e/P_e \cdot 100\ \% \leq 6{,}0\ \%$ for atmospheric pressure, $\delta T/T \cdot 100\ \% \leq 5{,}3\ \%$ for air temperature, $\delta\varphi/\varphi \cdot 100\ \% \leq 2{,}5\ \%$ for relative air humidity, and $\delta t/t \cdot 100\ \% \leq 4{,}3\ \%$ for the time.

Temperature measurements were performed by using the arrays of chromel-alumel thermocouples located longitudinally and vertically relative to the surface of a fuel sample.

When measuring the flame temperature of spreading flame fronts (Grishin et al. 2011) it was observed the change in temperature for sufficiently short time intervals (Figure 1).

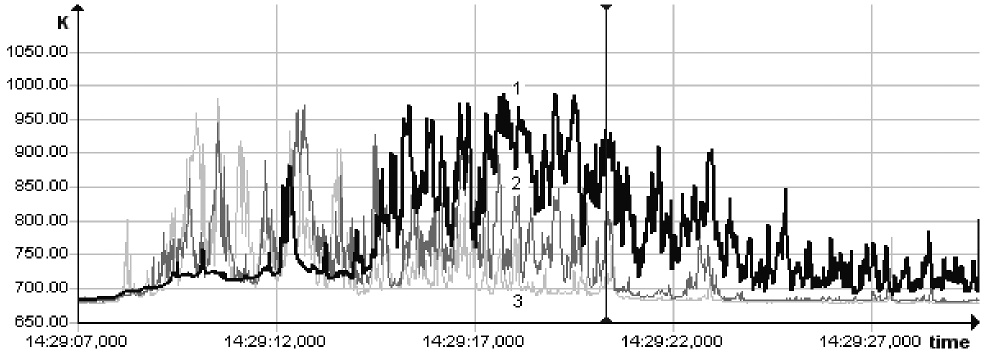

Figure 1. Flame front temperatures in the front of a steppe fire versus time at a height of 30 cm above the ground surface (curve 1), 60 cm (curve 2), 90 cm (curve 3).

Using the discrete Fourier transform, the frequency spectra of temperature changes were determined in the flame front. The input data were taken from the thermograms obtained during full-scale experiments (Grishin et al. 2011) conducted in the Karasuk area of the Novosibirsk Region. The vertical and horizontal lines located in the fire front were selected in the thermogram to choose 20 sequentially arranged points. Next, the spectra obtained for every point were averaged according to all the points on the line.

2. RESULTS

Figures 1 to 3 show the results of the Fourier transform for full-scale experiments. In Figure 1 the wind speed was varied during the experiment in the range of 0.2-1 m s, in Figure 2, 3-5 m/s, and in Figure 3, 5-8 m/s.

After analysing Figure 1 to 3, the characteristic frequency peaks were found to be in the range from 2 to 7 Hz. They become practically inexistent with increases in wind speed more than 5 m/s. For this reason, additional experiments were conducted in laboratory conditions.

Due to the fact that the JADE J530SB IR-cameras allow the temperature to be measured with frequency up to 170 Hz, it was possible to observe that the spatial structure of temperature changes very quickly in flame. The measurement scheme was used together with a channel of high-speed temperature recording; the discretization frequency was 500 Hz (16 bit). The measurement sensor was a tungsten-rhenium thermocouple (type TR) with a junction diameter of 50 μm. Next, a comparative analysis of the temperature variation versus time was carried out. The recorded data from thermal imagers according to characteristic frequencies were compared with the results of the high-speed thermocouples.

A mixture of steppe fuels (SF), which are typical of the Karasuk area, was used as a sample. The mass of the samples was varied from 50 to 200 g. The moisture content of the SF samples varied from 3.6 to 21.6%. The sequence of thermograms (one 42,500 frames implementation) and the temperature profiles were processed by discrete Fourier transforms. The input data were selected in the flame similarly (Figure 4).

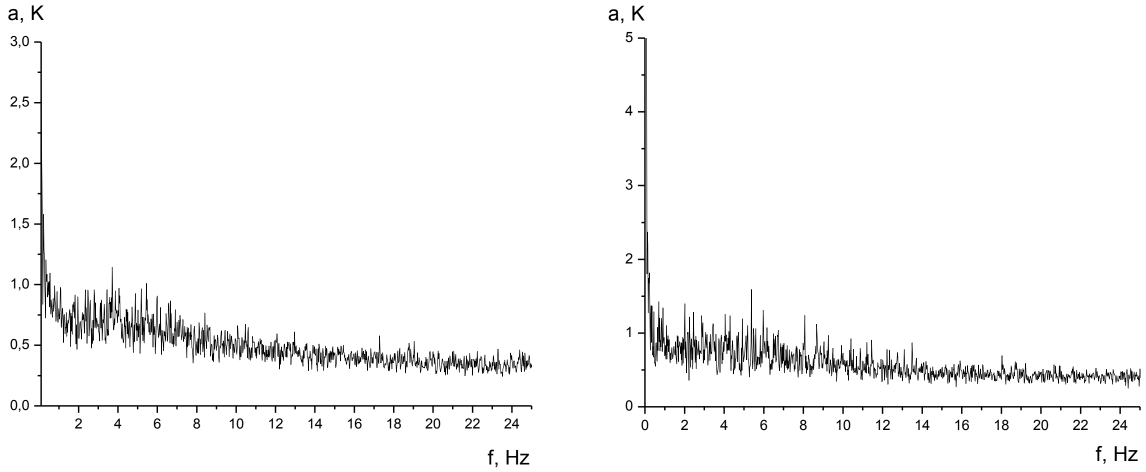

Figure 1. Frequency spectra of the flame temperature according to the JADE-J530SB IR-camera for the experiment with a wind speed of 0.2-1 m/s. Horizontal (left) and vertical (right) arrangements of measurement points are showed.

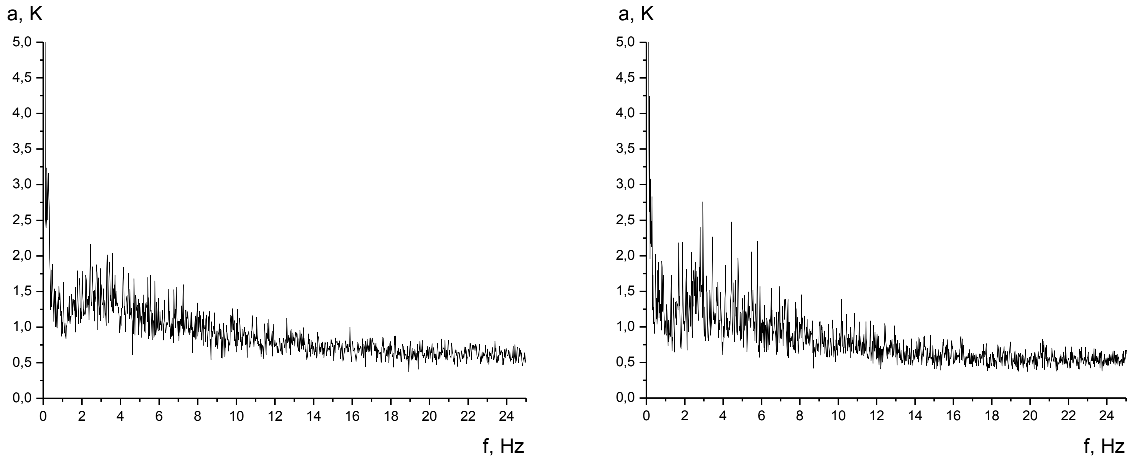

Figure 2. Frequency spectra of the flame temperature according to the JADE-J530SB thermal imager for the experiment with a wind speed of 3-5 m/s. Horizontal (left) and vertical (right) arrangements of measurement points are showed.

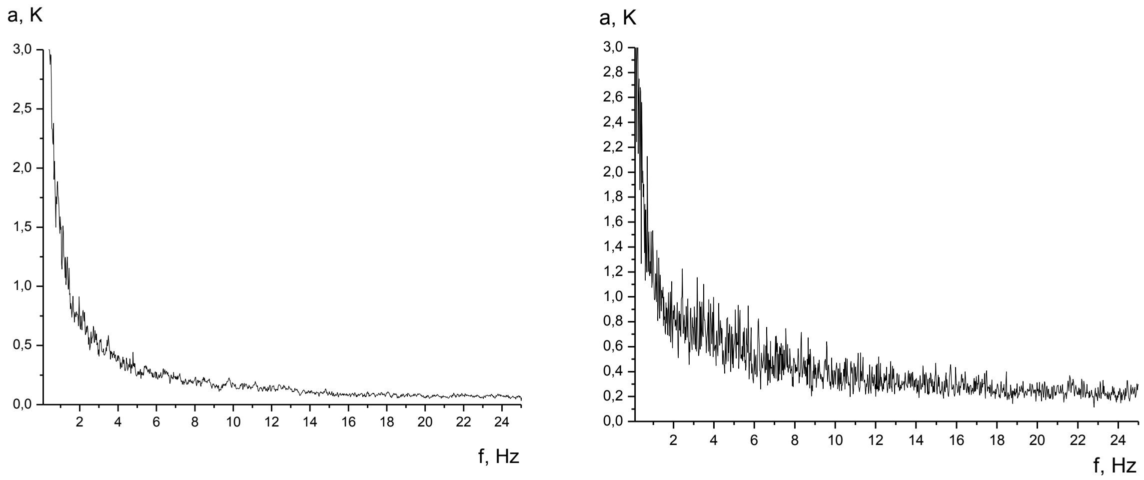

Figure 3. The frequency spectrum of the flame temperature according to the JADE-J530SB IR-camera for the experiment with a wind speed of 5-8 m/s. Horizontal (left) and vertical (right) arrangements of measurement points are showed.

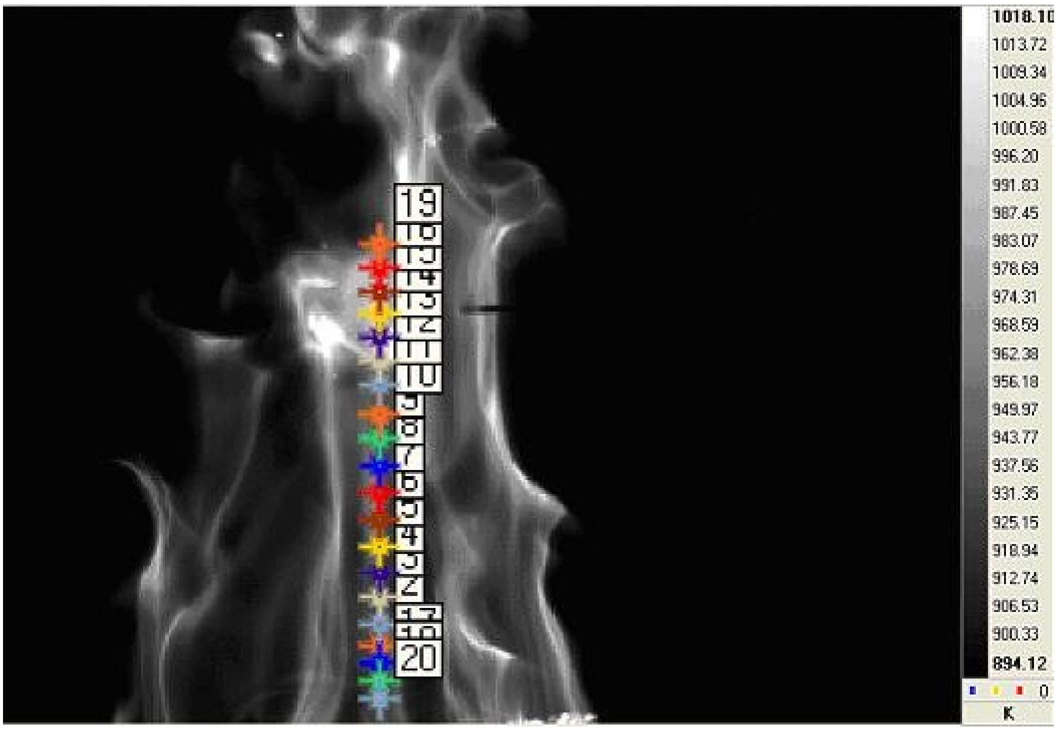

Figure 4. Thermogram of the flame during SF combustion, the emissivity coefficient is ε = 0.77, moisture content is w = 5.9%; and the spectral range is 2.5-2.7 µm.

Using discrete Fourier transforms, the frequency spectra of temperature were obtained at every point on a vertical line, and then they were averaged. Figure 5 (left) shows the averaged frequency spectrum of the temperature change for the points in Figure 3.

From Figure 5 (left) it can be seen that temperature fluctuations take place with a significant amplitude in a range of about 0.01 Hz. These values are not given in the graphs by reason of complexity to compare temperature fluctuations with other frequencies. In the range of 2.7 Hz there are characteristic frequency peaks of temperature fluctuations with an amplitude of up to 8 K.

Similar results were obtained for the points located on a horizontal line. These results allow us to conclude that these frequencies are characteristic for the physical process of combustion. To eliminate the influence of scale, the size of a combustion source, the mass and the moisture content of the samples were varied. These changes of parameters did not influence the frequency spectrum of the temperature.

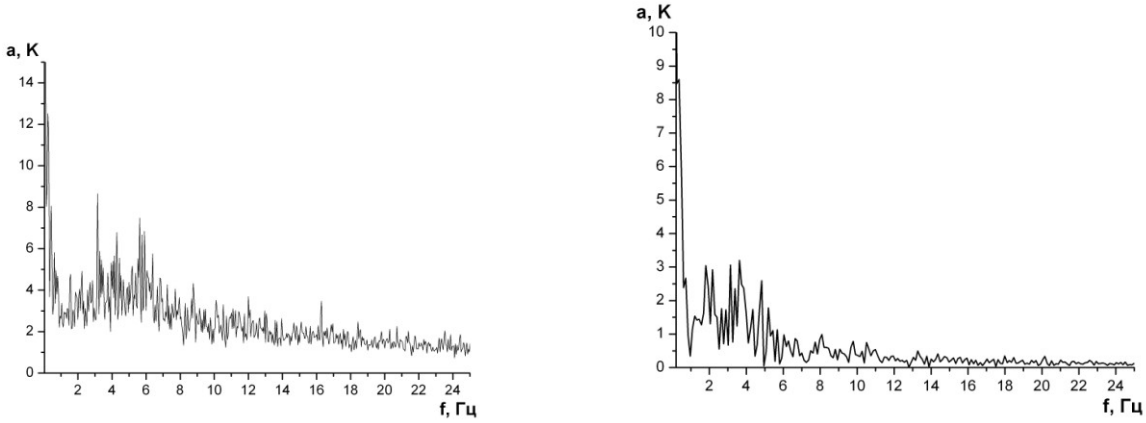

Figure 5. On the left, the frequency spectrum of the flame temperature according to the data of the JADE-J530SB IR-camera is showed. On the right, the frequency spectrum of the thermocouple temperatures in flames according to the tungsten-rhenium thermocouple (type TR) with a junction diameter of 50 µm is presented.

Figure 5 (right) shows the frequency spectrum of the thermocouple temperature for a data implementation 250 seconds. From Figures 4 (right) and 5 (left) it is seen that there are characteristic frequency peaks of temperature fluctuations with an amplitude of several degrees in the range of 2-6 Hz. Probably, the lower amplitude of the thermocouple temperature compared to the IR-camera readings is connected with the fact that the thermocouple changes the structure of flame and has some thermal inertia. In addition, if the combustible flow gas is low, then it is necessarily to take into account the loss of heat at the junction due to radiation and the heat conduction along the wires of the thermocouple (Lewis et al. 1957)

It should be noted that the coincidence of the frequency characteristics when measuring the temperature by both the IR-camera and the thermocouple illustrates the dependence of fluctuations on the physical processes of combustion. The work presented in Golovanov (1999) provides a frequency analysis for the temperatures measured by thermocouples during combustion of forest fuels, where the author points out the frequencies 7-6 Hz which, in the author’s opinion, are connected with the natural oscillations of PF elements.

This work was supported by the Grant of the President of the Russian Federation for State Support of Young Russian Scientists (project no. MK-4331.2011.1) and the Federal Science and Innovation Agency (project no. 02.740.11.0674).

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Study of the combustion of the evolved gases in wildland fires and the emission of pollutants: the effect of H2O

Perez Y., Santoni P.A., Leroy V., Leoni E.

CNRS UMR 6134 University of Corsica, Corte 20250, France
perez-ramirez@univ-corse.fr, santoni@univ-corse.fr

Abstract

Studies on combustion of the evolved gases in wildland fires are mainly focused on fire behaviour modelling. In these studies it is often assumed that the mixture of gases released from the thermal degradation of vegetation is composed only by CO_2 and CO. This assumption reduces the CPU time requirements, but it also removes important chemistry processes that can be important in determining fire behaviour and fire emissions. In this work it has been studied the role of the H_2O released during the thermal degradation of vegetation, on the combustion and on the emission of pollutants. For this purpose several simulations have been run using the CHEMKIN II package (PSR code) with two different detailed kinetic mechanisms (GRI-Mech 3.0 and GDF-kin® 3.0) and for different gaseous mixtures. The results obtained varied depending on the mechanism, but as a general tendency the presence of H_2O showed implications on the efficiency of the combustion and on the formation of certain pollutants.

Keywords: Global mechanism, gas oxidation, wildland fires combustion, pollutants emissions

1. INTRODUCTION

Combustion processes in wildland fires primarily involve the oxidation of the thermal decomposition products of vegetation (degradation or evolved gases and char). Although both gas-phase combustion and char oxidation lead to the release of heat, as well as the production of soot particles and other pollutants, fire spread is mainly sustained by the energy released from the gas-phase combustion reactions (Sullivan 2009). Consequently, the analysis of gas-phase combustion kinetics is decisive for wildland fire spread modelling.

Many current fully physical models of fire spread use simplified mixtures which consider only CO and CO_2 as the products released from the thermal degradation of vegetation. While considering a simplified composition of the degradation gases of vegetation can be a solution computationally economical, it can also remove important chemistry processes for determining fire behaviour and also fire emissions (Sullivan and Ball 2012). Thus, the number of chemical species to consider must be a balance of the competing needs of accuracy and simplicity to attain the computation time requirements.

The gases released from the thermal degradation of vegetation form a complex mixture containing a great variety of chemical species, mainly CO, CO_2, CH_4 and other light hydrocarbons, and H_2 (Grishin 1997). However, recent studies have revealed that H_2O is a main product on the pyrolysis gases from vegetation. Worasuwannarak et al. (2007) analyzed the pyrolysis behaviour of different vegetal species –rice straw, rice husk and corncob– and model compounds –lignin, cellulose and hemicelluloses (xylan)–, paying close attention to H_2O and tar formation. The authors found that H_2O was the main product on the pyrolysis gases from all the studied samples. Moreover, their results clearly indicate that a higher content of hemicellulose in the biomass results in a larger amount of water production during the pyrolysis.

In addition, Worasuwannarak et al. (2007) found significant interactions between cellulose and lignin during pyrolysis, resulting on a decrease in tar formation but an increase in the char. They concluded that the suppression of tar formation during the pyrolysis of biomass was brought about by the cross-linking reactions between lignin and cellulose to form H_2O and ester groups during pyrolysis.

Tihay and Gillard (2010) quantified the gases released during the pyrolysis of different Mediterranean vegetation species usually involved in wildland fires –*Cistus creticus, Myrtus communis* and *Genista corsica*. The authors found that CO_2 was the main product found on the pyrolysis gases followed by H_2O. According to them, the emission of water follows two steps. A first step consisting on the evaporation of the moisture content of the plant, and a second step, from 100°C upward, in which water is generated by the cleavage of aliphatic hydroxyl groups in the lateral chains.

The presence of H_2O in the evolved gases of vegetation can has significant implications when studying the combustion processes. For instance the oxidation mechanism for CO depends on the presence of hydrogen-containing compounds, and small quantities of H_2 or H_2O may tremendously increase the oxidation rate of CO. In the presence of these components, OH radicals are formed. Under these conditions CO is largely consumed by the reaction with OH, which is quite fast (Kee et al. 2003).

Thus, the aim of this study is to analyze how the fact of considering the H_2O on simplified mixtures of gases representatives of the degradation gases of vegetation affects on their combustion and on the emission of the pollutants often released during wildfires. For this purpose, several simulations have been run using the PSR code from the CHEMKIN II package with a two full mechanisms (GRI-Mech 3.0 and GDF-Kin® 3.0) and different simplified gaseous mixtures.

2. MATERIALS AND METHODS

2.1. Composition of the degradation gases mixtures

Two studies were found on the literature that quantified the H_2O released during the pyrolysis of several vegetation samples (Worasuwannarak et al. 2007; Tihay and Gillard 2010). From the results of both studies it can be derived that the amount of H_2O released differs depending on the vegetation species and on the conditions of the thermal degradation, mainly in terms of temperature. The mass fractions of H_2O (g-H_2O/g-sample) measured by Worasuwannarak et al. (2007) ranged between 18 % and 25%, whereas the values obtained by Tihay and Gillard (2010) ranged between 17% and 31%. According to these results we decided to test the effect of different amounts of H_2O on the degradation gases of vegetation.

Thus, three different gaseous mixtures were studied (Table 1). A first mixture *M0* composed by CH_4, CO and CO_2, and representative for the thermal degradation of *Pinus pinaster* needles (Leroy et al. 2008), and two other mixtures, *M10* and *M50*, that were formulated by adding different quantities of H_2O (10% and 50% mole fraction) to the mixture *M0*, and keeping the same proportion between CH_4, CO and CO_2 than in *M0*.

Table 1. Composition of the three gaseous mixtures studied M0, M10 and M50.

	% Mole fraction		
	M0	**M10**	**M50**
H_2O	**0.00**	**10.00**	**50.00**
CO	30.50	27.45	15.25
CO_2	51.10	45.99	25.55
CH_4	18.40	16.56	9.20

2.2. Numerical method

The PSR code (Glarborg et al. 1986) from the CHEMKIN II package (Kee et al. 1989) allows predicting steady-state temperature and species composition in a perfectly stirred reactor by solving the equation of mass conservation for each species at each temperature and fuel/air equivalence ratio. This package was used to simulate the combustion (gas phase reactions) of different gaseous mixtures. In order to obtain the same inlet concentrations of CO, CO_2 and CH_4 for all the cases, the proposed gaseous mixtures were diluted with argon by different dilution factors (*M0*: 9.1, *M10*: 8.3 and *M50*: 4.6).

Simulations were run at atmospheric pressure, for fuel equivalence ratios of 1.0 and 1.4; and temperatures ranging from 773 K to 1273 K. Two detailed mechanism were used to run the simulations, GRI-Mech 3.0 (Smith et al. 2000) and GDF-kin® 3.0 (El Bakali et al. 2006). Both mechanisms were designed to model natural gas combustion, including NO formation and the C2 chemistry. However, even though any of these mechanisms has been developed for the combustion processes in wildland fires, they have been validated for several devices (shock tube and jet-stirred reactors, premixed flame), and in various different conditions.

3. RESULTS AND DISCUSSION

Concerning the results, the mole fractions as a function of temperature were evaluated on the one hand for the major species involved on the oxidation of the gaseous mixtures –CH_4, CO, CO_2, O_2–, and on the other hand for some minor species corresponding to pollutants usually released during wildfires –NO, HCN, CH_2O–.

3.1. Major species: CH_4, CO, CO_2, O_2

Figure 1 shows the CH_4 mole fraction profiles as a function of the temperature, at stoichiometric (Figure 1a) and fuel-rich (Figure 1b) conditions. According to the numerical values obtained by using the GDF-kin® 3.0 mechanism, H_2O has practically no effect on the oxidation of CH_4, whereas according to the GRI-Mech 3.0 mechanism values, the greater the amount of H_2O, the smaller the temperature at which oxidation of CH_4 is efficient, especially at stoichiometric conditions. The same behaviour was observed for O_2.

Regarding CO, Figure 2a displays the mole fractions obtained by the simulations run at stoichiometric conditions. In these conditions, there are also differences depending on the mechanism used to run the simulations. Results obtained with the GDF-kin® 3.0 mechanism indicate a slight effect of H_2O in the consumption of CO only for the mixture *M50*. When using GRI-Mech 3.0 mechanism, results denote a change in the temperature at which CO is started being consumed. Moreover, the shape of the curve molar fraction vs. Temperature is also different, indicating a slower consumption.

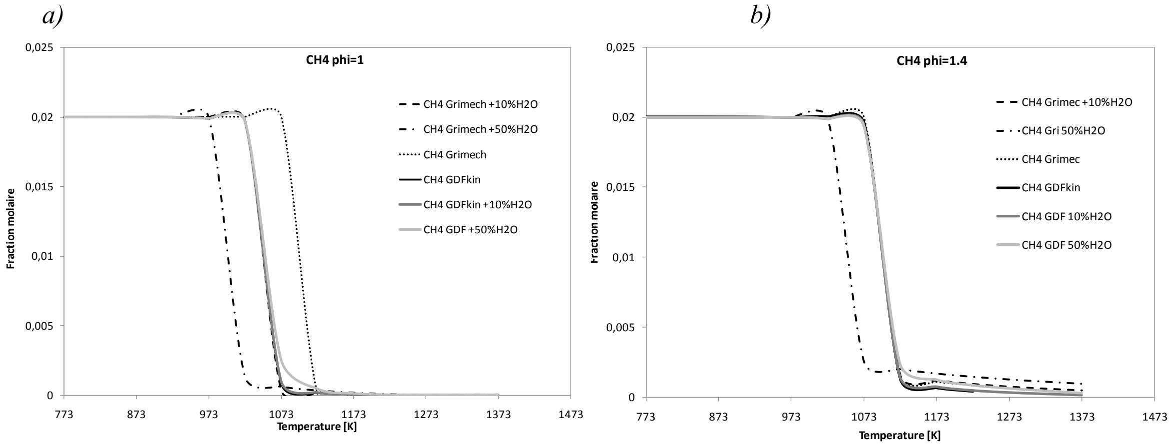
a) *b)*

Figure 1. Consumption of CH_4. a) Equivalence ratio 1. b) Equivalence ratio 1.4.

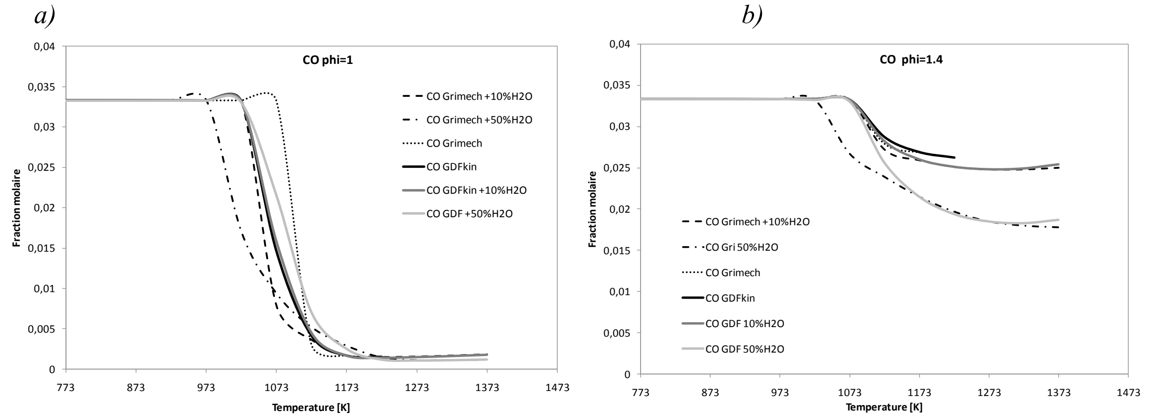
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Figure 2. Consumption of CO. a) Equivalence ratio 1.0. b) Equivalence ratio 1.4.

In fuel-rich conditions (equivalence ratio 1.4) the consumption of CO depends strongly on the amount of H_2O present on the mixture. In these conditions, the concentration of CO decreases substantially with the increasing amount of H_2O in the inlet mixture (Figure 2b). For both mechanisms, the values obtained are in agreement, but when using the GRI-Mech 3.0 mechanism for the gaseous mixture *M50* containing a 50% of H_2O the consumption of CO starts at a lower temperature.

The consumption of CO is linked to the production of CO_2. So, similar behaviour was observed for both chemical species. At stoichiometric conditions the production of CO_2 obtained when using the GDF-kin® 3.0 mechanism is not greatly affected by the presence of H_2O on the gaseous mixture, while when using the GRI-Mech 3.0 mechanism the presence of H_2O and its amount causes a decrease on the temperature at which the production of CO_2 is efficient. Nevertheless, the amount of CO_2 produced at the higher temperatures is the same for both mechanisms in the different studied conditions. At fuel-rich conditions an increase on the CO_2 formation of approximately 8% can be observed for the mixture *M50* in comparison with the mixture *M0*. This is because the CO is largely consumed in the presence of H_2O by the reaction $CO + OH \rightleftharpoons CO_2 + H$, which is quite fast, forming CO_2 and H.

3.2. Emissions of NO, HCN, CH_2O

Concerning the NO production, results obtained with both mechanisms present the same tendencies, so that the presence of H_2O produces a reduction on the NO concentrations, in all the studied conditions. Figure 3a displays the results at fuel rich conditions. It is worth noting, that when comparing the results of both mechanism for the mixture without H_2O (*M0*), there is a great difference on the values obtained depending on the mechanism used, while for the mixture with an H_2O fraction of 50% (*M50*) the values are very similar. As for the NO, the presence of H_2O on the gaseous mixture reduces the formation of HCN at fuel rich conditions (Figure 3b). However, at stoichiometric conditions, the results from the simulations using the GDF-kin® 3.0 mechanism show only a slight difference due to the presence of H_2O, whereas the results from the GRI-Mech 3.0 mechanism have the same trend that those at stoichiometric conditions.

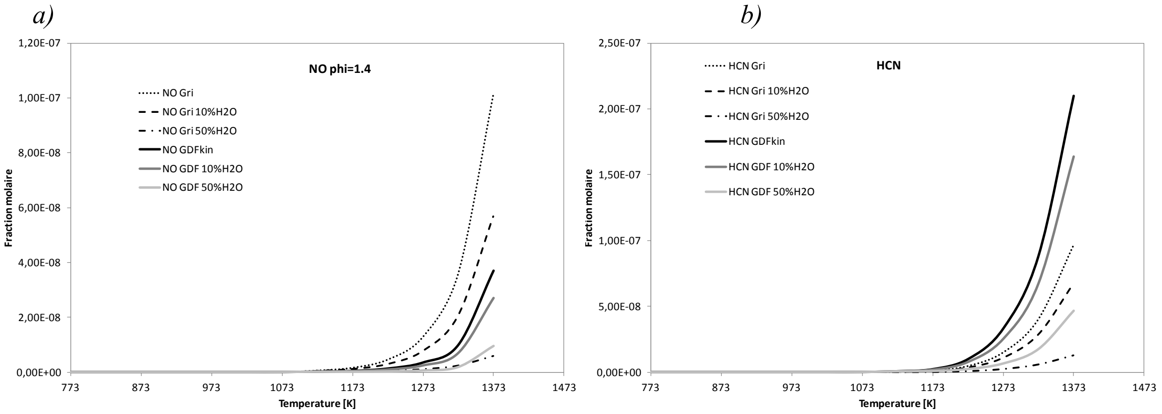
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Figure 3. Consumption of CO. a) Equivalence ratio 1.0. b) Equivalence ratio 1.4.

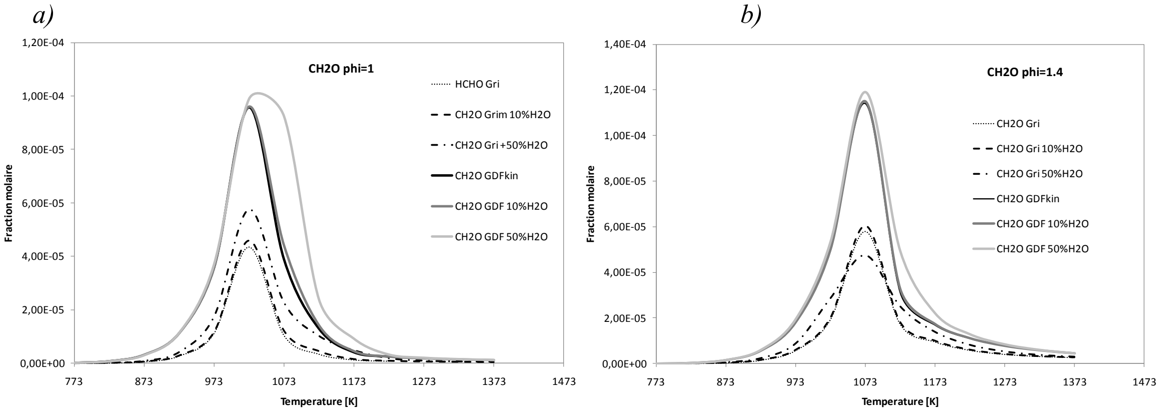
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Figure 4. Production of CH_2O. a) Equivalence ratio 1.0. b) Equivalence ratio 1.4.

Unlike NO and HCN, the CH_2O production is favoured by the presence of H_2O on the gaseous mixtures (Figure 4). Predictions of both mechanisms at stoichiometric conditions reveal a rise in the formation of CH_2O as the amount of H_2O present in the mixture increases (Figure 4a). At fuel-rich conditions (Figure 4b) the same conclusions can be drawn from the simulation results obtained by the GDF-kin® 3.0 mechanism. However, when using the GRI-Mech 3.0 mechanism in these conditions, the formation of CH_2O increase for the mixture *M10* (10% of H_2O) while for the mixture *M50* (50% of H_2O) the production of CH_2O decrease below the values obtained for the mixture without H_2O, *M0*.

4. CONCLUSIONS

Studies on combustion of evolved gases in wildland fires are mainly focused on fire behaviour modelling. In these studies is often considered that the mixture of gases released from the thermal degradation of vegetation is composed only by CO_2 and CO. In this work it has been studied the role of H_2O released during the thermal degradation of vegetation, on the combustion and on the emission of pollutants. The simulation results have shown that the presence of H_2O enhances the consumption of CO and therefore the formation of CO_2. This can have important implications in wildfire modelling since the emissions of CO/CO_2 reflect the burning efficiency and are strongly coupled to the heat released by the fire. Moreover, neglecting H_2O can affect the accuracy of the predictions of pollutants emissions since the presence of H_2O enhance the formation of CH_2O, and decrease the formation of NO and HCN. Some discrepancies have been observed depending on the kinetic mechanism used. Experimental datasets are therefore important to validate the numerical results.

5. ACKNOWLEDGMENTS

This research is supported by the *Agence nationale de la recherche*, under the project ANR-09-COSI-006 and by the CNRS (*Centre National de la Recherche Scientifique*).

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Analysis of smoke from Mediterranean species burned with a cone calorimeter

Romagnoli E., Chiaramonti N., Barboni T., Santoni P.A.

SPE UMR 6134 CNRS–University of Corsica, Campus Grimaldi, 20250 Corte, France

romagnoli@univ-corse.fr

Abstract

This paper investigates the volatile organic compound (VOCs) and semi-volatile organic compounds (SVOCs) from three representative Mediterranean plant species (*Pinus pinaster* Ait., *Pistacia lentiscus* L. and *Rosmarinus officinalis* L.). The plant samples were burned using a cone calorimeter. The volatiles compounds were analyzed by Automated Thermal Desorption-Gas Chromatography/Mass Spectrometry (ATD-GC/MS) and 62 compounds were identified. These volatile emissions represented 6551.6 ± 563.4 to 12765.7 ± 1327.3 $\mu g.g^{-1}{}_{dw}$ of combustible fuel. Some compounds identified are toxic and can affect human health and environment.

Keywords: VOCs and SVOCs smoke; Cone calorimeter; GC/MS

1. INTRODUCTION

Every year, wildland fires burn a considerable area of the southern European region. The Mediterranean region is the most affected by these fires. Vegetation fire smoke consists of water vapor, permanent gases, volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs) and others particles matter. Permanent gases include carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NOx, NO and NO_2) and methane (CH_4)). Hydrocarbons identified are aliphatic compounds such as alkanes, alkenes and alkynes (Miranda et al. 2004; Greenberg et al. 2005; Statheropoulos et al. 2007; Barboni et al. 2010a,b). Many aromatic hydrocarbon are identified, especially benzene, toluene, ethylbenzene, and xylenes (Barboni et al. 2010c). Among VOCs emitted by vegetation fire smoke, there are oxygenate compounds such as: alcohols (phenol), aldehydes (furfural, benzaldehyde), ketones (acetone, 2-butanone), furans (furfural, benzofuran), carboxylic acids (acetic acid) and esters (Blake et al. 2009; Estrellan et al. 2010). The semi-volatile compounds (SVOC) identified in vegetation fire smoke are polycyclic aromatic hydrocarbons (PAHs) such as naphthalene (Oros et al. 2001). Particulates matters are also emitted during wildfires as fine ($PM_{2.5}$) and coarse ($PM_{2.5\text{-}10}$) and released into the atmosphere, where physical or chemical transformations may occur (Alves et al. 2011). Smoke can have impacts on the environment (air quality, water and soil) and human health (Reisein et al. 2009; Margossain 2002).

The aim of this work is the characterization of volatile organic compounds emitted during the combustion of three representative species of Mediterranean vegetation. The combustion of vegetal made from the cone calorimeter is an innovative approach to the analysis of volatile organic compounds contained in smokes.

2. MATERIALS AND METHODS

2.1. Experimental part

The combustion was performed on three representative species of the Mediterranean scrub. This is *Pinus pinaster* Ait., *Rosmarinus officinalis* L., and *Pistacia lentiscus* L.. Species were collected during the spring season from March to June in Corsica. Samples were previously dried in an oven at 60 °C for 24 hours before experimental burning. 20 grams of plants (leaves and needles) are placed in a basket (e.g.: Figure 1) and subjected to an external radiative heat flux (20 kW m^{-2} (570 °C)), and a pilot ignition source. Smoke was sampled from the exhaust pipe of the cone calorimeter on an active sorbent tube, through a transfer line (Teflon tube, Supelco) connected to a pump (AirbusTox, Noselab). The sorbent tubes used were Multibed glass tubes (11.5cm×6mm o.d; 4mm i.d.; Supelco, Tenax TA) in order to capture organic compounds of low or medium volatility. After combustion, the sorbent tubes were immediately transferred to the laboratory and analyzed by ATD–GC-FID and ATD–GC/MS. The repeatability of the method is verified by performing the same pattern three times for each sample plant.

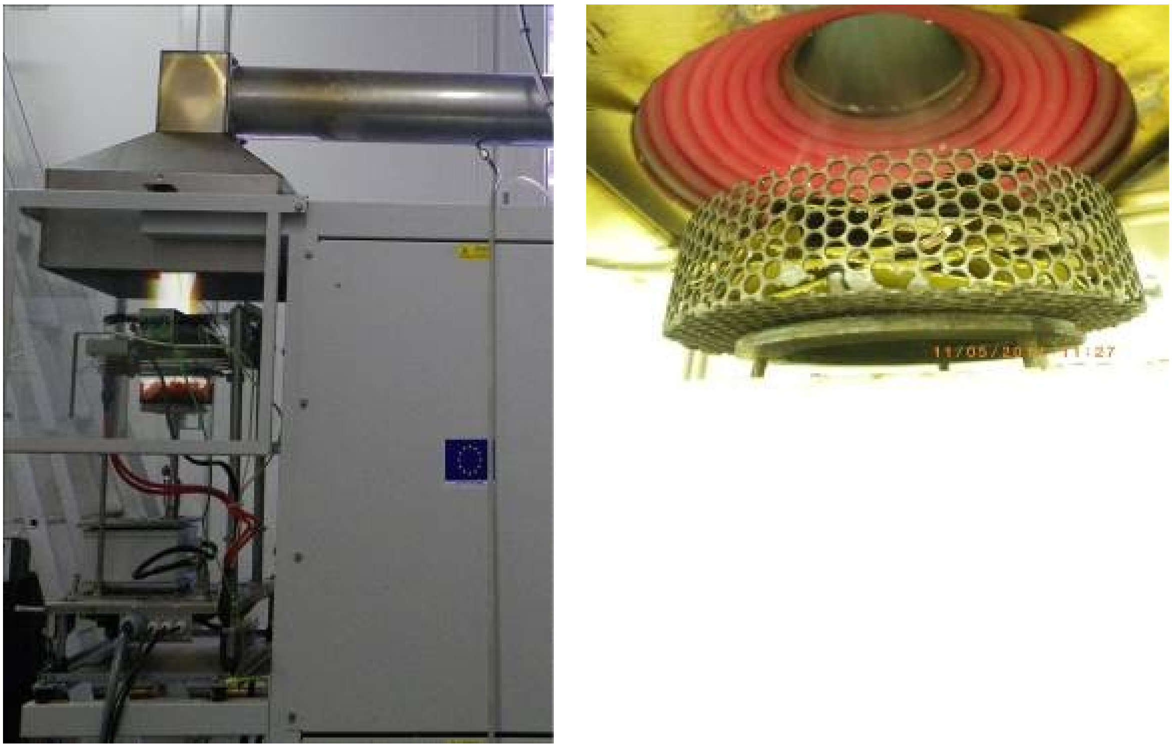

Figure 1. Picture of the cone calorimeter and the heating resistance and basket

2.2. Analysis of volatile compounds

The analyses were carried out immediately after sample collection using an Automatic Thermal Desorber Perkin Elmer ATD turbomatrix. The chromatograph (GC-FID) and the (GC/MS) mass spectrometer were Perkin Elmer Clarus 500 apparatus. The chromatograph was equipped with a non-polar column (Rtx-1, dimethylsiloxane; length: 60 mm, internal diameter: 0.25 µm). This column was coupled with the mass detector and the FID detector.

The oven temperature of the chromatograph was programmed from 50° to 260°C at 2°C min^{-1} and then held isothermally at 260°C for 10 min. The method followed is the same as the report by Barboni et al. 2010b.

2.3. Identification and quantification

The methodology used to identify individual components was based on the comparison of their GC retention indices (RI) on non-polar columns (Rtx-1), with those of authentic compounds. The results spectra were compared with those in our laboratory-made library. The method of calibration was used with a commercial standard of benzene in methanol.

3. RESULTS AND DISCUSSION

The analyses of smoke with ATD-GC-FID and ATD-GC/MS permitted the identification of 62 compounds representing 6551.6 ± 563.4 to 12765.7 ± 1327.3 µg g^{-1}_{dw} for three species studied (*P. pinaster*, *P. lentiscus*, *R. officinalis*). The compounds identified were classified according to their chemical family. Among them, there are 27 terpenic compounds, 16 benzene derivatives, 18 linear compounds, 4 other cycles such as pyrrole and 1 volatile Polycyclic Aromatic Hydrocarbon (PAH). The list of identified compounds in smoke is presented in Table 1.

Terpenes were emitted during the preheating phase of combustion. Ferlay-Ferrand et al. (2000) reported that aromatic compounds identified in smoke of aromatic species such as rosemary or thyme are characterized by high frequencies in terpenes. Terpenes are found in high proportions ranging from 2296.5 ± 293.7 (*P. pinaster*) to 3314.8 ± 647.8 µg g^{-1}_{dw} (*P. lentiscus*). In the smoke from *P. pinaster, (*E)-β-caryophyllene (548.8 µg g^{-1}_{dw}), myrcene (316.4 µg g^{-1}_{dw}) were the major terpenic compounds. Myrcene is also the major terpenic compound in smoke of *P. lentiscus* (2095.2 µg g^{-1}_{dw}). The study of the essential oil of *P. lentiscus* realized by Castola et al. (2000) also shows that the major compound is myrcene. In the smoke of *R. officinalis*, α-pinene (719.6 µg g^{-1}_{dw}), bornyl acetate (600.8 µg g^{-1}_{dw}) were the major terpenes compounds. The same results from *R. officinalis* essential oil were reported by Pintore et al. (2002).

Benzene and benzene derivatives concentrations vary from 934.7 ± 54.0 to 2076.2 ± 145.3 µg g^{-1}_{dw}. Benzene, toluene, ethylbenzene and xylenes (BTEX) represent significant values of this chemical family. Benzene varies between 110.0 ± 5.0, 165.6 ± 10.1 to 168.2 ± 3.8 µg g^{-1}_{dw}. The largest proportion of toluene is found for *Rosmarinus* (260.0 ± 31.6 µg g^{-1}_{dw}), whereas it is equivalent for *Pinus* and *Pistacia*. The ethylbenzene concentration was low for *P. pinaster* (68.9 ± 9 µg g^{-1}_{dw}) comparatively of the *P. lentiscus* and *R. officinalis* which were respectively 214.3 ± 21.2 and 175.6 ± 24.0. Xylenes concentrations were equivalent for *Pinus* and *Pistacia* and higher for the rosemary (Table 1).

The inhalation of benzene causes headaches, dizziness, nausea, confusion and respiratory tract irritation. In long term, it is carcinogenic to humans. Exposure to toluene can cause psycho-organic syndromes and cardiac problems. Xylenes have an effect on metabolism, they can cause vomiting and risk of pulmonary edema in the short term (Barboni et al. 2011). This is why many authors measured BTEX during prescribed burning. Reisen and Brown (2009) showed that benzene and toluene exposures ranged from 0.002–0.26 mg m^{-3} and 0.002–0.95 mg m^{-3}.

Other cycles family represents concentrations ranging from 925.8 ± 38.5 µg g^{-1}_{dw} for *P. pinaster* burning to 5825.3 ± 354.2 µg g^{-1}_{dw} from the combustion of *P. lentiscus.* There are other compounds presenting important risk for human health. Furfural compounds identified in the smoke from the plants are important because they are serious irritants and are produced in large quantities.

Linear compounds were found in higher proportion in the smoke of *Rosmarinus* (3074.5 ± 450 µg g^{-1}_{dw}) compared to the value in *Pistacia* fire smoke (1549.4 ± 180.1 µg g^{-1}_{dw}). Although acetic acid were detected in smoke from *Pistacia* and *Pinus* burning at 1050.5 ± 107.8 and 565.8 ± 35.7 µg g^{-1}_{dw}, it was not identified in the smoke of *Rosmarinus.*

Regarding the family of PAH, one compound was identified, the naphthalene, whose values were 67.3 ± 4.8 to 92.0 ± 15.1 µg g^{-1}_{dw}. Naphthalene is carcinogen. Barboni et al. (2010b) identified the same compounds as those found in this study and they demonstrated that differences in smoke compositions observed for different plants can be explained by structural differences of plants.

Table 1. Mean concentrations and standard deviations of VOCs and SCOVs emissions from needles of Pinus pinaster (Ait.), leaves of Pistacia lentiscus (L.) and leaves of Rosmarinus officinalis (L.).

No.	**Compounds**	**RIl**	***P. pinaster L***	***P. lentiscus L***	***R. officinalis L***
1	Isoprene	504	662.1 ± 74.2	386.8 ± 31.9	496.7 ± 84.5
2	2-methylfuran	604	-	759.5 ± 59.2	-
3	Benzene	654	110 ± 5	165.6 ± 10.1	168.2 ± 3.8
4	Acetic acid	660	565.8 ± 35.7	1050.5 ± 107.8	-
5	Heptene	685	240 ± 35.2	-	-
6	2,5-dimethylfuran	695	282.2 ± 9.7	1045.3 ± 63.4	1174 ± 136.8
7	Methylpyrrol		-	3145.4 ± 155.6	-
8	Toluene	750	155.6 ± 4.6	177.7 ± 12	260 ± 31.6
9	Octene	764	229.9 ± 29.4	-	863.9 ± 168.5
10	Octane	800	224 ± 27.7	-	241.3 ± 55.3
11	Furfural	836	643.6 ± 28.8	875.1 ± 76.1	662.11 ± 43.32
12	Benzene,ethyl-	844	68.9 ± 2.1	214.3 ± 21.2	175.6 ± 24
13	(m+p+o)-xylene	853	231.1 ± 23.0	236.7 ± 26.3	314.7 ± 24.0
14	Phenylethyne	870	-	-	87.9 ± 5.4
15	Styrene	873	158 ± 8.5	874.9 ± 34.2	567 ± 130
16	Nonene	883	239 ± 24.6	243.7 ± 35.2	185.2 ± 17.6
17	Nonane	900	47.8 ± 7.8	203 ± 34.7	100.3 ± 13.7
18	Cumene	916	-	107.3 ± 16.6	-
19	Benzaldehyde	929	-	100.5 ± 12.4	-
20	α-pinene	931	127.6 ± 13.8	182.7 ± 20.2	719.6 ± 63.3
21	Benzene,propyl-	938	-	72.7 ± 15.5	-
22	Toluene,ethyl-(m)	945	-	233.7 ± 13.6	171.6 ± 11.5

Table 1. Continued

23	Toluene,ethyl-(p)	947	53.5 ± 5.6	-	41.8 ± 7.8
24	Camphene	950	-	-	91.5 ± 13.5
25	Benzene,trimethyl-	953	12.7 ± 0.6	-	-
26	Toluene,ethyl-(o)	961	46.2 ± 0.3	-	68.7 ± 15.1
27	Styrene,methyl-	984	34.3 ± 2.5	-	116.6 ± 24.4
28	Allocimene		-	-	19.8 ± 2.2
29	Decene	987	41.4 ± 7.1	-	104.5 ± 15.4
30	Myrcene	990	316.4 ± 33.1	2095.2 ± 514.6	268.3 ± 13.7
31	Decane	1000	13 ± 0.6	-	32.7 ± 5.4
32	p-cymene	1010	-	190.9 ± 18.1	-
33	α-terpinene	1013	-	-	64.4 ± 12.5
34	o-cymene	1017	77.8 ± 2.5	-	-
35	Limonene	1020	164.9 ± 16	145.6 ± 6.9	-
36	(δ)-3-carene	1024	-	31.5 ± 10.9	-
37	β-phellandrene	1026	-	50.5 ± 13.4	-
38	α-phellandrene	1027	22.3 ± 2.1	124.3 ± 15.5	20.5 ± 2.8
39	Butenylbenzene	1032	-	-	-
40	Indene	1036	64.4 ± 1.9	-	48.5 ± 2.7
41	Eucalyptol	1055	-	-	400 ± 69.2
42	Linalol	1089	22.6 ± 4.9	-	-
43	Undecane	1100	3.8 ± 0.3	-	-
44	Camphre	1125	45.8 ± 4.5	-	-
45	Undecene	1135	46.3 ± 2.4	52.1 ± 2.5	49.9 ± 6.1
46	Naphtalene	1141	67.3 ± 4.8	-	92 ± 15.1
47	Borneol	1148	-	-	174.7 ± 41.9
48	Verbenone	1184	69.4 ± 3.7	-	123.6 ± 7.33
49	Dodecene	1193	6.9 ± 1.8	-	63.6 ± 6.7
50	Bornyl acetate	1269	59.1 ± 1.2	-	600.8 ± 78.8
51	Tridecene	1289	-	-	126.2 ± 7.6
52	Tridecane	1300	-	-	26.6 ± 1.8
53	α-copaene	1374	19.4 ± 16.8	-	-
54	Teradecene	1395	-	-	191.1 ± 46.3
55	Tetradecane	1400	-	-	50.9 ± 4
56	E-β-caryophyllene	1424	548.8 ± 72	-	-
57	α-Humulene	1456	267.7 ± 12.8	-	60.5 ± 11.1
58	D-germacrene	1480	130 ± 3.6	-	-
59	E-α-bisabolene	1494	51.1 ± 5.3	-	-
60	Pentadecane	1500	-	-	146.2 ± 13.6
61	Cadinene	1507	350.6 ± 0.9	-	-
62	α-amorphene	1536	23 ± 0.5	-	-

Family compounds	***P. pinaster L***	***P. lentiscus L***	***R. officinalis L***
Terpenes	2296.5 ± 293.7	3314.8 ± 647.8	2483.2 ± 389.7
Benzene and derivatives	934.7 ± 54.0	2076.2 ± 145.3	2020.5 ± 280.2
Other cycles	925.8 ± 38.5	5825.3 ± 354.2	1896.6 ± 194.2
Linears	2327.3 ± 172.5	1549.4 ± 180.1	3074.5 ± 450.5
PAH	67.3 ± 4.8	0 ± 0.0	92 ± 15.1
Total concentration	6551.6 ± 563.4	12765.7 ± 1327.3	9566.9 ± 1329.8

Compounds are listed in order of elution from the apolar (Rtx-1) column. The results reported in this table are the average of three results for each plant in µg g^{-1}_{dw}. *± represents the standard deviation. RIl, retention indices obtained in the literature (Jennings and Shibamoto 1980; WebBook NIST)*

4. CONCLUSION

This study analyzed the VOCs and SVOCs emitted by the combustion of three plant species. The combustion was carried out using a cone calorimeter. Chemical analysis of C_5–C_{30} volatiles enabled the identification of 62 compounds, including hydrocarbons and oxygenated compounds, resulting from the thermal degradation of plants. Many compounds identified are toxics such as BTEX and represent a threat for the health of firefighters. The biomass burning using the cone calorimeter coupled with analysis by ATD-GC/MS is a new approach in the analysis of smoke.

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Estimating vegetation fire emissions from Sardinian wildland fires (2005-2009)

Bacciu V.[1,2], Pellizzaro G.[3], Salis M.[1,2], Arca B.[3], Duce P.[3], Spano D.[1,2]

[1]Department of Science for Nature and Environmetal Resources (DipNeT), University of Sassari, Italy; [2]Euro-Mediterranean Center for Climate Changes, IAFENT Division, Sassari, Italy;[3]National Council of Research, Institute of Biometeorology (CNR-IBIMET), Sassari, Italy

vbacciu@uniss.it

Abstract

Vegetation fire emissions (VFE) are recognized to be an important public health and environment issue. The estimates of VFE are affected by several errors and uncertainties, principally related to fuel status and characteristics, but also to fire behaviour. In addition, improvements of emission estimates are possible knowing the amount of fuel consumption both in the flaming and smoldering combustion period. In this context, the aim of this work is to develop a methodology for fire emission estimation in a Mediterranean area, with a focus on the evaluation of VFE in relation to different type of vegetation burned. The First Order Fire Effects Model (FOFEM) (Reinhardt et al. 1997) was selected for estimating combustion and emission processes due to the input needed and its physical model of heat transfer and burning rate. Particular attention was paid to develop and survey comprehensive and accurate data inputs. FOFEM input fuel load data, for several fuel types, were surveyed to represent those combusted. The data on area burned, fuel loadings, and emissions were assembled into a Geographical Information System (GIS) to improve manipulation and visualization of data. Results showed the crucial role of appropriate fuel and fire data and maps to attain reasonable simulations of fuel consumption and smoke emissions. FOFEM outputs and the derived smoke emission maps are useful for several applications including emissions inventories, air quality management plans, and emission source models coupled with dispersion models and decision support systems.

Keywords: FOFEM, Vegetation fire emissions, smoke emission maps

1. INTRODUCTION

Fires have always been an integral part of ecosystems, affecting negatively and positively biosphere from local to global scale. One of the main primary effects of wildland fires is the production of remarkable amount of greenhouse gases and solid particulate matter that interfere in local, regional and global biosphere phenomena (Forster et al. 2001; Spichtinger et al. 2001). Due to the large amount of pollutants emitted into the atmosphere in short time periods and in limited areas, forest fire emissions impact on air pollution levels, air quality, and human health (Sandberg et al. 1978; Bowman and Johnston 2005).

Emissions from forest fires are commonly estimated using the mathematical expression proposed by Seiler and Crutzen (1980), based on the amount of burned biomass and emission factors associated with each specific chemical species. This approach, with minor modifications and improvements, has been widely used in a variety of ecosystems and emission inventory purposes (e.g. French et al. 2000; EMEP/CORINAIR 2006; Tan et al.

2007; Wiedinmyer and Neff 2007; Miranda et al. 2008). However, the estimate of emissions is affected by several errors and uncertainties. As indicated by Battye and Battye (2002), burned surface area is one of the more difficult parameters to obtain. Also, the largest errors are related to fuel characterization and fuel consumption evaluation (Peterson 1987; Peterson and Sandberg 1988; Hardy et al. 2001). Several authors (e.g. Ottmar et al. 2008) pointed out that separate calculations of flaming and smoldering consumption are required to improve assessment of total emissions. In this context, modelling approaches are useful to appraise fuel consumption and the resultant emissions, but models need comprehensive and accurate vegetation data inputs for accurate prediction of source and composition of fire emissions.

The general aim of this work was to develop a methodology for fire emission estimation in a Mediterranean area. Specific objectives were: (1) to estimate the type and quantity of Mediterranean vegetation fire emission (VFE) from fires observed in Sardinia (Italy) during the period 2005-2009, and (2) to evaluate the VFE in relation to different type of vegetation burned. In addition, for the purpose of assessing the importance of VFE emissions compared to anthropogenic emissions, fire emission estimates were compared with data from the Italian National Emission Inventory (NEI-IT) report.

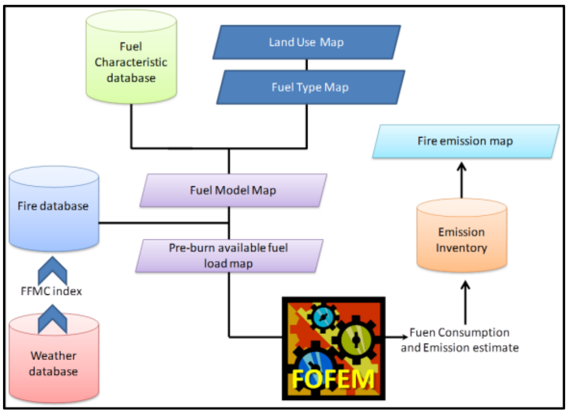

Figure 1. Diagram of the integrated approach used in the present work

2. MATERIAL AND METHODS

The integrated approach used for estimating fuel consumption and emissions during fire seasons from 2005 to 2009 is showed in Figure 1. Fire data (number of fires and burned surface areas) were obtained from the Sardinian Forestry Corp global positioning system (GPS) survey. Daily values of the Canadian Fine Fuels Moisture Code (FFMC) were calculated for the whole 2005-2009 period, obtaining relative indications of the moisture content of fine and dead forest fuel. The daily FFMC values were then associated to maps of fire perimeters with the aim to group fires based on fine fuel moisture status, and moderate or elevated burning conditions. To obtain the fuel type map, the original 70 classes of the 2003 land use map of Sardinia (1:25,000) were aggregated into 13 main land cover types. For each cover type, fuel loading was assigned by a combination of experimental observations (Bacciu et al. 2009; Delogu et al. 2010; DLV 3.2.3 Proterina-C Project 2011) and literature data (Marchetti 1994; Dimitrakopoulos 2002; Caritat et al. 2006; Fernandes et al. 2006). Finally, a fuel model map was obtained.

The fuel load map was overlaid with the FFMC-fire perimeter map to quantify the surface area burnt annually by fuel type, and the pre-burn available fuel load. 10-hour dead fuel moisture content (FMC) values were also assigned to fuel based on FFMC values associated to each fire. Analysing the relationship between observed FMC and FFMC data (Pellizzaro et al. 2009a, 2009b) allows to find correspondence between FFMC and FMC values. Five burning conditions classes were identified: extreme (FFMC >90, FMC from 8 to 13%), medium-high (FFMC 87.5, FMC from 11 to 14.5%), medium (FFMC 87, FMC from 13 to 16%), medium-low (FFMC 85, FMC from 15 to 18%), and low (FFMC <82.5, FMC from 18 to 20%). All layer themes were acquired and managed using Geographic Information System (GIS) technology (ArcGIS 9, ESRI Inc., Redlands, CA, USA). The pre-burn available fuel load layer was then processed to determine fuel consumption and emission amount using the FOFEM model. The fuel consumption and smoke emission estimates were summarized by fuel categories, types and year. To facilitate data management and improve data visualization, fuel models were grouped according to the four principal fuel categories/classes: “Shrub”, “Understorey”, “Crops”, and “Herbaceous”. To examine the role of wildfire in the context of industrial emissions, data from NEI-IT report on 2005 emissions from fossil fuel combustion (De Lauretis et al. 2009) were used to compare VFE with anthropogenic emission. Then, emission data obtained previously were linked to the pre-burn available fuel load layer for spatial allocation of the emission estimates.

3. RESULTS

From 2005 to 2009, the Sardinian Forestry Corps recorded more than 100,000 burned hectares, with an average of 1,582 fires per year. The 2009 and 2007 appeared to be the most critical years during the five-year study period. In 2009 the total burned area accounted for 44,500 hectares, with permanent crops and croplands representing 51% of the total. Also in 2007, the “crop” category, with 16,400 burned hectares, accounted for a large proportion (48%) of the total burned area (data not shown). Figure 2 (A) shows the estimated pre-burn fuel load in absolute terms (Gg). Both in 2009 and 2007, the main amount of fuel available to burn was due to the “shrub” categories. This class consisted of 128 Gg in 2009 (44% of the total), and 96 Gg in 2007 (42% of the total). Finally, Figure 2 (B) illustrates the percent contribution of the five burning condition groups to total fire number. In 2009, 59% of fires fell in the extreme FFMC class, and 44% in 2007. On the other hand, 2008 was the less severe year in terms of burning condition occurrence, where the class from low to medium FFMC accounted for 76%.

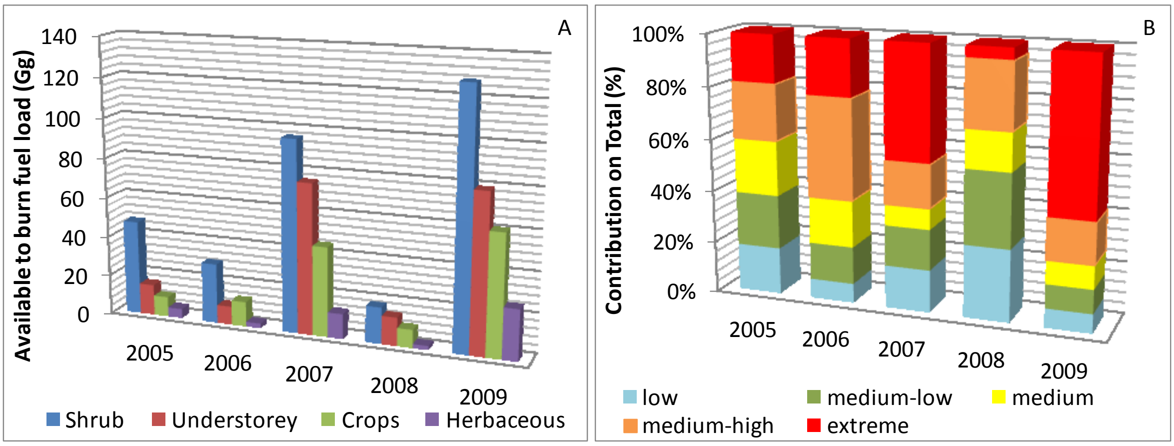

Figure 2. (A) Fuel load available to burn partitioned in the four main vegetation type classes; (B) Percent contribution of the five burning condition groups to total fire number

In general, fires generated a considerable amount of emissions (Table 2). In 2007, emission amount was more than 345 Gg, about 78% of the emissions estimated in 2009 (443 Gg). About 1.34 and 1.61 Gg of particulates were released into the atmosphere in 2007 and 2009, respectively. Table 2 shows also that our emission estimations for 2005 are in good agreement with the NEI-IT report. Without considering CO_2 (data not present for fire emission activity in NEI-IT report), our total, was equal to 4.14 Gg against 4.74 Gg reported by NEI-IT. It is also interesting to notice that particulate emission from fires in 2005 corresponds to the equivalent of 9% of the annual particulate emissions from 2005 anthropogenic activity.

*Table 2. Pollutant and greenhouse gas mass (Gg) by category and fire season compared with anthropogenic emissions of 2005. * indicates the sum of pollutants and greenhouse gases without CO_2. F.E. and A.E. indicate the 2005 Fire Emission and Anthropogenic Emission estimations from De Lauretis et al. (2009). % indicates the ratio between our estimation and A.E.*

YEAR	PM_{10}	$PM_{2.5}$	CH_4	CO	CO_2	NO_X	SO_2	TOTAL
2005	0.41	0.34	0.16	2.98	110.78	0.18	0.07	114.92 ***4.14***
2006	0.32	0.27	0.14	2.59	75.05	0.12	0.05	78.52
2007	1.34	1.13	0.55	10.39	331.21	0.52	0.20	345.35
2008	0.24	0.20	0.10	1.84	61.07	0.10	0.04	63.58
2009	1.61	1.36	0.65	12.07	426.74	0.68	0.25	443.37
Mean	0.78	0.66	0.32	5.97	200.97	0.32	0.12	209.15
F. E.	**0.62**	**0.62**	**0.34**	**3**	**-**	**0.09**	**0.03**	**4.74**
A. E.	**4.18**	**3.22**	**88.93**	**105.55**	**21,640.80**	**38.47**	**37.98**	**21,919.13**
%	**9.8**	**10.6**	**0.2**	**2.82**	**0.5**	**0.5**	**0.2**	**0.5**

Figure 3 illustrates the contributions of each fuel type to total burned area, and to totals of CH_4, CO_2, and CO emissions. This analysis shows that the majority of the greenhouse gas emissions comes from “shrub” and “crop” categories. In 2009, for example, “crop” category accounted for 51% of the total burned surface area, greatly contributing to CH_4 and CO emissions (42 and 48%, respectively). On the other hand, “shrub” class contributed significantly to the total amount of CO_2 emissions in both 2009 and 2007 (43% and 42%, respectively).

Finally, the tabular emission data were linked to the original fuel model burned areas layer for spatial allocation of the emission estimates. Figure 4 represents an example showing spatially explicit CO_2 emissions (Mg ha^{-1}) for large fires occurred during 2009.

4. CONCLUSION

In this study, the survey and the development of comprehensive and accurate input data, such as fuel models, fuel moisture and fuel map, was emphasized in order to reduce bias in predicting and quantifying the source and the composition of fire emissions and achieve realistic vegetation fire emission estimates. The comparison with NEI-IT report on 2005 emissions from fossil fuel combustion (De Lauretis et al. 2009) showed a good agreement taking also into account the different methodology used to estimate the emission. In addition, our data showed that also a short fire season can release a relevant amount of pollutants if compared with the annual emissions from the entire transportation and energy sectors. Moreover, our data showed the primary contribution of shrub layers to the total greenhouse gas emissions. It implies the importance of fuel management both for wildfires controlling and for mitigation of greenhouse gases and C emissions. Finally, FOFEM outputs and derived smoke emission maps can be useful for developing emission source models coupled with dispersion models and decision support systems. These tools are crucial for air quality managements, mitigation of wildland fire environmental effects, and to assist decision makers in prescribed fire activities.

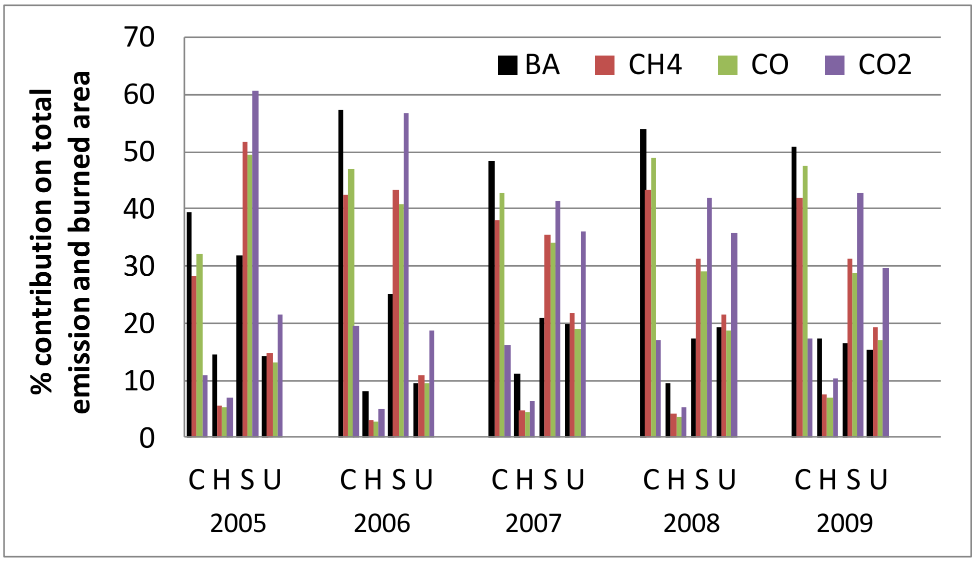

Figure 3. Contributions of each fuel category to total burned area, and to total emissions of CH_4, CO_2, and CO (C=crop, H=herbaceous, S=shrub, U=understorey,)

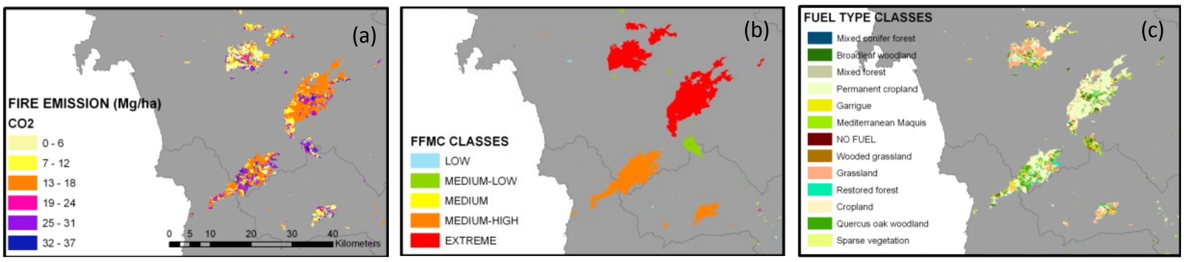

Figure 4. (a) estimated CO_2 emission (Mg ha^{-1}) from large fires occurred in western Sardinia during 2009; (b) and (c) show fire perimeters with their corresponding FFMC classes (b) and the fuel type covered by fires (c)

5. ACKOWLEDGEMENT

This research was funded by the Italian Ministry of Education, University and Scientific Research (MIUR) under grant agreement n.° 232/2011.

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A method to estimate the ignition characteristics of forest litter

Schunk C., Leutner C., Leuchner M., Menzel A.

Chair of Ecoclimatology, Technische Universität München, Hans-Carl-von-Carlowitz Platz 2, 85354 Freising, Germany

schunk@wzw.tum.de

Abstract

There is a huge interest in ignition and burn studies of surface fuels, since they represent a critical fuel type. A large amount of studies has already been done, however, a wide range of different experimental devices and setups have been used. We present a novel experimental device using an infrared heating panel and test three different setups with the same basic equipment: individual fuel elements suspended above the heating panel, bulk samples suspended above the panel and bulk samples placed directly on the radiative panel surface. The properties of these setups are discussed with a special regard to comparability of test conditions and recommendations are given for procedures to be used in the future.

Keywords: dead fine fuels, moisture content, ignition time, combustion, heating panel

1. INTRODUCTION

The start of almost every wildland fire takes place within the surface fuel layer; therefore surface fuels (especially forest litter) have been in the focus of many fire studies (Pyne et al. 1996). Most of these covered the fuel moisture-ignitability relationship, e.g. Blackmarr (1972), Dimitrakopoulos and Papaioannou (2001), de Groot et al. (2005), Petriccione and Moro (2006), Plucinski and Anderson (2008). The common rationale is that the presence of moisture in and on fuels can reduce or even inhibit both their ignitability and fire behaviour. This is because any present moisture has to be driven off before a fuel can reach pyrolysis and be ignited (Pyne et al. 1996), and evaporated water leads to a dilution of combustible gases (Chandler et al. 1983) as well as to a cooling effect (Britton et al. 1971). Although a wide range of experimental approaches to ignition testing is reported, most studies were carried out with the use of radiative heat sources, e.g. using cone calorimeters (Madrigal et al. 2009), the ISO 5657 device (Dimitrakopoulos and Papaioannou 2001) and the epiradiateur heater. Especially for the latter device, a large amount of studies with varied experimental setups (heating the samples from above or below, placing them on a grid or on the radiative surface directly, different temperatures etc.) is reported (Valette 1992; Grossiord et al. 1998; Petriccione and Moro 2006; Alessio et al. 2008). Our aims are to present an improved experimental device based on the epiradiateur and to investigate the influence of three different experimental setups on the test results. Recommendations are given for experimental procedures to be used in future studies.

2. MATERIALS AND METHODS

2.1. Litter sampling and preparation

Litter samples were obtained from four major tree species in southern Germany (Norway spruce (*Picea abies* (L.) Karst.), Scots pine (*Pinus sylvestris* L.), European beech (*Fagus sylvatica* L.) and Pedunculate oak (*Quercus robur* L.)). Sampling of the litter was done directly after leaf fall in autumn 2010 in order to obtain fresh and unweathered material of all species and to ensure comparability. Deciduous leaf litter was flattened by pressing to minimize the complex three-dimensional structure of the crumpled leaves. Leaves randomly selected for individual ignition test were weighed and measured for surface area and thickness under laboratory conditions. For tests of several needles and bulk fuel beds, the needles equivalent to the weight of one average leaf were counted and 2g (wet mass at a constant climate of 23°C and 20% relative humidity) of the fuels were weighed in, respectively. Conditioning to pre-defined fuel moisture levels was achieved by the use of a climate chamber, drying oven, storage over distilled water in desiccators as well as artificial wetting of the fuels in damp fabric.

2.2. General experimental setup

The new test device is shown schematically in Figure 1. Following most of the epiradiateur arrangements, the sample is heated from a quartz-faced electrical heater (20x20cm², 6000W, Omega QH-101060-T) underneath and a pilot flame is present for a more consistent ignition. The heat plate can either be run at any given percentage of its maximum power or the surface temperature of the heat plate can be set and maintained with a thermocouple and PID controller.

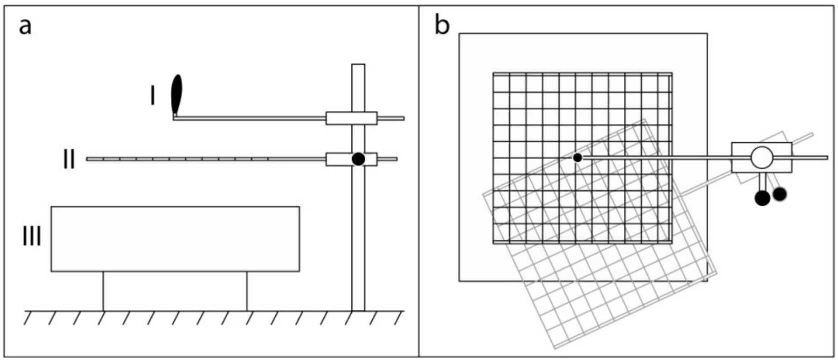

Figure 1. General setup used in the ignition experiments; a: side view; b: top view. I: pilot flame; II sample holder/grid; III: radiative heating panel. Drawings not to scale.

An arm for swivelling in of the samples (single leaves or bulk samples placed on a grid) could be positioned at an adjustable height above the heating panel surface; the same was true for the pilot flame. The whole setup was installed in a suction funnel constructed from sheet metal and driven by a welding fume filter for extraction of the smoke after each experiment. All experiments were filmed by a webcam (30 frames per second) and the ignition time, duration of burning and maximum flame height was determined from the videos. Additionally, surface temperature of the heat plate, temperature directly beneath the sample (measured at the grid of the sample holder described below and called grid temperature) and other process parameters were recorded by a data logger.

2.3. Experimental procedures tested

In a first series of tests, single leaves and few needles with the approximate weight of an average leaf (single needles did not ignite) were placed on a grid suspended 20mm above the heating panel with a surface temperature of 530°C. A pilot flame of 25mm length was placed 10mm above the sample. Thus, >1000 experiments were performed with litter of the four different species and at up to 6 different fuel moisture contents (cf. Figure 2). As a variation, bulk samples (2g of the respective fuel weighed after equilibration at a climate of 23°C and 20% relative humidity, later conditioned to the desired fuel moisture content and placed in a 12x12x1cm³ mesh wire basket) were used, which were also suspended above the heating panel with a distance of 50mm and the pilot flame located 30mm above the sample. In this case, the heating panel was run at 47.5% of its maximum power and only few experiments (<50) were performed. Finally, the bulk samples (as described above) were placed on the heating panel directly, with the panel run at 40.0% of its maximum power and the pilot flame 30mm above the samples. An intermediate number of experiments (>500) was performed with this setup.

3. RESULTS AND DISCUSSION

3.1. Single litter elements suspended above the heat plate

Results of the single litter elements experiments for two species are presented in Figure 2. There is a slight increase in ignition time with rising fuel moisture content, however the differentiation is not adequate e.g. for modelling purposes. It can be assumed that the few water contained within the small samples evaporates and disperses too quickly to have much influence on the ignition time, which may also be linked to the very high (530°C) heating panel temperature. Results for European beech (not shown) are very similar to Pedunculate oak, whereas the results for coniferous needles (Scots pine and Norway spruce) are distinctly different and not comparable as they had to be measured from small bulk samples.

3.2. Bulk fuel beds suspended above the heat plate

When bulk fuel beds were placed in roughly the same position, not all samples ignited. The grid temperatures underneath the samples are shown in Figure 3a. Grid temperatures rise much faster and higher underneath the deciduous leaf samples (European beech and Pedunculate oak) than under coniferous needle samples. A temperature threshold for ignition seems to be present at 250-275°C, which is barely reached by the Norway spruce samples, but not by Scots pine samples.

Accordingly, Norway spruce samples ignited later than the deciduous samples and Scots pine samples did not ignite at all. When the sample mass of Scots pine is tripled (data not shown), they also produce a high enough grid temperature and ignite as well. Obviously, the much greater porosity of the needle samples and their consequently lower thermal thickness and higher thermal conductivity leads to this effect. Accordingly, even though there is a much better differentiation of ignition times (Figure 3b) for Pedunculate oak, this setup cannot be used as there are no uniform test conditions for all litter types.

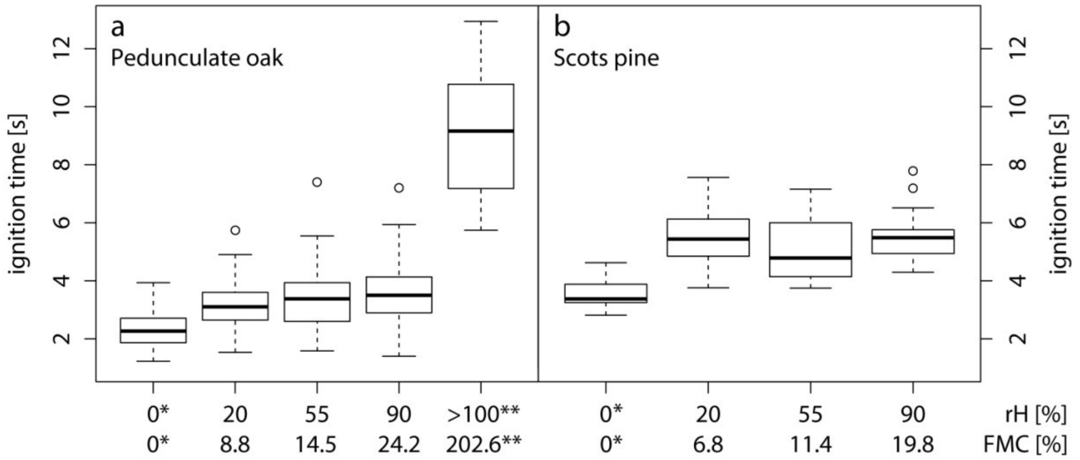

*Figure 2. Ignition time for a) Pedunculate oak and b) Scots pine samples at several climate steps when single leaves/few needles as described above are suspended above the heat plate. FMC: fuel moisture content; rH: relative humidity. * Oven-drying for 24h at 105°C; ** wetting in damp fabric; all others: conditioning at the given rH and 23°C in a climate chamber.*

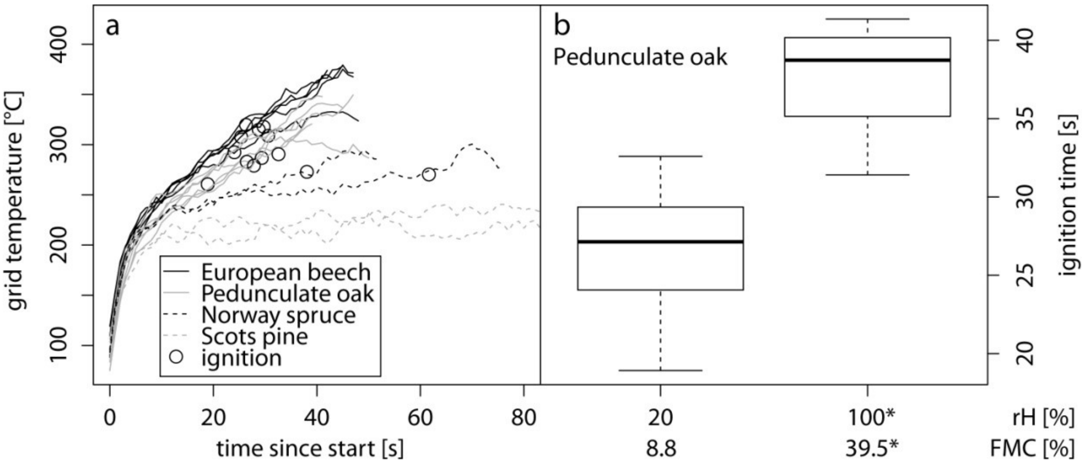

*Figure 3. a) Grid temperature of bulk fuel beds suspended above the heat panel during sample preheating and burning and b) ignition time for Pedunculate oak samples with this test method (right). * Samples conditioned over distilled water in desiccators at 23°C.*

3.3. Bulk fuel beds placed on the heat plate surface

When identical bulk samples of all fuel types are placed on the quartz surface of the heater directly, a much more uniform grid temperature can be observed (cf. Figure 4a), since the heater surface temperature influences the sample directly and effects of radiant heating and heat accumulation on the underside of the samples are much less pronounced. Consequently, ignition occurs for all fuel types across a wide range of fuel moisture. There is a relatively pronounced influence of fuel moisture on ignition time, as can be seen in Figure 4b, and good comparability across the different fuel types (data not shown).

4. CONCLUSIONS

Uniform experimental conditions (i.e. heating curves in this context) for different materials are an essential factor when the results are meant to be comparable. In our experiments, both suspending individual fuel particles and bulk samples above an infrared heating panel did not produce sufficient comparability of ignition times for different fuel types since individual needles did not burn and small bulk samples had to be used instead in the first method. Furthermore, the grid temperatures invoking the ignition of the bulk samples varied depending on the fuel porosity in the second setup. Much more uniform conditions, however, could be achieved when the samples were placed directly on top of the radiant surface, leading to useable results. Alternatively, using a radiative ignition source from above (e.g. the cone-shaped heaters in the ISO 5657 device (Dimitrakopoulos and Papaioannou 2001) or the cone calorimeter (Madrigal et al. 2009)) may also produce suitably uniform conditions.

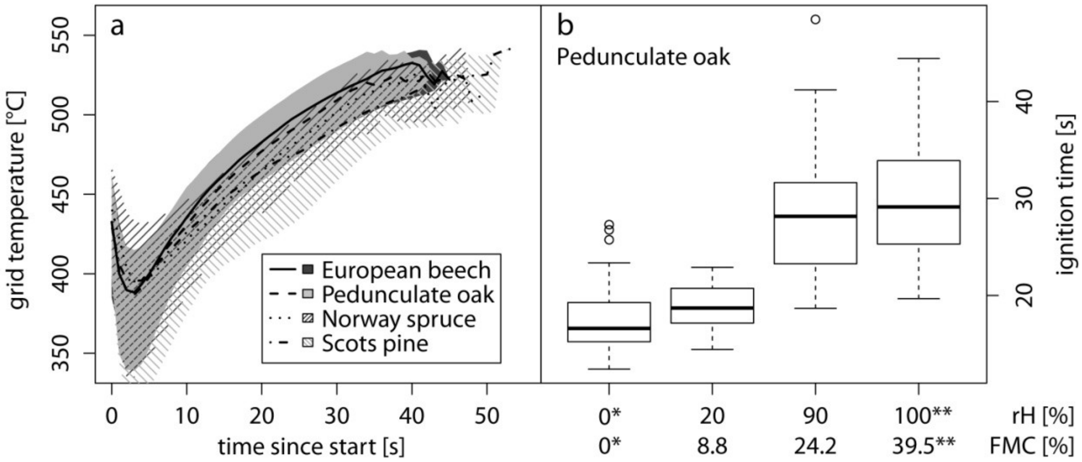

*Figure 4. a) Grid temperature means (lines) and 5th-95th percentile values (shaded areas) during sample preheating and burning for bulk fuel beds placed directly on the heat plate and b) ignition times for Pedunculate oak samples determined with this method. *Oven-drying for 24h at 105°C; ** samples conditioned over distilled water in desiccators at 23°C; all other fuel moistures obtained by conditioning at the given rH and 23°C in a climate chamber.*

5. ACKNOWLEDGEMENTS

The authors would like to thank the Bavarian State Ministry for Food, Agriculture and Forestry (project KLIP 8) and the European Union (ERDF Alpine Space ALP FFIRS project (no. 15-2-3-IT)) for financial support. The authors furthermore gratefully acknowledge the support by the Faculty Graduate Center Weihenstephan of TUM Graduate School at Technische Universität München, Germany.

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Mathematical Modelling of Peat Layer Drying

Filkov A.I., Grishin A.M., Gladky D.A.

National Research Tomsk State University, 36, Lenin ave., Tomsk, 634050, Russia

Filkov@mail.tsu.ru

Abstract

A one-temperature mathematical model for drying of a peat layer is proposed in the work. Peat is considered to be a multiphase media consisting of a dry organic substance, free and bound water, and gas phase. The iterated-interpolation method is used to solve numerically the mathematical model. The volume fraction of water, gas phase, and temperature of a peat layer versus time were obtained. The influence of initial volume fractions content on the drying rate of a peat layer was investigated for different time intervals.

Keywords: multiphase medium, mathematical model, drying, peat layer

1. INTRODUCTION

Peat fires occur regularly. It is very difficult to extinguish such fires even despite extensive rains or attempts of firefighters. These fires may last for a long period of time (from a week to several years (Page et al. 2002; Svensen et al. 2003)) and propagate through a very large area. For example, only in Russia, large-scale peat fires were registered during 50 years in 1972, 1992, 2002, and 2010.

Despite the negative consequences of peat fires, a scientifically based system for fire prediction has not been yet developed, which would allow us to estimate the probable initiation of a peat fire taking into account natural and anthropogenic loads, characteristics of terrain and ground cover, and meteorological conditions as well.

According to (Grishin 2003), among the fundamental factors influencing on initiation of ground forest and peat fires, it is necessary to note the following:

1. The ability of fuels to ignition, i.e. a condition when fuels can ignite from an external source of fire.
2. The ability of fuels to fire propagation, i.e. a condition when fire can propagate spontaneously along a layer of fuels.
3. The presence of natural and anthropogenic sources of fire.

The investigation in the influence of the first two factors is of greater interest. It is obvious, that they are directly connected with the moisture content and drying of fuels. It should be noted that the moisture content of fuels at which fuels can ignite differs from the moisture content at which a fire may propagate along the layer of PF without additional energy sources; in addition, these values are different for different types of fuels. Therefore, the problem solution of fuels drying is of great importance for fire hazard prediction.

With knowledge of the peat layer characteristics for a specific area, it is possible to estimate the probability of fire hazard, which allows us to effectively use the resources directed to prevent and extinguish a fire.

2. FORMULATION OF THE PROBLEM

It is assumed that the peat layer is dried under the influence of the environment. A one-dimensional problem is considered in Cartesian coordinates. The Z-axis is directed vertically downward, the origin of coordinates for the Z-axis is chosen at the boundary between a peat layer and atmosphere. The mathematical model for drying of a peat layer is a single-temperature one, i.e. the gas and condensed phase (carcass) have the same temperature.

Since the drying of a peat layer takes place in nature at low temperatures, we assume that only free water evaporates in the peat layer. Peat during drying is considered to be a multiphase medium consisting of a dry organic substance with a volume fraction φ_1, free and bound water with a volume fraction φ_2, and gas phase φ_3. The peat layer under consideration has a small initial volume fraction of the gas phase φ_{3in} ($0.1 < \varphi_{3in} < 0.2$) compared to the volume fractions of the condensed phase. This mathematical model represents a special case of the model proposed in (Grishin 2005).

The above mathematical problem taking into account the assumptions is reduced to solving the following system of equations:

$$\frac{\partial \rho_3 \varphi_3}{\partial t} + \frac{\partial \rho_3 \varphi_3 v}{\partial z} = Q, \tag{1}$$

$$v = -\frac{\xi}{\mu}\frac{\partial P}{\partial z}, \quad P = \frac{\rho_3 RT}{M_3}, \tag{2}$$

$$\sum_{i=1}^{2} c_{pis}\rho_{is}\varphi_i \frac{\partial T}{\partial t} + c_{p3}\rho_3\varphi_3\left(\frac{\partial T}{\partial t} + v\frac{\partial T}{\partial z}\right) = \frac{\partial}{\partial z}\left(\lambda \frac{\partial T}{\partial z}\right) - q_{2s}R_{2s}, \tag{3}$$

$$\varphi_1 = \varphi_{1in}, \quad \varphi_3 = 1 - \varphi_1 - \varphi_2, \tag{4}$$

$$\rho_{2s}\frac{\partial \varphi_2}{\partial t} = -R_{2S}, \tag{5}$$

$$Q = R_{2s}, R_{2s} = \frac{\rho_{2s}\varphi_2 k_{2s}\exp(-E_{2s}/RT)(1-RH)}{\sqrt{T}}. \tag{6}$$

To solve the system of equations (1)-(6), the following initial and boundary conditions are used:

$$T|_{t=0} = T_{in}, \quad \rho_3|_{t=0} = \rho_{3in}, \quad \varphi_i|_{t=0} = \varphi_{i\,in}, \quad i = 1{,}2, \tag{7}$$

$$P|_{z=0} = P_e, \quad \frac{\partial P}{\partial z}|_{z=L} = 0, \quad \lambda\frac{\partial T}{\partial z}|_{z=0} = \alpha_e(T_e - T_w) + \varphi_{sw}q_{rw} - q_{2s}R_{2s}, \quad T|_{z=L} = T_{in}, \tag{8}$$

$$q_{rw} = (1-A)q_R(h)\cos\alpha - \varepsilon_s \sigma T_w^4 + J_w \cos\alpha. \tag{9}$$

where t is the time; z is the spatial coordinate; φ_i, i=1,2,3 is the volume fraction; i=1,2,3 is peat, free and bound water, gas phase, ρ_i, i=1,2,3 is the density; v is the rate of gaseous products during the reaction of evaporation; Q is the mass rate of the gas phase formation; P is the gas pressure in pores; $\mu = \mu_{in}(T/T_{in})^{0,5}$ is the dynamic viscosity coefficient of a gas mixture; $\xi = \xi_* \varphi_3^3/(1-\varphi_3)^2$ is the function describing the influence of a volume fraction on resistance; $\xi_* = d_p^2/120$ is the characteristic permeability; d_p is the pore diameter; M_3 is the molecular weight of gas; R is the universal gas constant; T is the peat temperature; c_{pi}, i=1,2,3 is the heat capacity coefficient; k_{2s} is the pre-exponential factor of an evaporation reaction; E_{2s} is the energy of activation characterizing evaporation of water; R_{2s} is the mass rate of water evaporation in peat; q_{2s} is the thermal effect of a reaction R_{2s}; λ is the heat conductivity coefficient; T_e is the environment temperature; $\alpha_e = \sqrt{\upsilon}\left(7 + 7.2/\upsilon^2\right)$ is the heat exchange coefficient between peat and environment; υ is the wind speed; q_{rw} is the flux density of resulting radiation on the boundary line; A is the albedo of a peat layer; $q_R(h)$ is the total radiation flux at the upper boundary of a peat layer; α is the angle between a horizontal plane and peat layer; ε_s is the emissivity coefficient of a layer; σ is the Stefan-Boltzmann constant; J_w is the flux density of longwave radiation at the upper boundary of a peat layer; RH is the relative air humidity. Indexes: s is the condensed phase; e is the environment; in is the initial value; w is the state parameter at $z = 0$.

3. METHOD OF CALCULATION AND DATABASE

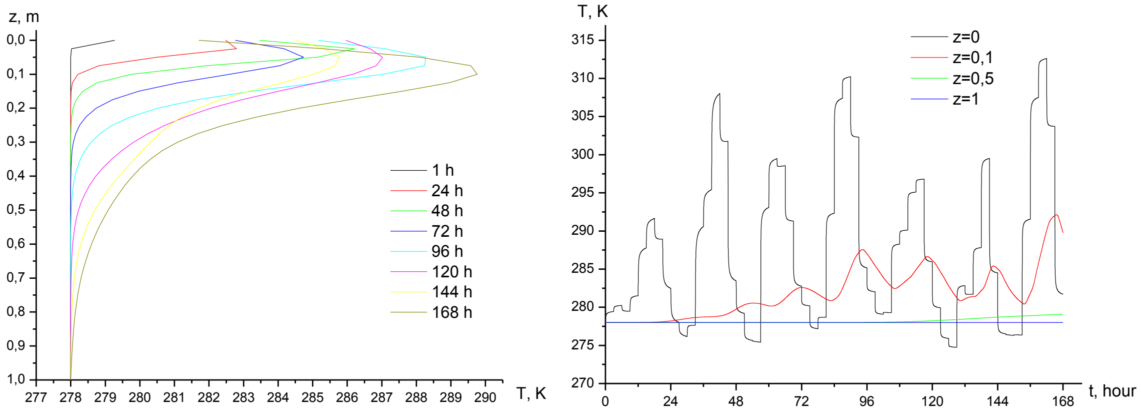
The system of equations was numerically solved by the iterated-interpolation method with a constant time-step in compliance with the technique described in (Grishin et al. 2004). The changes of the initial volume fractions, pressure, and temperature were analyzed according to the results of simulation for various time intervals.

The following parameters were used in the calculations: L=1 m, T_{in}=278 K, λ_1=0,041 W/(m·K), C_{p1}=951 J/(kg·K), C_{p2}=4183 J/(kg·K), C_{p3}=1020 J/(kg·K), M_3=0,029 kg/mole; ρ_2=1000 kg/m^3, ρ_3=1,18 kg/m^3, d_p=5·10^{-4} m, R=8,314 J/(mole·K); $\alpha=0°$; q_{2s}=2250 J/kg; ε_s=0.7; A=0.6; $\sigma = 5.67\cdot10^{-8}$ W/m^{2}K^4; φ_{1in}=0,243; φ_{2in}=0,598; φ_{3in}=0,159; μ_{in}=1,81·10^{-5} Pa·s; E_{2s}=36762 J/mole; k_{2s}=0,482·10^4 K$^{0.5}$·s^{-1}; ρ_1=815 kg/m^3; W=312 %. The formulas proposed in (Grishin, 1994) were used to change from a moisture content to the volume fractions. As meteorological information we used the data on the temperature of air and soil, relative air humidity, wind speed, total radiation flux from 18 to 24 May 2000 at an interval of 3 hours provided by the Goverment Institution CHME-RSMC (Novosibirsk) and V.E. Zuev Institute of Atmospheric Optics of SB RAS.

For a quantitative check, the results of numerical modelling were compared with the experimental data on drying under isothermal conditions at the temperature of 50 ºC, and dynamic conditions at heating rates of 20 and 30 K/min (Cancellieri et al. 2012, Kuzin et al. 2012) obtained for the three types of peat.

4. RESULTS OF NUMERICAL SOLUTIONS AND ANALYSIS

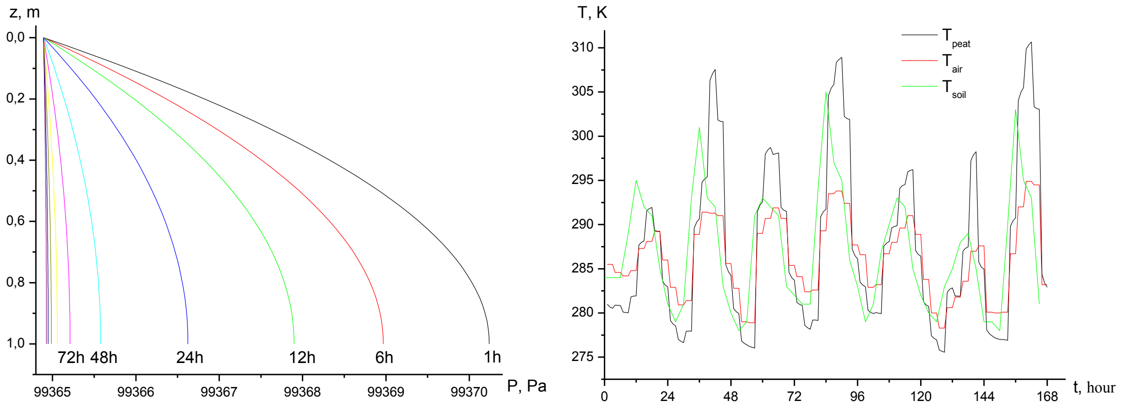
The numerical solution of a mathematical model (1)-(5) based on real weather conditions over a time interval of one week allowed us to carry out test calculations and obtain the peat layer temperature (Figure 1), pressure and parameters of the environment state at the upper boundary of peat (Figure 2), and moisture content (Figure 3) versus time.



a b

Figure 1. Temperature distribution of the peat layer at different moments of time: a - according to the depth of the layer, b - for different values of z

The analysis of the numerical solution (Figure 1a) demonstrates that the increase in time leads to the increase in temperature at the upper boundary, and the layer is uniformly warmed from a surface into the depth of a layer. The temperature inflection of the peat layer at the upper boundary is connected with the selected air temperature. The curves in Figure 1a correspond to midnight. At this time, the air temperature is low, and the temperature of the upper peat layer is higher due to heating over the previous day and peat does not cool down by 00.00 hours. From Figure 1b it is seen that the temperature of the peat layer at z = 0 depends on the parameters of the environment, increases and decreases depending on the time of day. With the increase in depth of the layer the dependence decreases and daily fluctuations of meteorological parameters do not influence on the layer temperature at z = 0.5, which corresponds to (Kovrigo et al. 2000). At the same time, a heat wave comes to a depth of 0.5 m only after 4 days.



a b

Figure 2. a - pressure of the gas phase versus the depth of the peat layer for different moments of time, b - temperature profiles for the parameters of the environment at the upper boundary of the peat layer for different moments of time

The Figure 2a shows that the pressure of the gas phase in a layer of peat increases in depth, which corresponds to the physics of the process. However, during drying the pressure is counterbalanced and tends to atmospheric pressure due to gas filtration. It is also seen that the temperature curve of the peat layer in Figure 2b is in qualitative agreement with the data. The increase in air temperature leads to the increase in peat temperature correspondingly. At the same time, the temperature of the peat layer and soil is much higher than the air temperature at the hottest hours. It can be explained by heating due to radiation from the Sun. In addition, since the emissivity coefficient of peat is higher than the emissivity coefficient of soil, the maximum temperature of peat exceeds the maximum temperature of soil by several degrees. The maximum difference in temperature between the air and peat is about 15 degrees. According to (Mironov et al. 2004), the temperature of the upper peat layer can be 15-17 °C higher than the temperature of environment under the influence of solar intensity, which corresponds to our results. It is also known (Solov'ev, 2006) that daily evaporation is almost in direct proportion to the number of sunshine hours during the day. In addition, the drying of peat requires about 60% of the total solar radiation falling on the surface of peat. At the same time, the peat surface temperature greatly exceeds the environment temperature.

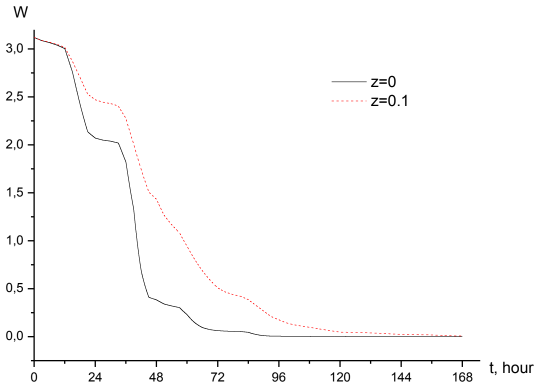


Figure 3. Change in moisture content of the peat layer during a week for the different depth of z. Time 0 h corresponds to midnight.

The analysis of the curves in Figure 3 shows that the upper layer of peat is dried quite fast with the increase in time. However, the drying depends on the parameters of the environment. It is seen that the absence of precipitations and the positive air temperatures result in the fact that after 4 days the upper layer 0.1 m in thickness dries out to the moisture content that is less than critical one. And, accordingly, it can be ignited by any source of ignition. For a quantitative comparison of the received results, the numerical experiments were conducted for isothermal conditions at a drying temperature of 50 ºC for three types of peat. It was modeled drying with a halogen lamp in the AND MX-50 moisture analyzer (Kuzin et al. 2012). The analysis of the experimental curves showed that starting from a certain moment of time, the rate of peat drying decelerated in contrast to the calculated data. This moment of time was determined by the final stage of drying, when the experimental curve was stationary. This difference of the numerical data is connected with a peculiarity of the mathematical model that takes into account only evaporation of free water in the layer of peat. It means that in the model (1) - (5) the free and bound water are combined and described by the parameter φ_2. Thus, this model will give lower values of moisture content and, correspondingly, increased fire hazard for the long-term prognosis (more than a week). For dynamic drying, the conditions of evaporation were modeled in the thermogravimetric analyzer (Cancellieri et al. 2012) for the three types of peat. The comparison results were in good agreement with the data for the 1 and 2 peat samples. The difference in the data for the sample 3 it can be explained by a low degree of decomposition (10.5% against 20% and 40% for the samples 1 and 2) and, accordingly, strong heterogeneity. It also follows that the increase in temperature results in the difference between experimental and numerical data. However, this process starts at 350 K for the samples 1 and 2, and at 330 K for the sample 3.

5. CONCLUSION

The conducted mathematical investigation shows that the obtained numerical results are in qualitative and quantitative agreement with the experimental data. However, this model, like any other, has some restrictions. In particular, for optimum accuracy, the maximum drying temperature should not exceed 330 K and the time of prediction is no more than one week. For the reason that the air temperature in the boreal zone is rarely higher than 320 K, we can draw a conclusion that the proposed model (1)-(5) can be used to predict the behavior of moisture content and temperature in the layer of peat for the subsequent prediction of peat bog fires.

This work was supported by the Russian Foundation for Basic Research (projects no. 1-01-00673-a, 11-01-00228-a and 10-01-91054 SCSR-a).

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CLIMATE AND FIRES

Fire–weather relationship in the Italian peninsula

Masala F.[1], **Bacciu V.**[1,2], **Sirca C.**[1,2], **Spano D.**[1,2]

[1]*Department of Science for Nature and Environmental Resources (DipNeT), University of Sassari, Italy,* [2]*Euro Mediterranean Center on Climate Change (CMCC IAFENT), Sassari, Italy*

masala.francesco@email.it, valentina.bacciu@cmcc.it

Abstract

Climate and weather are two of the main key factors influencing fire regime and they have a number of different effects on fire. The objective of this work is to improve our knowledge of the relationship between meteorological variables and forest fire across Italian peninsula. In the first part of this work, we collected meteorological and fire events data. The second part of the work involved the assemblage of fire and weather data into a GIS to facilitate manipulation and display of the data and the classification of Italian peninsula in homogeneous climatic areas, through hierarchical cluster analysis of meteorological data. A set of parametric and not parametric statistical tests were used to analyse the fire-weather relathionships. The results showed that both fire number and burned area are highly related with rainfall in summer and winter, considering both peninsular Italy and each cluster. The results confirmed the crucial role of high resolution datasets in analyzing fire and weather trends and relationships, and could be promisingly applied as input to develop and calibrate models for studying the impacts of climate change on fires.

Keywords: fire regime, MARS, piro-climatic areas

1. INTRODUCTION

Fire is one of the most frequent and widespread ecosystem disturbing phenomena (Bowman et al. 2009; Krawchuk et al. 2009), in particular in areas with a Mediterranean climate (Keeley et al. 1999; San Miguel and Camia 2009; van Wilgen et al. 2010). According to several studies, the Mediterranean Basin wooded areas affected by fires cover annually an area of 1000 x 10^3 ha, causing significant economic and ecological damage (Velez 1997). On average, from 2000 to 2005, about 95,000 fires occurred annually in 23 European countries, burning almost 600,000 ha of forest land every year. Within these, about two-thirds (65,000 fires) occurred in 5 Euro-Mediterranean countries (France, Greece, Italy, Portugal, and Spain) where, on average, half a million hectares of forest land were burned every year (Barbosa et al. 2008).

Climate and weather are two of the main key factors influencing fire regime and they have a number of different effects on fire. Weather determines fuel moisture, influences lightning ignitions, and contributes to fire growth through wind action (Carvalho et al. 2008). Worldwide, a number of studies have analyzed the relationship between weather and forest fires but only few analyzed this relationship in Mediterranean ecosystems and at broader scale.

In Spain, Vázquez and Moreno (1993) showed strong relationships between temperature and precipitation variables, particularly of extreme values of these variables and burned area. These relationships, however, varied among areas with different climate. In Portugal, Viegas and Viegas (1994) indicated a non-linear relationship between burned area and rainfall so that, depending on the time of rainfall, this could promote or deter the burned surfaces. Pausas (2004) showed how summer rainfall was significantly related to the inter-annual variability in the burned area, showing also a significant cross-correlation for a time lag of two years in Valencia district (Spain). In Canada, weather–climate has been established as the most important natural factor influencing forest fires (Stocks and Street 1983; Flannigan and Wotton 2001; Hely et al. 2001).

Despite all these efforts, region specific analysis of the driving forces of fire regime are still needed to better understand this issue. In this context, this paper aims to contribute and improve our knowledge about the relationships between meteorological variables and wildfires at National level in Mediterranean ecosystems.

2. MATERIALS AND METHODS

In the first part of this work we collected meteorological and fire data to analyze the relationships between fire and weather in the Italian peninsula. The meteorological variables (maximum and minimum temperature, relative humidity, precipitation and wind speed) were obtained at daily scale through the MARS (Monitoring Agricultural Resources) database interpolated at 25x25 km scale. The fire database available for Italy was provided by JRC (Join Research Center) and contains the monthly number of fires and total area burned at provincial level from 1985 to 2008.

To analyze the effects of weather variables on fire, it was decided to homogenize the time scale of MARS database to the JRC, therefore monthly mean were calculated from MARS daily data for each year.

The second part of the work involved the assemblage of fire and weather data into a GIS to facilitate manipulation and display of the data, and the classification of Italian peninsula in homogeneous piro-climatic areas, through a non-hierarchical cluster analysis of meteorological and fire data. In each identified area, descriptive statistics were initially calculated to determine the differences on fire regime and weather conditions. Then, we proceeded with the seasonal and annual trend analysis through parametric and non-parametric tests to assess whether the inter-annual variability in weather patterns and in fire events had a significant trend. Finally, Pearson correlation and linear regressions were carried out to characterize the relationship between meteorological variables and forest fires.

3. RESULTS

The results obtained from cluster analysis showed, for peninsular Italy, five different piroclimatic areas with different fire regime (Figure 1). Cluster 1 represents the Alpine zone with severe winter and high amount of cumulative rainfall, where the fire regime is typically concentrated in winter and fire occurrence is very low compared with the other areas. Cluster 2 and 3 are very different from fire statistic and termo-pluviometric points of view. Cluster 3, mainly constituted by Liguria region, has a typically Mediterranean climate (T max 17.26 °C, T min 9.87 °C, rainfall 780 mm), but fire regime is not exclusively on summer and occurrence is higher than Cluster 2 and 1 (Table 1). Cluster 4 represents mainly the center of the peninsula, and although fire regime is framed mainly during summer, it has some fire occurrence during spring. Finally, Cluster 5 is represented by Southern Italy. In this zone, fire occurrence is concentrated during summer. This Cluster represents the area were the fire occurrence is the highest among all clusters: the recorded number of fire is more than 89,000 and the burned area is more than 1,086,000 ha. This is probably due to the type of climate, represented by mild winters, T min 11.47 °C, and dry summers, with T max of 19.97 °C and rainfall of 626 mm (Table 2).

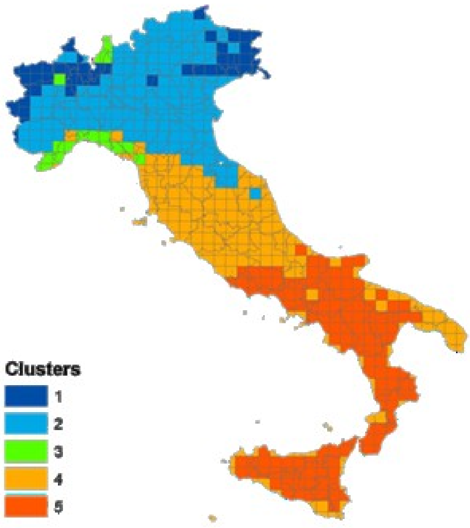

Figure 1. Categorization of Italy in the five cluster recognized by the cluster analysis.

Table1. Fire statistics and fire seasonal occurrence for the 5 different clusters recognized by the cluster analysis

Region	Burned area (ha)	Number of Fires	Fire season
CL 1	96,794	9,981	Jan-Apr
CL 2	178,867	20,892	Jan-Apr, Jul-Sept
CL 3	179,576	19,989	Jan-Apr, Jul-Sept
CL 4	407,519	43,167	Mar, Jul-Sept
CL 5	1,086,523	89,092	Jun-Sept

Table 2. Termo-pluviometric characteristics for the 5 clusters recognized by the cluster analysis

Region	T max (°C)	T min (°C)	Rainfall (mm)
CL 1	14.12	5.26	1,123
CL 2	16.31	7.00	734
CL 3	17.26	9.87	780
CL 4	19.80	10.48	666
CL 5	19.97	11.47	626

The trends of the fire data were analyzed both for all peninsula and for each cluster to have some inferences on the evolution of fires through the investigated period, and in the different piro-climatic areas. Trend analysis was done using parametric and non-parametric tests. Table 3 and 4 show the slope of the regression line, the standard error, and the Mann-Kendall test for fire and weather data. In general, our study showed that fire activity is decreasing, despite the overall trend of increasing temperatures in most of Italy (Table 3, 4). Considering the entire peninsula, the annual trend of burned area is decreasing (F= 0.75, $p<0.05$), even if the result is not confirmed by the Mann-Kendall test. On the other hand, the Mann-Kendall test confirmed the decreasing trend of fire number ($p<0.01$). Different clusters have been undergoing different trends. For example, in Northern Italy the Cluster 1 showed a significant decreasing trend for fire number, and for burned area, while Cluster 2 had a significant trend only for fire number. Cluster 3 showed a very significant decreasing trend for both fire number and burned area, while Cluster 4 trend was not confirmed by Mann-Kendall test (Table 3). Finally, Cluster 5, that represents the Southern part of the Peninsula, showed not significant trends.

Table 3. Anova and Mann-Kendall results for burned area (BN) and fire number (FN) trend for peninsular Italy and for each cluster

	Variable	**Slope**	**Standard error**	**F**	**p**	**Test Z**	**Sig.**	**Q**
Italy	BA	-1176.88	1354.96	0.75	*	-1.46	n.s.	-1693.696
	FN	-195.76	70.13	7.79	n.s.	-2.60	**	-181.654
CL 1	BA	-244.92	113.24	4.68	*	-2.80	**	-153.30
	FN	-15.93	4.54	12.33	**	-2.95	**	-13.88
CL 2	BA	-440.41	244.18	3.25	+	-2.21	+	-224.22
	FN	-28.80	11.06	6.78	*	-2.51	*	-25.57
CL 3	BA	-480.98	187.54	12.23	**	-3.55	***	-412.30
	FN	-49.42	8.44	34.29	***	-4.29	***	45.51
CL 4	FN	-48.51	20.39	5.66	*	-1.86	+	-41.37

n.s.= not significative; + p= 0.10; * p= 0.05; ** p= 0.01; ***p= 0.001

Table 4. Anova and Mann-Kendall results and for maximum temperature (Tmax), minimum temperature (Tmin) and Rainfall for peninsular Italy

	Variable	**Slope**	**Standard error**	**F**	**p**	**Test Z**	**Sig.**	**Q**
Italy	T max (°C)	0.04	0.01	12.58	**	2.95	**	0.045
	T min (°C)	0.06	0.010	35.29	***	4.14	***	0.062
	Rainfall (mm)	3.19	2.63	1.47	n.s.	0.97	n.s.	3.098

n.s.= not significative; + p= 0.10; * p= 0.05; ** p= 0.01; ***p= 0.001

In order to analyze the relationships between fire and weather, Pearson's correlation coefficients were calculated at national and cluster scale, both annually and seasonally. The variable that seems to be mostly correlated with the fire occurrence is the precipitation (Table 5, Figure 2). Considering the whole Italy, summer and winter rainfall are highly correlated with summer and winter fire number ($r=0.68$, $p<0.01$). This pattern is also present at cluster scale: for example, in the Southern Clusters (4 and 5) summer rainfall is strongly correlated with fire number (respectively, $r= -0.72$ and -0.70, for $p<0.01$) and burned area ($r=-0.66$ and -0.65, with $p<0.01$). On the other hand, Northern Clusters 1 and 2 are highly correlated with summer T max (respectively, $r= 0.75$ and 0.71 with $p<0.01$ for fire number, and $r=0.73$ and 0.62 with $p<0.001$ considering burned area). Finally, linear regressions were calculated for all Italy and for all significant Pearson's correlation (Table 6). In particular, the best results were obtained analysing the relationship between winter and summer rainfall and fire number (R^2=0.46, p<0.001; R^2=0.47, p<0.001).

Table 5. Statistically significant Pearson's correlation between number of fires, burned area and selected meteorological variables.

	Italy		**Pearson's correlation**
Annual	Rainfall (mm)	Fire Number	-0.51 *
		Area burned (ha)	-0.56**
Winter	Rainfall (mm)	Fire Number	-0.68**
		Area burned (ha)	-0.58**
Spring	Rainfall (mm)	Fire Number	-0.43*
	T min (°C)	Fire Number	-0.50*
Summer	Rainfall (mm)	Fire Number	-0.68**
		Area burned (ha)	-0.52**

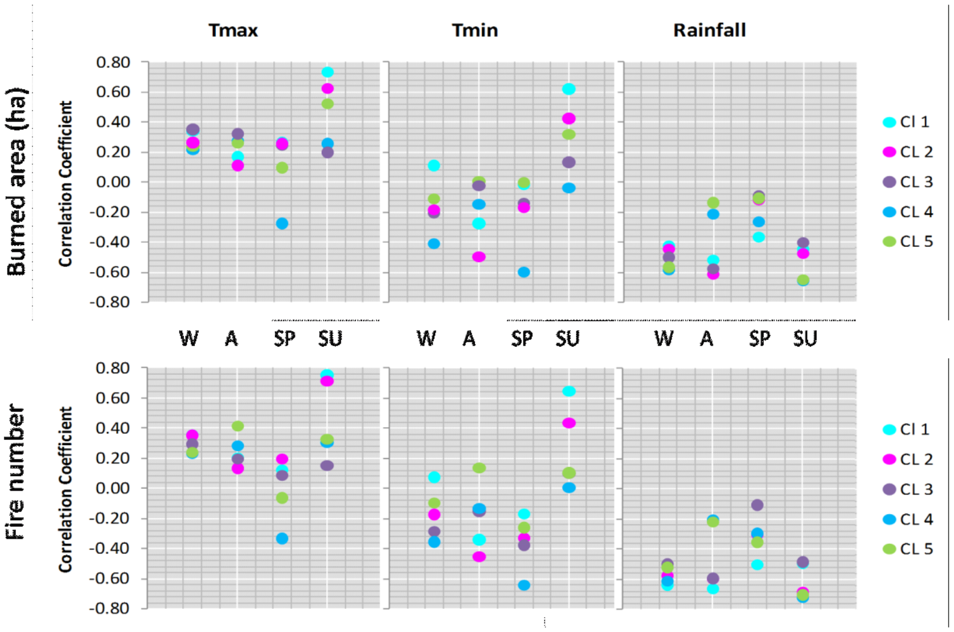

Figure 2. Pearson's correlation between the number of fires and burned area with meteorological variables (Tmax, Tmin and Rainfall) for each season and for each cluster

Table 6. Relation between yearly fire number and burned area and rainfall in Italy

Season	Fire variable (y)	Weather variable (x)	Slope	R^2	R^2adj	F	*p*
Annual	Fire number	Rainfall	- 15.34	0.26	0.23	7.7	*
	Burned area		- 285.67	0.32	0.29	10.2	**
Winter	Fire number	Rainfall	-11.86	0.46	0.43	18.64	***
	Burned area		-133.04	0.33	0.30	10.89	**
Summer	Fire number	Rainfall	- 35.25	0.47	0.44	19.35	***
	Burned area		- 583.28	0.30	0.24	8.12	**

* *p*= 0.05; ** *p*= 0.01; *** *p*= 0.001

4. CONCLUSION

The present work investigated the relationship between the weather and fire occurrence. The use of cluster analysis showed this tool as useful method to characterize fire-weather relationships at national level, allowing to clusterize the different piro-climatic situations.

In general, both the fire number and burned area are highly significantly related with rainfall in summer and winter in Southern Italy, while in the Northern areas, especially in the plains, both fire number and burned area are significantly related to summer Tmax. This could be due to the different factors that interfered with climatic variables. In Southern areas, for example, where the main economy is agriculture and the land use is highly exploited by anthropogenic activities, the fire causes are strongly related with socio-economic factors. Going Northern, as highlighted by Zumbrunnen et al. (2009), the abandonment of traditional land use, due to the transformation of the economy, could have incremented the debris in the forest, and then the influence of climatic factors in the indirect way could explain the fire activity.

The results of this work provide a valuable contribution in understanding the effect of weather conditions on fire number and burned area, and can be used as input for the development and calibration of models for the assessment of future impacts of climate change on fire.

5. ACKNOWLEDGEMENTS

This work was partially funded by the European Union Seventh Framework Programme (FP7/2007-2013) under Grant Agreement 243888 (“FUME” Project - Forest fires under climate, social and economic changes in Europe, the Mediterranean and other fire-affected areas of the world).

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Analysis of climatic conditions influencing wildfire static risk in Sardinia and Liguria (Italy)

Bodini A.[1], Entrade E.[1], Cossu Q.A.[2], Fiorucci P.[3], Biondi G.[3]

[1]*Institute of Applied Mathematics and Information Technology "E. Magenes", Milano (Italy); [2]Environmental Protection Agency of Sardinia, Sassari (Italy); [3]Cima Foundation, Savona (Italy)*

antonella.bodini@mi.imati.cnr.it

Abstract

Climate variability influences the occurrence of large wildfires on multiple time scales through its effects on the availability and flammability of fuels. In a recent study conducted in Sardinia and Liguria (Italy), fire perimeters have been used to inquire spatialized climate indexes and the vegetation cover (Bodini et al. 2011). Based on the statistical analysis, a certain number of Type of Homogeneous Areas (THA) has been defined by introducing information on vegetation cover. The comparison of THA and climatic indexes allowed the definition of a risk index. In this paper, more details about the climatic conditions affecting wildfire static risk are presented.

Keywords: climate change, linear regression test, Mann-Kendall test, wildfire risk

1. INTRODUCTION

Fire is the most important natural threat to forests and wooded areas of the Mediterranean basin, where a large percentage of fires are human-induced (Alexandrian et al. 1999). Despite the fact that in the Mediterranean basin fires have occurred for millennia and plants have the capacity to cope with them, current fire regimes may causes disasters, i.e. ecosystem degradation like irreversible soil losses or strong vegetation changes. Moreover, wildfires introduce a high risk of direct damage to humans and structures in most of the highly populated Mediterranean countries and especially in coastal regions (Pausas et al. 2008). Extreme weather events, such as extended drought, accumulation of fuels (often due to years of suppression activity), increasing human occupation of fire-dependent ecosystems, unchecked biomass burning and escaped fires in tropical regions and climate change are some of the main factors determining an increased frequency of catastrophic wildfires (Liu et al. 2009). Climate variability influences the occurrence of large wildfires on multiple time scales through its effects on the availability and flammability of fuels. Climate controls the spatial distribution of vegetation, and the interaction of that vegetation and climate variability largely determines the availability and flammability of the live and dead vegetation that fuels wildfires (Westerlin 2010).

In Bodini et al. (2011; hereafter referred to as B2011) fire perimeters have been used to inquire spatialized climate indexes and the vegetation cover in Sardinia and Liguria (Italy). Liguria is a region of 5400 km^2 lying on the northwest coast of the Tyrrhenian Sea. In this Mediterranean region, wildfires are recurrent phenomena both in summer and winter: an average of 365 wildfires of size greater than 0.01 km^2 burns an area of 55 km^2 per year. Sardinia is the second-largest island in the Mediterranean Sea. Wildfires represent a severe threaten to life and goods during summer. On average, between May and October more than 2500 fires burn more than 310 km^2 of shrubland, grassland and forests per year. Based on a statistical analysis, in B2011 a certain number of Type of Homogeneous Areas (THA) has been defined by introducing information on vegetation cover. The comparison of THA and climatic indexes allowed the definition of an index of static risk. In this work, more details about the climate analysis yielding the risk maps proposed in B2011 are presented.

2. MATERIAL AND METHODS

In Italy, meteorological data have been collected by the Governmental Hydrographic Service since 2002. After that, competences have been transferred to Regional Institutions. In Sardinia, historical data are managed by ADIS (*Agenzia del Distretto Idrografico della Sardegna*). In Liguria, the current meteorological network OMIRL (*Osservatorio Meteo Idrologico della Regione Liguria*) is managed by the Civil Protection Hydrometeorological *Centro Funzionale* with the technical support of the Regional Environmental Protection Agency of Liguria.

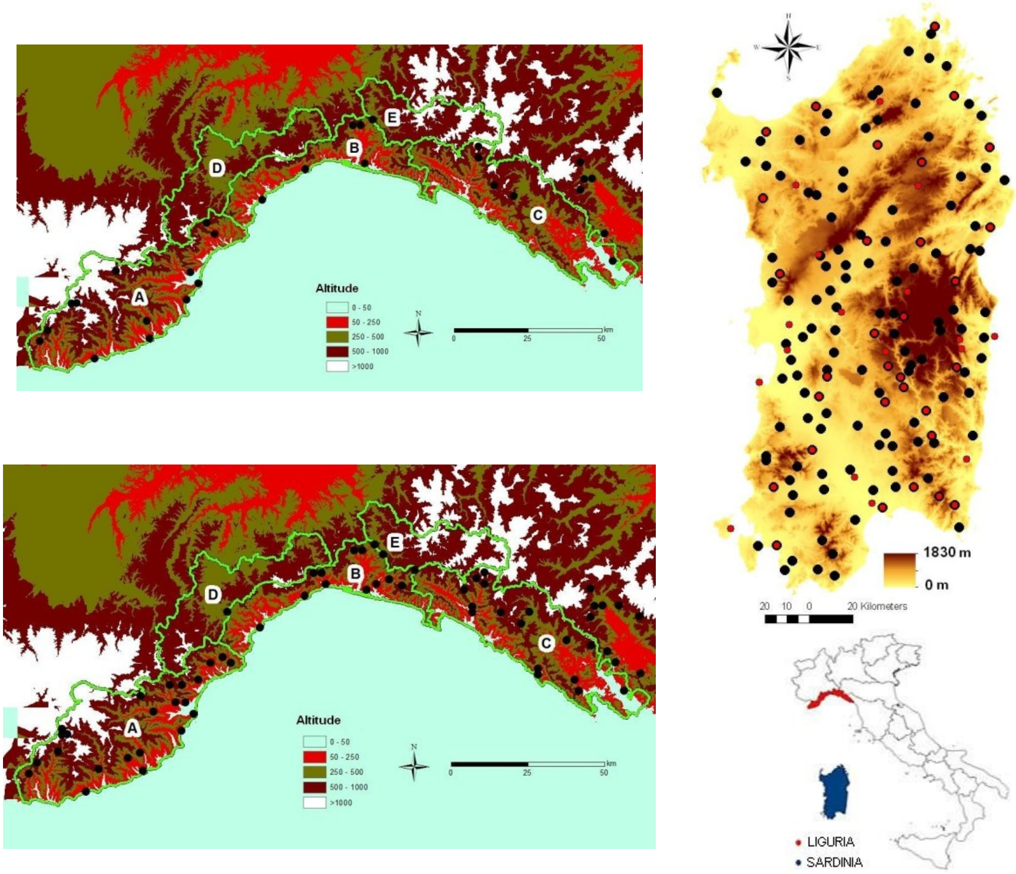

Figure 1. Spatial distribution of the meteorological stations on a Digital Elevation Model of Liguria (left) and Sardinia (top right). On the left, thermometric (top) and pluviometric (bottom) stations in Liguria. On the top right: pluviometric (black) and thermometric (red) stations in Sardinia.

Daily rainfall and temperature data referring to the period 1951–2008 have been analyzed using time series a) with more than 30 years of complete records for trend analysis, and b) with more than 20 years of complete records in the standard period 1971-2000, for climate analysis. Data quality has been originally checked by the data provider and further by the authors, through the analysis of the temporal and spatial coherence of several summaries of the data. Data inhomogeneity has been dealt with a careful examination of graphs: stations showing step changes have been discarded (Alexander et al. 2006). This procedure allowed to select 144 stations for rainfall analysis and 47 stations for temperature analysis in Sardinia, and 57 and 24 stations respectively in Liguria (see Figure 1). To increase the spatial coverage in Eastern Liguria, data from about 10 stations in Tuscany (Italy) have been analysed as well. Trend analysis is generally based on a subset of these time series: in Liguria, only 2 meteorological stations can be considered for the analysis of temperature trend, which has been therefore omitted.

Several climate indexes recommended by the ETCCDMI (see, e.g., Alexander et al. 2006) have been analyzed: frequency of rainy days (≥ 1 mm), F; total precipitation, TP; minimum (Tmin), maximum (Tmax) and mean (Tday) daily temperature; maximum number of consecutive dry days, CDD; heat wave duration index, HWDI: maximum period > 5 consecutive days with Tmax > 5 °C the 1971-2000 Tmax normal; maximum 5 days total precipitation, R5D.

Trends have been checked by both the linear regression test and the non parametric Mann-Kendall test (statistical significance equal to 0.05; Sneyers 1990), to take into account missing data. As estimates of the linear trend are sensitive to points at the start or end of the data set (Wigley 2006), a sensitivity analysis has been carried out, and trends have been considered as significant when significance has been obtained after removing eventually influencing points as well.

Interpolated maps of both long-term (over the entire period) and normal values (over the standard period 1971-2000) have been obtained by either kriging or multiple regression with geomorphological variables (elevation, sea distance, latitude and longitude).

3. RESULTS

As Sardinia is affected by the fire phenomenon only in summer whilst Liguria is affected by fires also in winter, the analysis has been carried out at two different scales: annual in Sardinia and seasonal in Liguria. Two seasons have been considered: winter (November-April) and summer (May-October).

3.1. Trend analysis

In the following, only significant trends will be discussed. In almost all the cases, the linear regression test and the Mann-Kendall test have provided the same results: discordant results have been considered here as an indication of a doubtful result, and in turn, the trend has been considered as not significant.

In Sardinia, only the 8% of the considered stations shows both annual total precipitation (TP) and number of rainy days (F) to be decreasing. More in general, TP decreases in the 40% of the cases, while F only in the 15%. In the 37% of the cases with decreasing TP, R5D decreases as well and this trend is shown by a further 8% of cases. This is particularly relevant from the point of view of hydro-geological risk. Indeed, Figure 2 highlights that

R5D decreases in areas with high values. In the 22% of cases, the maximum number of dry days (CDD) decreases and this mainly occurs in the area with the longest dry spell.

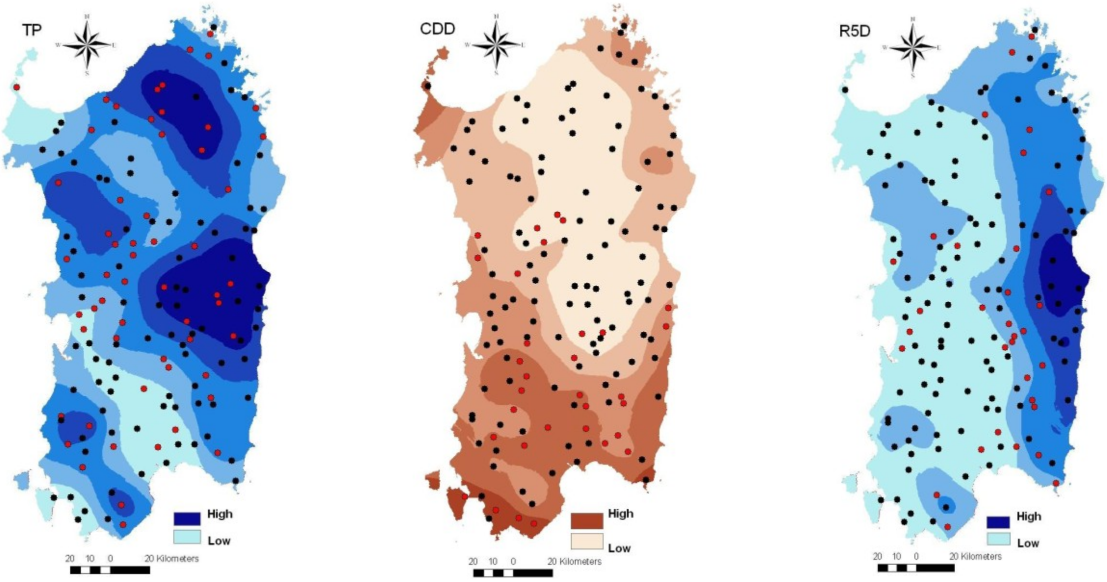

Figure 2. Spatial distribution of the long-term values of TP (left), CDD (centre) and R5D (right) in Sardinia, based on kriging for the safe of a clear representation. Red dots: significant decreasing trend.

Regarding the temperatures, the trend is less clear also due to the lower number of available time series (40) and to contrasting results. The mean temperature (Tday) increases in about 15 stations (37%): only in 5 cases both Tmin and Tmax increase. However, five stations show decreasing Tday, corresponding to decreasing Tmax. Sparsely distributed increasing trends are obtained for the extreme indices HWDI and Tn90 as well, in 15 and 17 cases respectively.

In Liguria, the 13.5% of the considered stations shows both TP and F to be decreasing at the annual time-scale, and a further 21% shows either TP or F to be decreasing. The seasonal analysis indicates that decreasing TP is obtained in winter (42%, see Figure 4) but not in summer, and the trend concerns the area with lower TP. Unlike Sardinia, a complete lack of trend is obtained for CDD in both seasons. As in Sardinia, decreasing R5D is often (46%) obtained in time series showing decreasing TP, however in Liguria the area showing the highest R5D values is not interested by trend.

3.2. Long-term and normal values

In B2011, for each climate index a finite number of classes has been defined on the basis of a preliminary analysis of the fire perimeters. These classes have been compared to land cover classes to derive the THAs. Figure 3 shows the obtained risk maps. The highest risk areas are characterized by high air temperature and long dry periods in summer, and winter rainfall amounts from moderate to high, but not extreme. In Sardinia, the relevance of high temperatures to wildfire risk is stressed by high HWDI values as well, as can be seen by comparison of Figure 3 (right) and Figure 4 (centre). The spatial distribution of all but HWDI indices strongly varies with altitude. In Sardinia, long-term rather than normal values have been considered for rainfall data to include heavy and extreme rainfall occurred during the period from 1951-1965.

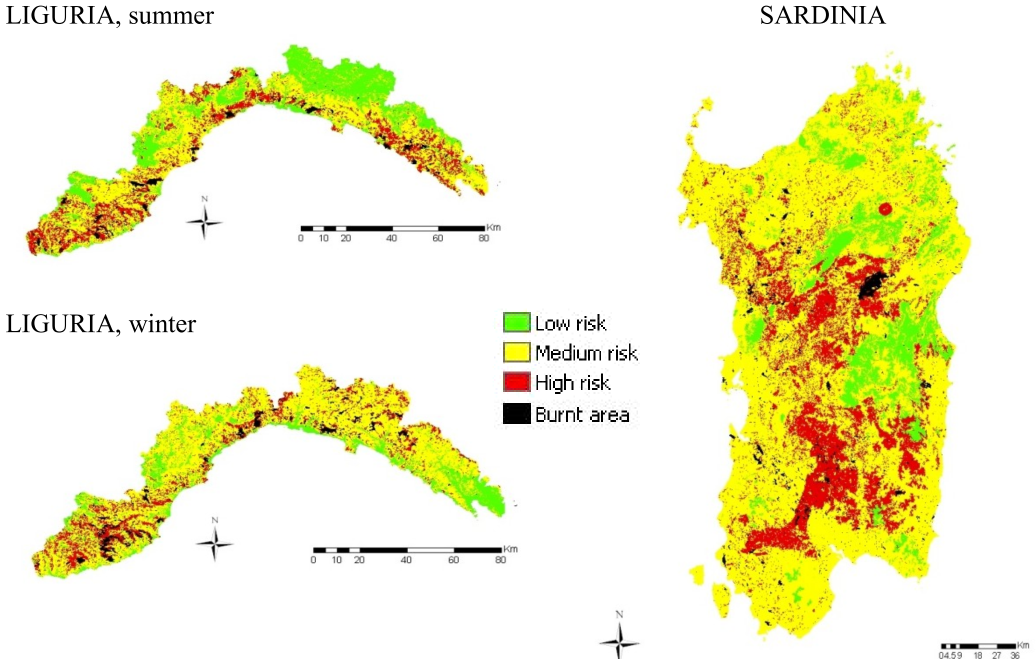

Figure 3. Risk maps in Liguria and Sardinia (from Bodini et al. 2011).

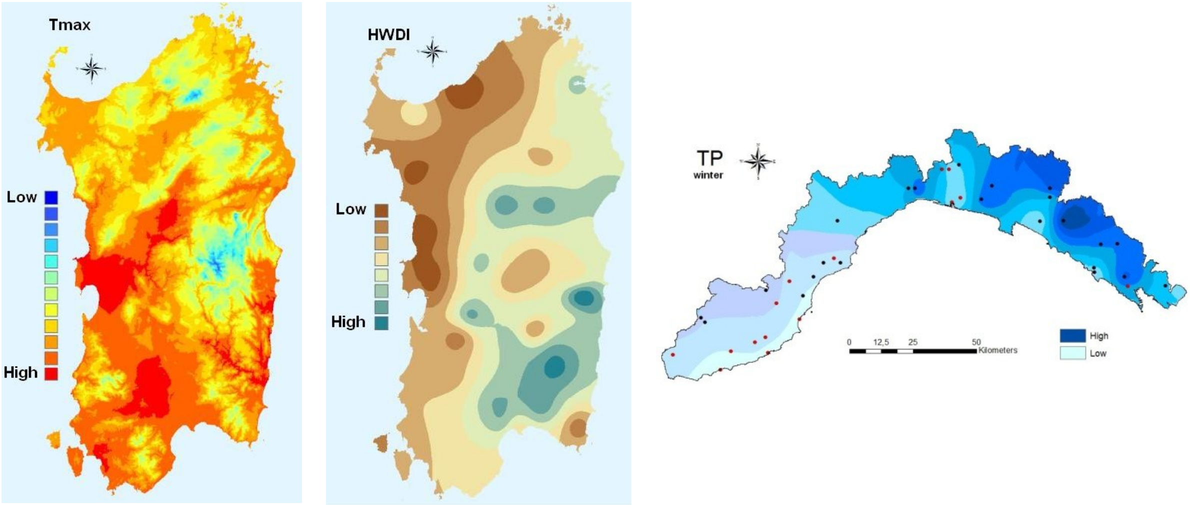

Figure 4. Spatial distribution of the normal values of Tmax (left) and HWDI (right) in Sardinia, based on multiple regression. Spatial distribution of the normal values of TP-winter (left) in Liguria based on kriging, for the safe of a clear representation. Red dots: significant decreasing trend.

4. CONCLUSIONS

The main signal of climate change in the study area refers to decreasing precipitations, reflecting what is currently well assessed by the International Panel on Climate Change. On the contrary, decreasing CDD and R5D in Sardinia seem to be in contrast with recent literature, reflecting the lower spatial coherence between regions shown by extreme indices (Alexander et al. 2006). As all over the globe (Alexander et al. 2006), in Sardinia a signal of increasing Tn90 has been obtained as well. This does not seem to have an influence on static wildfire risk, however it is fundamental for the impact on human health. Sustained night time high temperatures are characteristic of the most severe heat waves, which contribute to increased discomfort and mortality rates (Meehl and Tebaldi 2004).

The lack of high quality observational data sets of daily temperature with good coverage has posed a major hindrance to the climatic analysis in both regions. Contrasting results, often occurring at close stations, suggest that part of the significant trends could be due to non-climatic causes. A great effort in digitalizing all the available data should be done to guarantee an adequate spatio-temporal coverage, improve the analysis and so obtain a deeper insight into the significance of the most relevant results.

5. ACKNOWLEDGMENTS

This work has been carried out within the ARPAS-IMATI agreement n. 1124 (2009), project PROTERINA-C: *A system for the forecast and the prevention of the impact of the variability of the climatic conditions on the risk for the natural and urbanized environment*. Funded by the EU (2009-2011), "Obiettivo 3 Italia-Francia Marittimo" program.

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Historical relationship between climate and fire regime in Asagı Köprüçay Basin (Antalya, Turkey)

Kavgaci A.[1], Salis M.[2,3], Arca B.[4], Cosgun U.[1], Gungoroglu C.[1], Spano D.[2,3]

[1]Southwest Anatolia Forest Research Institute, Pob 264 07002 Antalya, Turkey;
[2]Department of Science for Nature and Environmental Resources (DipNeT), Sassari, Italy;
[3]Euro-Mediterranean Center for Climate Changes, IAFENT Division, Sassari, Italy;
[4]National Research Council of Italy, Institute of Biometeorology (CNR-IBIMET), Sassari, Italy

alikavgaci1977@yahoo.com

Abstract

In this work, we analyzed fire regime, climatic trend and relationships between fire and climate in the Asağı Köprüçay basin (Antalya, Turkey), an area of about 205,000 hectares. The study area is intensively affected by forest fires. Since the historical data on fires were consistent in detail after 1979, we analyzed the historical period 1979-2009. Regarding the climate analysis, data of four meteorological stations representing the different climatic conditions of the study area were taken into consideration. Daily records of maximum, mean and minimum temperatures, precipitation, wind speed and direction, relative humidity were used for the analysis. In the study period, mean and minimum temperatures showed a statistically significant increasing trend with time. The trends of fire number, burned area and meteorological data were analyzed by using correlation and linear regression techniques. Regarding the historical trends in terms of fire number, no statistically significant trends were observed, because of the high inter-annual variability of the data. The burnt areas showed a general increasing trend that is not statistically significant. No statistically significant correlation between fire number and burnt area was observed. The relationships between weather parameters and the main indicators of fire activity: fire days (FD, at least 1 fire per day), large fire days (LFD, at least 20 hectares per day), multiple fire days (MFD, more than 1 fire per day), were investigated by the application of the logistic regression. The historical relationship between weather variables and the main indicators of the fire activity (FD, LFD, MFD) were analyzed by a set of logistic regression models. In particular, 4 models provided the best combined response in predicting the different fire activity indices on both annual and seasonal data. The different models were characterised by low estimation accuracies for FD, while the best results were obtained for LFD. Temperature and relative humidity are the weather variables mostly correlated with the fire activity probability as predicted by the logistic models. An increase in the accuracy was generally obtained where the 3 and 7 days minimum and maximum average values were used instead of the daily mean values of the weather variables.

Keywords: Antalya, Climate, Fire, Logistic regression, Turkey.

1. INTRODUCTION

Total forested area in Turkey is 21.5 millions of hectares (27.6% of all land) (Anon. 2011). The largest amount of forests is represented by Mediterranean type ecosystems such as *Pinus brutia* forests and maquis, mainly dominated by *Arbutus andrachne*, *Arbutus unedo*, *Calicotome villosa, Ceratonia siliqua*, *Quercus coccifera*, *Myrtus communis*, *Phillyrea latifolia*, *Pistacia terebinthus*, *Pistacia lentiscus*, *Spartium junceum, Styrax officinalis*. These fire prone ecosystems especially appear in southern and western parts of Turkey. Each year, many forest fires occur in these areas. Thousand hectares of forested areas are affected by fires; additionally, they threat the rural and urban life. Forest fires are the most important issues of the forestry management activities in south and western Turkey. Big amount of the budget dedicated to forestry practices are spent for fire prevention and suppression efforts. In this context, investigations on fires and on the related issues are crucial in order to improve fire management. Weather conditions are one of the most important factors that influence forest fires (Pausas, 2004) and directly affect fire ignition, spread and severity. Because of that, the relationships between forest fires and weather conditions were analyzed in this work and for this goal the trends of forest fires and weather factors were firstly defined and then the relationships between these components were analyzed for the study area.

2. MATERIAL AND METHODS

In Turkey, one of the areas most intensively affected by forest fires is the Antalya province; the Aşağı Kopruçay basin, with 8 forest provinces and 80 forest villages, was defined as the study area in the work (Figure 1). The study area is approximately 205,000 hectares of which about 120,000 hectares are represented by forests, and about 70,000 hectares by agricultural areas. The main vegetation type in the study area is characterized by *Pinus brutia* forests that have been intensively affected by fires.

Figure 1. Map of the study area. Legend indicates the altitudinal variation

The fire data from the period 1979-2009 were used in this work. During this period, 1,084 forests fires occurred in the area and about 30,000 hectares were burned. The years with the highest burned areas were 2008, 1994, 1979 and 2000 respectively. The year 2008 was especially important since the largest fire of the history of Turkey was observed in this year, with a burned area of more than 15,000 hectares. Moving to the meteorological analysis, we used the data of Antalya and Manavgat weather stations, which represent an indicator of the typical weather conditions of the lowlands and coasts of the study area, where the fires are mostly concentrated. The trends of fire number, burned area and meteorological data were analyzed by correlation and linear regression techniques. Regarding the relationship between historical weather and fires, only the meteorological data showing important correlations with fire data were reported in the text. The weather data were analyzed considering both the average annual and seasonal (July-October) values, in order to investigate the historical trends and the relationship between fires and weather. The analyses were carried out with the R software.

The relationships between the weather parameters and the main indicators of fire activity: fire days (FD, at least 1 fire per day), large fire days (LFD, at least 20 hectares per day), multiple fire days (MFD, more than 1 fire per day) were detected by the application of the logistic regression, which is one of the main methods used in this field (Martel et al. 1987, Andrews et al. 2003). Due to the large numbers of weather parameters, the first steps of the analysis were conducted by automatic methods, mainly by the stepwise regression, in order to find the weather parameters characterized by high values of significance. The analysis was conducted (i) on daily basis using the mean values of the weather parameters, and (ii) on a moving window of 3 days and 7 days calculating the maximum, the minimum and the summation of the values observed during the period. The estimates provided by the logistic regressions are characterized by a large number of statistical indicators, and the evaluation of the best models can be obtained only by an interactive process considering an integrated response between different parameters, mainly the classification accuracy, the Hosmel-Lemeshow test, and the values of the coefficient of determination (r^2). Two different groups of estimations were realized, considering two different sets of daily data, covering the entire years (1st set) and only the period from May to October (2nd set). The two set were characterized by large differences in number of records (≈ 11,300 for annual data and ≈ 3,800 for seasonal data) and in the variability of the weather parameters; therefore, the statistics are affected by these aspects and the accuracy of the models should be analysed separately for annual and seasonal data. The use of the interactive methods (mainly stepwise regression) produced logistic models characterized by a large number of independent variables, and therefore may lead to a limited accuracy in predicting the values of the fire danger indices on new data not used in this developing phase. In addition these models, and the values of their independent variable coefficients, are characterized by a low explanatory content and by a high degree of cross correlation between variables characterised by similar physical nature. For this reason, a limited set of models were developed by manual selection of the independent variables by using both the results of the statistical tests and the evaluation of the accordance with the physical and theoretical expectations.

3. RESULTS AND DISCUSSION

Regarding the historical trends of fire number, it is important to highlight that no statistically significant trends were observed, because of the high inter-annual variability of the data. Similarly the burnt areas in time showed an increasing trend that is not statistically significant. When we look to the correlation between fire number and burnt area, there is an increasing correlation, which is not statistically significant. This correlation did not show a statistically significant trend even if the big fire of 2008 is excluded.

Regarding the trend of weather parameters in time, maximum temperature, relative humidity and cumulated rain (precipitation) did not show relevant statistical trends. On the other hand, the trends of mean and minimum temperatures showed increases in time and these changes were also statistically significant (Figure 2, 3). The most frequent wind directions were WNW, S, SSE and SSW and no significant trends for wind directions and frequencies were observed for the study area. The correlations between fires and mean and minimum temperatures were not statistically significant (Figure 4,5,6,7).

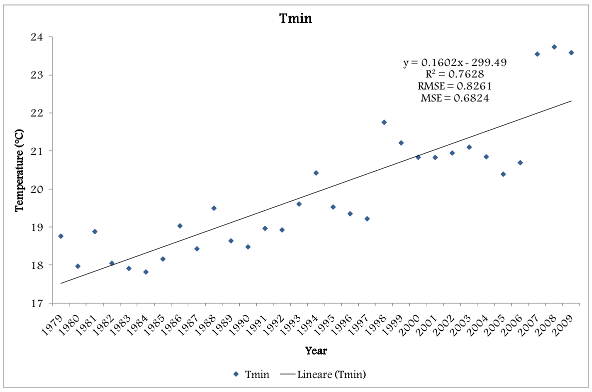

Figure 2. Minimum temperature trends: linear regression (slope significance<0.0001)

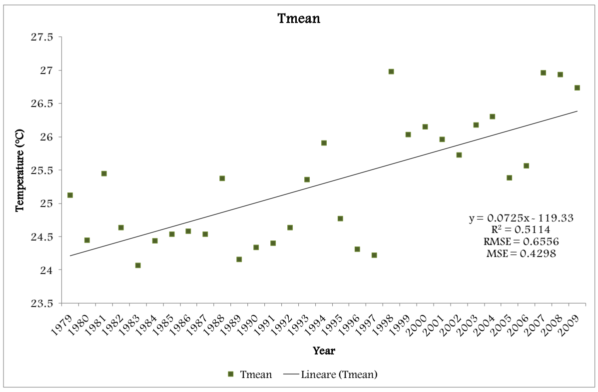

Figure 3. Mean temperature trends: linear regression (slope significance <0.0001)

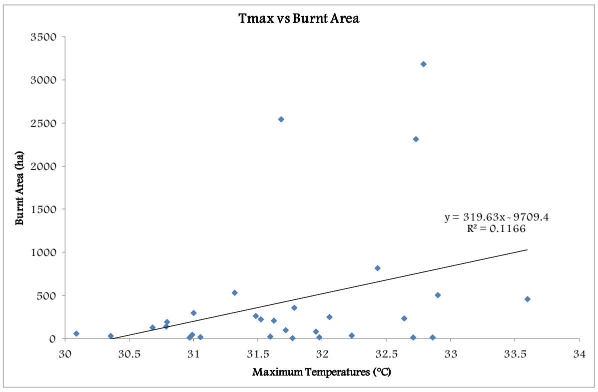

Figure 4. Correlation between Tmax and Burnt Area (excluding 2008)

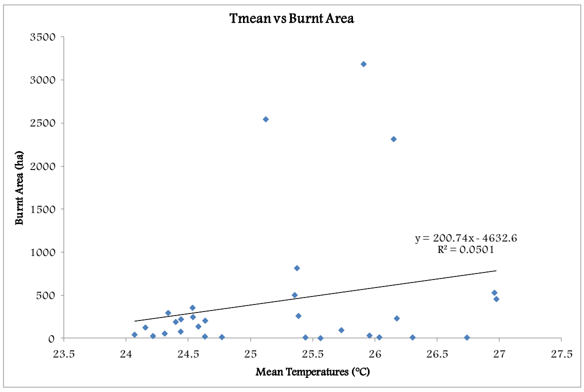

Figure 5. Correlation between Tmean and Burnt area.

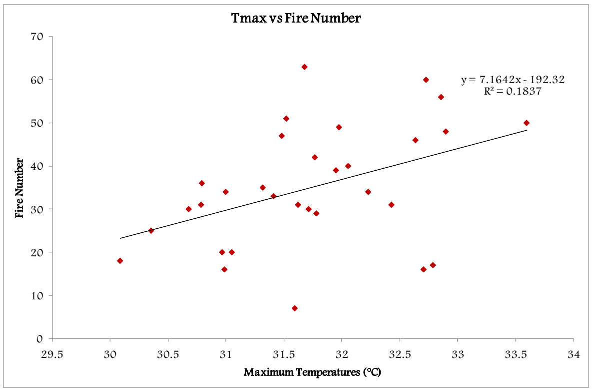

Figure 6. Correlation between Tmax and Fire Number

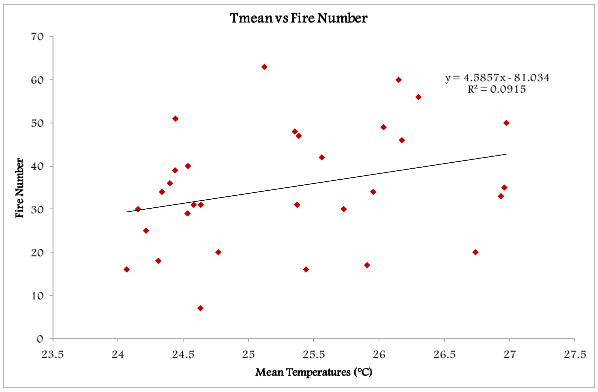

Figure 7. Correlation between Tmean vs Fire Number

Regarding the relationships between the weather parameters and the main indicators of the fire danger season (FD, LFD, MFD) we reported only a set of four logistic models (Table 1), developed by manual selection of the variables. These models provided the best combined response in predicting the different fire danger indices on both annual and seasonal data (Table 2); the statistical parameters provided by the logistic regression permitted to find the variables with the lower values of both the significance of the coefficients and the prediction accuracy. Table 3 reported the parameter estimates for the different models and dependent variables (FD, LFD, MFD).

Table 1. Independent variables included in the models. Tx3, Maximum value of the temperature observed on the previous 3 days; Tx7, Maximum value of the temperature observed on the previous 7 days; Tn3, Minimum value of the temperature observed on the previous 3 days; Tn7, Minimum value of the temperature observed on the previous 7 days; RHx3, Maximum value of the relative humidity observed on the previous 3 days; RHx7, Maximum value of the relative humidity observed on the previous 7 days; RHn7, Minimum value of the relative humidity observed on the previous 7 days.

Model n°	Independent variables
1	Tx3, Tn7, RHx3, RHn7
2	Tx3, RHx3
3	Tx7, RHx7
4	Tn3, RHn3

On both the seasonal and the annual data the different models (Table 2) are characterised by low estimation accuracies for the variable FD (correct classification lower than 33.6%), while the best results were provided by the variable LFD (correct classification greater than 82.5%). In few cases the Hosmer and Lemeshow test provided values lower than the P threshold of 0.05, and this is an indicator of lack of fit. This is true in particular for the models predicting FD by using annual data. The lack of fit is an indicator on limited generalization capacity on new data. The variable MFD is generally characterised by intermediate performances, with values of correct classification lower than 79.6% on annual data and 28.7% for seasonal data.

*Table 2. Statistical parameters used in order to define the accuracy of the models. ** Significance of the Hosmer and Lemeshow test (P=0.05) indicating no evidence of a lack of fit.*

Model n°	Dependent variable	Time step	Rescaled r^2	% Concord.	P-value Hosmer Lemeshow Chi-Square	% Correct classific.
1	FD	Annual	0.18	79.00	0.00	33.60
2	"	"	0.18	78.50	0.00	29.70
3	"	"	0.16	77.10	0.00	30.10
4	"	"	0.18	79.00	0.00	30.50
1	"	Seasonal	0.06	63.20	0.02	17.30
2	"	"	0.05	62.30	0.48**	17.30
3	"	"	0.03	58.30	0.58**	17.30
4	"	"	0.07	64.90	0.57**	17.30

Table 2. Continued

Model n°	Dependent variable	Time step	Rescaled r^2	% Concord.	P-value Hosmer Lemeshow Chi-Square	% Correct classific.
1	LFD	Annual	0.28	85.60	0.84**	94.80
2	“	“	0.23	84.40	0.35**	94.70
3	“	“	0.17	82.20	0.17**	95.00
4	“	“	0.27	86.30	0.01	94.10
1	“	Seasonal	0.23	85.70	0.91**	86.30
2	“	“	0.16	80.50	0.44**	84.70
3	“	“	0.09	72.90	0.92**	83.50
4	“	“	0.21	83.50	0.00	82.50
1	MFD	Annual	0.19	84.30	0.21**	85.10
2	“	“	0.18	83.30	0.58**	85.20
3	“	“	0.13	79.10	0.82**	79.60
4	“	“	0.20	85.50	0.84**	84.50
1	“	Seasonal	0.12	74.10	0.50**	54.40
2	“	“	0.10	72.40	0.17**	51.50
3	“	“	0.05	63.70	0.15**	28.70
4	“	“	0.13	76.90	0.63**	55.80

Table 3. Parameter estimates for the selected models.

Model n°	Time step	Dependent variable	Parameter estimates for the independent variables
1	Annual	FD	-2.41+0.02•Tx3+0.10•Tn7-0.03•RHx3-0.02•RHn7
2	Annual	FD	-3.05+0.12•Tx3-0.03•RHx3
3	Annual	FD	-2.65+0.12•Tx7-0.03•RHx7
4	Annual	FD	-3.22+0.12•Tn3-0.03•RHn3
1	Seasonal	FD	-1.14+0.09•Tx3-0.05•Tn7-0.02•RHx3-0.01•RHn7
2	Seasonal	FD	-1.37+0.06•Tx3-0.03•RHx3
3	Seasonal	FD	-0.91+0.05•Tx7-0.03•RHx7
4	Seasonal	FD	-1.00+0.04•Tn3-0.03•RHn3
1	Annual	LFD	-4.57+0.28•Tx3-0.15•Tn7-0.03•RHx3-0.08•RHn7
2	Annual	LFD	-6.55+0.19•Tx3-0.06•RHx3
3	Annual	LFD	-8.13+0.22•Tx7-0.04•RHx7
4	Annual	LFD	-4.29+0.15•Tn3-0.10•RHn3
1	Seasonal	LFD	-2.77+0.36•Tx3-0.32•Tn7-0.02•RHx3-0.07•RHn7
2	Seasonal	LFD	-6.91+0.20•Tx3-0.05•RHx3
3	Seasonal	LFD	-7.27+0.20•Tx7-0.04•RHx7
4	Seasonal	LFD	-2.97+0.11•Tn3-0.11•RHn3
1	Annual	MFD	-3.53+0.14•Tx3-0.02•Tn7-0.03•RHx3-0.03•RHn7
2	Annual	MFD	-0.15+0.12•Tx3-0.05•RHx3
3	Annual	MFD	-4.87+0.14•Tx7-0.04•RHx7
4	Annual	MFD	-3.33+0.11•Tn3-0.08•RHn3
1	Seasonal	MFD	-2.26+0.21•Tx3-0.17•Tn7-0.03•RHx3-0.02•RHn7
2	Seasonal	MFD	-3.10+0.10•Tx3-0.05•RHx3
3	Seasonal	MFD	-3.02+0.09•Tx7-0.04•RHx7
4	Seasonal	MFD	-1.60+0.05•Tn3-0.07•RHn3

Temperature and relative humidity were the weather variables mostly correlated with the probability estimated by the logistic models, and therefore with the fire danger indices (LFD, MFD, FD). An increase on accuracy was generally obtained where the 3 and 7 days minimum and maximum values were used instead of the daily mean values of the weather variables; this fact is an indicator of a sort of summation of the short term effects of weather variables on fire danger indices; this is true in particular for the relative humidity; Figure 8 showed the pattern of the relative humidity, the relationship with the fire danger indices, and the associated pattern of probability. Relative humidity and temperatures are the variables that explain most of the variability of fire danger indexes, and showed a similar distribution of data and relationship with the estimated probability (Figure 9 and Figure 10). The explanatory value of the wind speed and precipitation is very low, and the stepwise regression found low values of significance for their coefficients.

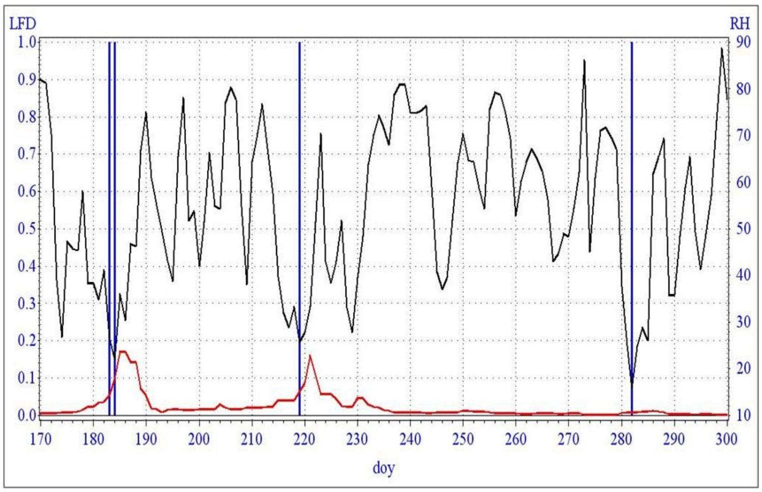

Figure 8. Estimation probability provided by the model n° 3 using annual data (red line); year 1998; the daily values of the relative humidity are also plotted (black line) in order to show the relationship with the actual events (LFD events, blue vertical lines). In many cases the lower peak values of relative humidity are associated with the short time probability of fires.

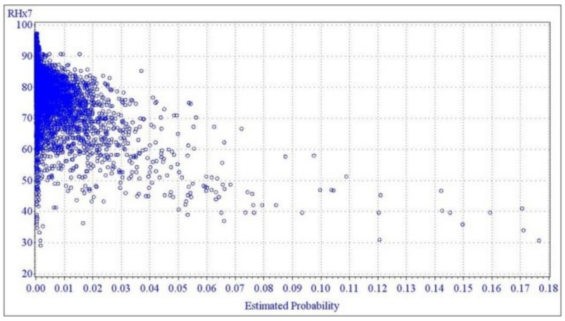

Figure 9. Relationship between the estimated probability provided by the model 3 and the maximum values of the relative humidity observed in the previous 7 days.

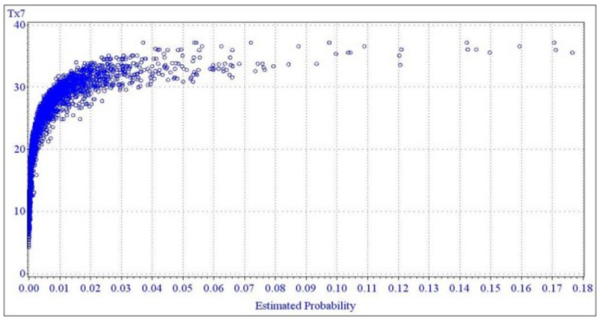

Figure 10. Relationship between the estimated probability provided by the model 3 and the maximum values of the temperature observed in the previous 7 days.

4. ACKNOWLEDGEMENTS

This work was partially funded by the European Union Seventh Framework Programme (FP7/2007-2013) under Grant Agreement 243888 ("FUME" Project - Forest fires under

climate, social and economic changes in Europe, the Mediterranean and other fire-affected areas of the world)

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Predicted and observed climate-induced fire in the Altai-Sayan Mts, Central Asia, during the Holocene

Tchebakova N.M.[1], Parfenova E.I.[1], Soja A.J.[2], Blyakharchuk T.A.[2]

[1]Institute of Forest, SB RAS, Academgorodok 28, 660036 Krasnoyarsk, Russia; [2] National Institute of Aerospace (NIA), NASA Langley Research Center Mail Stop 420, Hampton, VA 23681-2199, USA; [3]Institute for Monitoring Climatic and Ecological Systems, Akademichesky Prosp. 10/3, 643055 SB RAS, Tomsk, Russia

ncheby@ksc.krasn.ru

Abstract

Wildfire has been linked to forest-steppe transitions in both the geologic past and the present. Furthermore, there are indications this relationship will continue in the future. Palynology evidence, collected from southern Siberia, suggests fire increased during climate warming-induced forest-steppe transitions in the past. Currently, there is also evidence that wildfire is driving the transition of forest to steppe in southern Siberia. Additionally, under future climate change scenarios, it is predicted fire frequency, severity, area burned and fire season length will increase in boreal regions. The goal of this work is to estimate high fire danger in the past and presently, as well as to predict high fire danger in the future, over the vast Altai-Sayan mountainous region in Central Asia using climate data from 10000 before present (BP) through the present to 2080. To estimate potential fire danger for past, present and future climates, we developed a linear regression model that relates an annual number of days with high fire danger (Nesterov Index) to an annual moisture index, which characterizes the relative climatic dryness or wetness of vegetation or fuels. Climate change scenarios are derived from: 1) palynological pollen data; 2) current weather station data; and 3) A2 and B1 2080 Hadley Centre HadCM3 scenarios. In the past, under cooler climatic conditions, 10000 and 3200 BP, wildfire encompassed less than half the area in comparison to warmer climatic conditions, 8000 and 5300 BP Under the favorable wet and warm conditions, montane forests thrived and covered about three quarters of the Altai-Sayan Mts. With the climatic changes that have occurred in the last half century, from1960-2010, the number of high fire danger days has increased by 10 days over much of the region (mean 30-40). Simulations show that in the warmer and dryer 2080 climate, the number of high fire danger days will increase by another 10 days (mean 40-50), and these conditions would prevail on 60-70% of the remaining forested area. The dryer climate would result in increased tree mortality in the transition zone between forest and steppe, thus increasing fire fuel accumulation. Fuel load and fire weather create high risk for large fire escalation. In the future, fires are predicted to be more severe and extended than in the past, because future climates are predicted to be warmer and dryer, in comparison to the past warmer and wetter climate.

Keywords: fire danger**,** climate change, Holocene, Altai-Sayan mountains, Siberia

1. INTRODUCTION

Wildfires are largely under the control of weather and climate. If precedent weather has not been hot and dry enough to provide fuel that would be dry enough to be available to burn, then a large wildfire cannot be sustained. Wildfire maintains the current stability and diversity in boreal forests in synchronization with the climate. If one had a bird's eye view of the boreal forest, a patchwork mosaic of even-aged stands would appear, the beginning and end of which successionary processes are typically resolved by fire. Wildfire is also a catalyst for change, a mechanism by which forests can move more rapidly towards a new equilibrium with a new climate.

Palynology data derived from gyttja (mud) lake deposits, taken from southern Siberia, show large amounts of charcoal, and these data are associated with large fires that burned during forest-steppe transitions induced by climate warming. Satellite and ground data show an increase in extreme fire seasons in Siberia, which coincides with the warmer and longer fire seasons of the contemporary climate. Nine of the eleven years, from 1997-2007, resulted in extreme fire seasons, which could change the definition of what is considered a normal fire season (Soja et al. 2007). In the future, fire regimes (area, frequency, severity, and length of season) are predicted to increase in boreal regions (Overpeck 1990; Stocks et al. 1998).

For these reasons, we endeavour to predict high fire danger periods from weather and climate in the past, present and future over the vast mountainous southern Siberian Altai-Sayan Mts, using different climate change scenarios from 10000 before present (BP) through nowadays to the year 2080 AD.

2. METHODS

2.1. The study area

The Altai-Sayan mountains located in central Asia mainly in Russia (the northern half) and Mongolia (the southern part), with a small area in Kazakhstan (in the west) and China (in the southwest) within the window 82-106°E and 42-56°N. In interior central Asia with a continental climate, ecosystems vary from steppes in lowlands with warm and dry climates to forests at middle elevations to tundra and nival communities in cold/wet highlands. Current vegetation in the Altai-Sayan mountains varies on leeward and windward macroslopes. In the south, in the dry climate of Mongolia and Tyva (Russia), dry vegetation types dominate (deserts, semideserts and dry steppes) replaced by light-needled (predominantly Siberian larch) taiga upslope and then to tundra in the highlands. Over the major range, in moist habitats tundra occurs and is then succeeded by dark-needled (Siberian cedar and fir with some spruce) taiga down slope; and lush dark-needled "chern" (which means "black" in Russian) forests (Siberian cedar and fir with aspen), productive and rich in flora and ferns with some nemoral (temperate) tall herbs are found in lowlands; followed by light-needled (pine) and birch subtaiga; and again steppe in the northern foothills (Smagin et al. 1980). The current climate is of a continental type with cold winters and warm summers. Westerlies are the dominant factor of the atmosphere circulation resulting in high annual precipitation: up to 1500-2000 mm on northwestern windward slopes and as little as 200-300 mm of precipitation on foothills of leeward slopes and the inner intermountain depressions of Tuva and Mongolia. Most of the precipitation (up to 90% in Mongolia) falls in the summer.

2.2. Potential fire danger

Potential fire danger for past, present and future climates was estimated using a developed linear regression model ($R^2 = 0.52$) that related an annual number of days with high fire danger (Nesterov Index is greater than 4000, NI) to annual moisture index, a ratio between growing degree-days above 5°C, to annual precipitation, characterising dryness/wetness of the climate (Tchebakova et al. 2009a). We calculated an annual number of days with NI>4000 from climate data of 35 Siberian weather stations located in different vegetation zones for different periods from 1950 to 2000 using the model of Malevsky-Malevich et al. (2005). Our fire weather model was coupled with climate change scenarios for the past, present and future to predict fire potential (a number of days with high fire danger) distribution during the Holocene (Figure 1).

2.3. Past Climate Change Scenarios

Past climate change scenarios were derived from pollen-based reconstructions of paleo vegetation and climates for 10000 BP, 8000 BP, 5300 BP, 3200 BP (Tchebakova et al. 2009). We firstly simulated paleovegetation from pollen data at the biome level, using the "biomization" method of Prentice et al. (1996). Then, the montane bioclimatic vegetation model (MontBioCliM) was inversely used to predict average climatic indices (growing degree-days, base 5°C, GDD, and an annual moisture index, AMI, the ratio between GDD and annual precipitation) for each simulated paleo biome in each time slice of the Holocene (Tchebakova et al. 2009b). We converted these climatic indices correspondingly to average July temperatures and precipitation. The July temperature was derived from GDD, base 5°C, which are strongly correlated ($R^2 = 0.9$). Annual precipitation was derived from AMI and GDD. Climate change (departures) in the July temperature and annual precipitation in each Holocene time slice was evaluated as the differences between contemporary and paleo climates (3200, 5300, 8000, and 10000 BP).

2.4. Paleo Fires Events

Real paleo fires events were reconstructed from charcoal micro-particles of smoke. The size of small pieces of charcoal is some microns in diameter and weight is comparable with a pollen grain so that charcoal micro-particles are transferred, dispersed and buried with pollen and spores in bog and lake deposits by the same regularities. In paleo-ecological studies, to characterise fire history across landscapes, charcoal micro-particles are counted under spore-pollen analyses and shown in percentage with regards to total pollen and spore amounts in pollen diagrams (Bennett et al. 1990). For contemporary research we used the most detailed, full-scale microcharcoal data from lake Usunkol, which characterizes degree of fire spreading evenly through Late Glacial time and Holocene till present time in the Altai region. Numerous radiocarbon dates for Usunkol pollen diagram (Blyakharchuk et al. 2004) allowed to date the revealed maxima in the resulting microcharcoal curve (Figure 2) and to correlate them with environmental and archeological events in Altai-Sayan region for the 13,000 years since the last glaciation.

2.5. Observed present fire

From satellite data of 2000-2009, 17,928 fires were registered across the Altai-Sayan Mts. with 8.3 mln ha of area burned (Shishikin et al. 2012). So that, about 1,700 fires occur with 50-70 thousands ha of area burned at the annual basis. About 1,100 fires occur in non-arboreal areas and 600 fires occur in arboreal areas. The recent trend of fire numbers shows the growth of the fire activity: 2-3 years is the fire return interval for the last decade. High fire activity years were 2002, 2007, and 2008 with area burned 1.5 mln ha in each of those years. Most fires occur under NI class IV (40%) and NI class V (30%). Major wildfires are human-caused (60-90%) and lightning-caused (up to 36%) (Shishikin et al. 2012).

In the contemporary climate, there is evidence of increased fire and an increasing number of extreme fire seasons across Siberia, Russia and the entire boreal region (Soja et al. 2007). However, these increases are regional. For instance in southern Siberia, in the Republic of Tyva, the forest appears to be transitioning to steppe, but according to satellite data, area burned and the number fires are not increasing. In those forests, there have been two patterns observed: (1) the precedent weather is extremely hot and dry, thus the fires are severe, burning the organic layer to mineral soil, which grossly inhibits potential regeneration; and (2) the weather following fires is too hot and dry to sustain seedling establishment. This supports the supposition of the intimate relationship between climate, weather, wildfire and large-scale vegetation transitions.

2.6. Future projections

Two International Panel of Climate Change (IPCC, 2007) climate change scenarios of the Hadley Centre HadCM3 that reflect largest (A2) and lowest (B1) temperature increases by the year 2080 were used. The A2 scenario describes a continuously increasing population with regionally-oriented economic development that is slower than other storylines, and the B1 scenario emphasis in on global solutions to economic, social and environmental sustainability.

3. RESULTS

3.1. Predictions of paleo fire

In the past, on average over the mountains, July temperature anomalies with respect to the contemporary climate were reconstructed negative -2 to -3°C 3000 BP and especially greatly negative -2 to -5°C 10000 BP July anomalies were positive (2-4°C) both 8000 and 5300 BP. For comparison, in the Minusink depression located in the north of our study area, Koshkarova (2004) reconstructed July temperature as being 3°C higher in 7000-5800 BP than today and 1°C lower in 3000-2400 BP than today based on the macrofossil analysis. Zubareva (1987) used palynology to reconstruct July temperature anomalies at approximately -2°C about 3000 BP. At 10000 BP and 3200 BP, under cold and dryer climates, forests covered only 30% of the area and 30-40 high fire danger days occurred on about 55% of the forest area and 40-50 high fire danger days occurred on 35% of the forest area. Between 8000-5300 BP, under warm and moist climates, forests covered about three quarters of the Altai-Sayan mountains, mainly in the north. About 30-40 high fire danger days occurred on 60% of the entire forest area and 40-50 days occurred 30% of the area those times. Wild fires were spread across the Altai-Sayan Mts twice larger in the Boreal and Late Atlantic than in the PreBoreal and SubBoreal periods of the Holocene (Figure 1, left).

3.2. Charcoal-based reconstructions of paleo fires

A case study of a charcoal micro-particles concentration in lake deposits of Lake Uzunkol in the central Altai Mts. was conducted. A constructed diagram of a charcoal micro-particles concentration allowed to conclude that an increased charcoal micro-particles concentration started 5 thousand years ago is anthropogenic and is related to settlement of the first farming-stock-breeder tribes (Figure 2). Radiocarbon dating showed that the upper maximum of the amount of charcoal micro-particles at the depth 10-20 cm corresponds to the period of the Turk culture. The lower maximum at the depth of 38-55 cm is associated with the development of the Scythian culture. The population density of those tribes burning organic fuel seems to be rather high along the shores of Lake Uzunkol. At 10,000 BP, an elevated concentration of charcoal micro-particles was caused by wild fire in the climatically unstable period of the transition between steppe, forest-steppe and forest landscapes. These types of landscapes underwent only wild fires in the absence of humans around in those times.

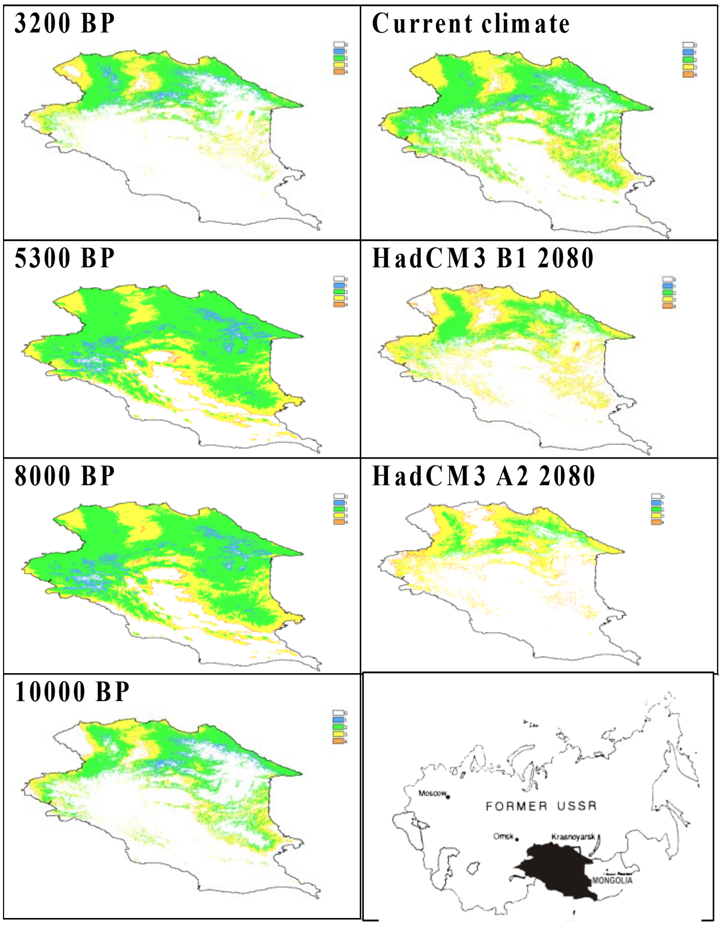

Figure 1. High fire danger days predicted by coupling our fire danger model with past (left), current and future climates (right). 0 – no forest, 1- <30 days, 2- 30-40, 3- 40-50, 4– 50-60. The study area (black) on the background of the former USSR (low right).

3.3. Predicted future fire

In the future warmer and dryer climates, the proportion between numbers of high fire danger days would be opposite regarding: the number of high danger days 40-50 would prevail on 60% (the B1 scenario) and on 70% (the A1 scenario) of the forest area (Figure 1, right). The forest area would decrease in the future about twice. A dryer climate would result in increased tree mortality in the transition between forest and steppe, thus increasing fire fuel accumulation. When superimposed, both factors, fuel load and fire weather create high risks of large fires escalation that would eliminate the forest at lower border and promote it to rise upslope.

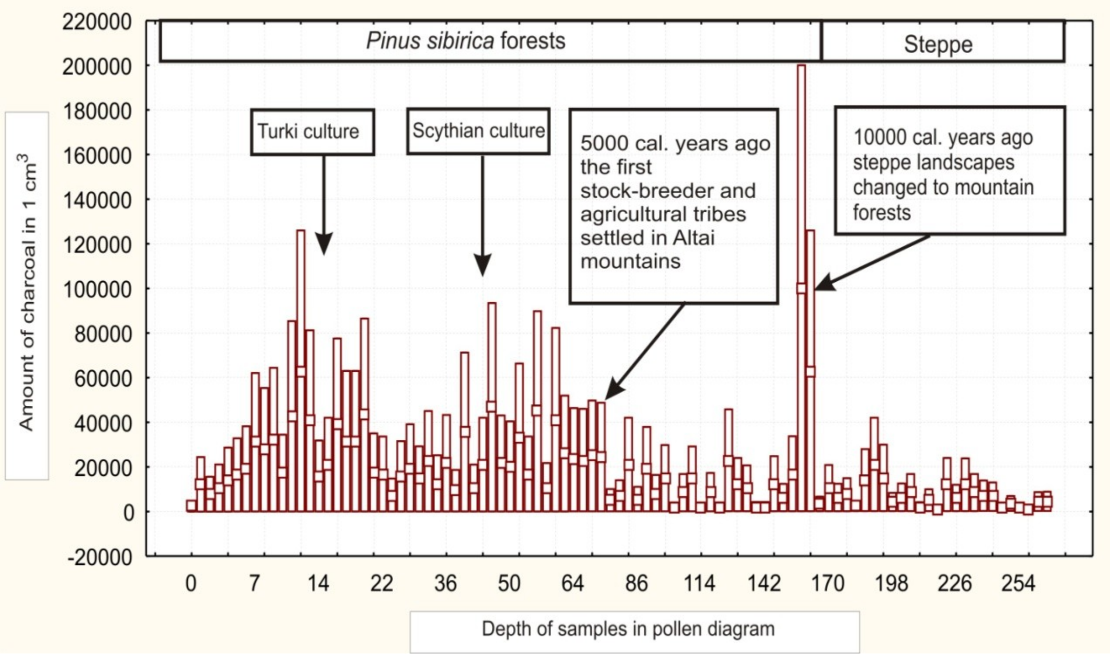

Figure 2. Palynology data taken from southern Siberia. Large amounts of charcoal micro-particles are found in gyttja deposits, and these are associated with large fires that burned during forest-steppe transitions induced by climate warming and peoples' (Turks, Scythians) migration in the past.

4. DISCUSSION AND CONCLUSION

Fires are predicted to be more severe and extended. The southern and lower treeline is being shaped by forest fire, which rapidly promotes equilibrium between the vegetation and the climate. Extreme and severe fire seasons have already occurred in about 80% of the years between 1998 and 2006 in Siberia, which is an early indicator of the predicted change (Soja et al. 2007). Tree decline in the southern taiga border in a dryer climate would facilitate the accumulation of woody debris. This accumulation, paired with increased fire weather, would result in a decreased fire return interval (time between fires) and an increased potential for severe and large fires. In a warmed climate, once forests are swept by fire and climate is not suitable for trees anymore because of high evapotranspiration and lack of precipitation, grass replaces trees. A shorter life cycle, a better adjustment to less precipitation and droughts, abilities to recover after frequent fire events helping to survive in dry climates are characteristic of grasslands. Future climate is predicted warmer and dryer compared to the past. Frequent fires would change forest structure, eliminating dark conifers (Siberian stone pine and fir). Slow growing dark conifers are not adapted to frequent fires and typically die. Dark conifers would be replaced by pine and larch in the lowlands and move upslope to the highlands, replacing montane tundra.

5. ACKNOWLEDGEMENTS

We acknowledge the support of the Russian Interdisciplinary integration project # 53 of the Siberian Branch, Russian Academy of Sciences; the NASA LCLUC NEESPI project and NASA Interdisciplinary Science NNH09ZDA001N-IDS.

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Detailed downscaling through ensemble techniques of the regional climate models for a fire weather indices projection in the Alpine region

Cane D.[1], Barbarino S.[1], Renier L.[2], Ronchi C.[1]

[1]Arpa Piemonte, Via Pio VII 9, Torino, Italy; [2]IPLA Spa, Corso Casale 476, Torino, Italy

daniele.cane@arpa.piemonte.it

Abstract

The Regional Climate Models (RCMs) outputs show significant model errors in the control period in areas of complex orography like the Alps, when compared with the observed climatology. In this work we show the use of the Multimodel SuperEnsemble techniques, including a new probabilistic Multimodel SuperEnsemble Dressing, on a selection of the EU ENSEMBLES project RCMs outputs to downscale statistically the temperature and precipitation fields both in the whole Alpine Area and on a high-resolution area over Piedmont (North-western Italy), in order to reduce these errors. The observations in Piedmont are obtained trough a careful assimilation via Optimal Interpolation of the daily ground station data on a selected regular grid map. Hence, the outputs of the reanalyses (from ERA40) and scenarios (nested in several Global Circulation Model runs on the A1B SRES scenario) from the RMCs were interpolated from their original grid to the same grids of observed climatology and the Multimodel SuperEnsemble technique was applied. The downscaled temperatures and precipitation so-obtained, in combination with other meteorological variables, are used to evaluate future scenarios of wildfire potential with the Canadian Fire Weather Index. The results were compared with the observed forest fires: the agreement with the modeled fields is surprisingly good and differences can be found in the Fire Weather Index skill versus the observed fires as a function of the altitude or the dominant weather regimes. The sharp evaluation of forest fire danger behaviour in future climate scenarios, comparing different downscaling techniques of the fire weather indices with fires observed over Piedmont area, can be a key-point for adaptation and mitigation strategies especially in a rich biodiversity region such as the Alpine one.

Keywords: Multimodel SuperEnsemble, Fire Weather Indices, climatic scenarios, Alps

1. INTRODUCTION

Forest fires are quite common in the southern Alps even if the fire number and the burned areas are low compared with the neighbouring Mediterranean area, where the climate is more in favour of the development of frequent and large wildfires.

In the last decades, however, the Southern Alpine regions experienced an increase in the number and intensity of forest fire events. Piedmont region, located in the south-west, is a "hot spot" for this phenomenon. This increase is coherent with climate change projections, that indicate the Alps as an area particularly sensitive to variations caused by global warming. The climatic scenarios show a strong signal of warming in the Alpine area already for the mid XXI century (Ruosteenoja et al. 2007).

The observed increase of wildfires and the projected enhancement of fire favouring conditions have potential significant impacts on the Alpine ecosystems and on human activities and infrastructures, given the quite dense population and the presence of important economical manufactures and services with particular emphasis on tourism.

The impact of climate change on several forest disturbances, including forest fires, has been already studied in many regions of the world (Seidl et al. 2010), while in the Alpine area most of the papers relate to the fire activity in the past (Tinner et al. 2005; Conedera et al. 2006), but few of them try to asses the behaviour of the wildfire regimes in the Alps in the future scenario (Lindner et al. 2010), relating usually only on a single model simulation.

This paper aims to evaluate the changes of the wildfire potential in Piedmont based on multi-model ensemble of numerical climate projections.

2. MULTIMODEL SUPERENSEMBLE AND FIRE WEATHER INDICES

Our evaluation is based on Regional Climate Models (RCMs) calculated on the SRES scenario A1B. The choice of a single scenario, instead of a range of different scenarios, is justified from the temporal target of this work: we are interested in the climate change until the mid XXI century, and for that period the larger variations are among the different models, while the different scenarios do not diverge so much (Christensen et al. 2007).
The RCM simulations used in this paper are a selection of 7 RCM runs from the ENSEMBLES project (www.ensembles-eu.org) (Table 1), carefully chosen in order to maximise the variety of leading Global Climate Models and of RCMs themselves.

Table 1.The models used in the Multimodel SuperEnsemble evaluation

Regional Climatic Model	Global Climatic Model	Run by
HIRHAM5	Arpege	DMI
REGCM3	ECHAM5	ICTP
HadRM3Q0	HadCM3Q0	Hadley Center
RM4.5	Arpege	CNRM
CLM	HadCM3Q0	ETH Zurich
RACMO2	ECHAM5	KNMI
REMO	ECHAM5	Max Plank Institute

Daily temperature and precipitation observations (1957-present) were gridded on a 14 km grid (0.125°) over Piedmont Region with an Optimal Interpolation technique, with careful description of the complex orography of the region (Ronchi et al. 2008).

The RCM fields were interpolated on the same grid (Figure 1) with bilinear interpolation from their original grid at a resolution of approximately 25 km.

A set of multi-model techniques was applied to the model reanalyses and scenarios to reduce the strong errors they show in the Alpine region: Multimodel SuperEnsemble (Krishnamurti et al. 1999) is a weighted mean with weights calculated in a training period and was applied to temperatures; a new probabilistic Multimodel technique (Cane and Milelli 2010) was applied for the first time on climatic data to estimate precipitation fields, reducing their strong overestimation in the Alps and well reproducing the monthly behaviour of precipitation in the control period; very few observations of relative humidity and wind speed are available, hence no correction was possible and a Poor Man Ensemble (simple average of the models) was applied.

The reanalyses and scenarios obtained with Multimodel SuperEnsemble, in particular with the use of the high resolution data, allow a better characterization of the temperature variations in the alpine area, with differences between mountains and plains. The scenario projection changes for precipitation are less significant (Cane et al. in preparation, 2012)

We applied the Canadian Fire Weather Index FWI (Van Wagner 1987) on OI gridded observations with certain limitations due to data availability: temperature is not the local noon temperature but maximum temperature; precipitation is accumulated from 0 to 24 UTC and not from 12 to 12; relative humidity and wind speed are not taken at noon but are daily average values and are obtained as Poor Man Ensemble of the RCM analyses. The FWI and sub-indices were also calculated from the Multimodel scenario temperature and precipitation fields, while scenario humidity and wind speed are again obtained with a Poor Man Ensemble technique.

Observed wildfires are available in Piedmont since 1957: the older records only report fire locations, while additional information like burned area or fire contours are available only since the 1990s. We assigned the forest fires to the OI gridpoints with a nearest point criterion, and we got a daily record of number of wildfires per each gridpoint in the period 1957-2009.

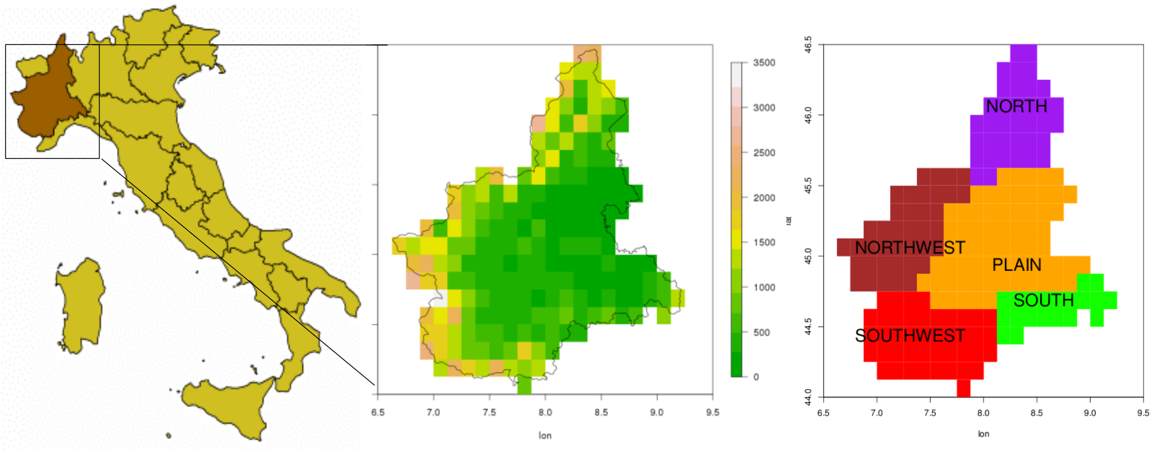

Figure 1. The study area with the average elevation of the gridpoints (left) and the five macro-areas of aggregation of the gridpoints.

3. RESULTS

3.1. Comparison of Fire Weather Indices and observed fires in the past

Due to the limitations in wildfire observation availability, the indices we obtain are only a proxy of the original FWI. First of all, we checked if they have some skill in identifying the correct wildfire climatology. We decomposed the FWI and sub-indices and wildfire timeseries with the Seasonal Decomposition of Time Series by LOESS (Cleveland et al. 1990) and compared the trend components (Figure 2).

In the period 1961-2000 the fire number correlates with temperature, and among the indices it agrees better with Fine Fuel Moisture Code (FFMC), as expected. This result is surprisingly good, because in Piedmont 95% of wildfires have an anthropogenic cause, and the fire statistics is also affected by the changes in land use in the considered period. We checked also the agreement of high values of FFMC and fire occurrences at the gridpoint scale (not shown).

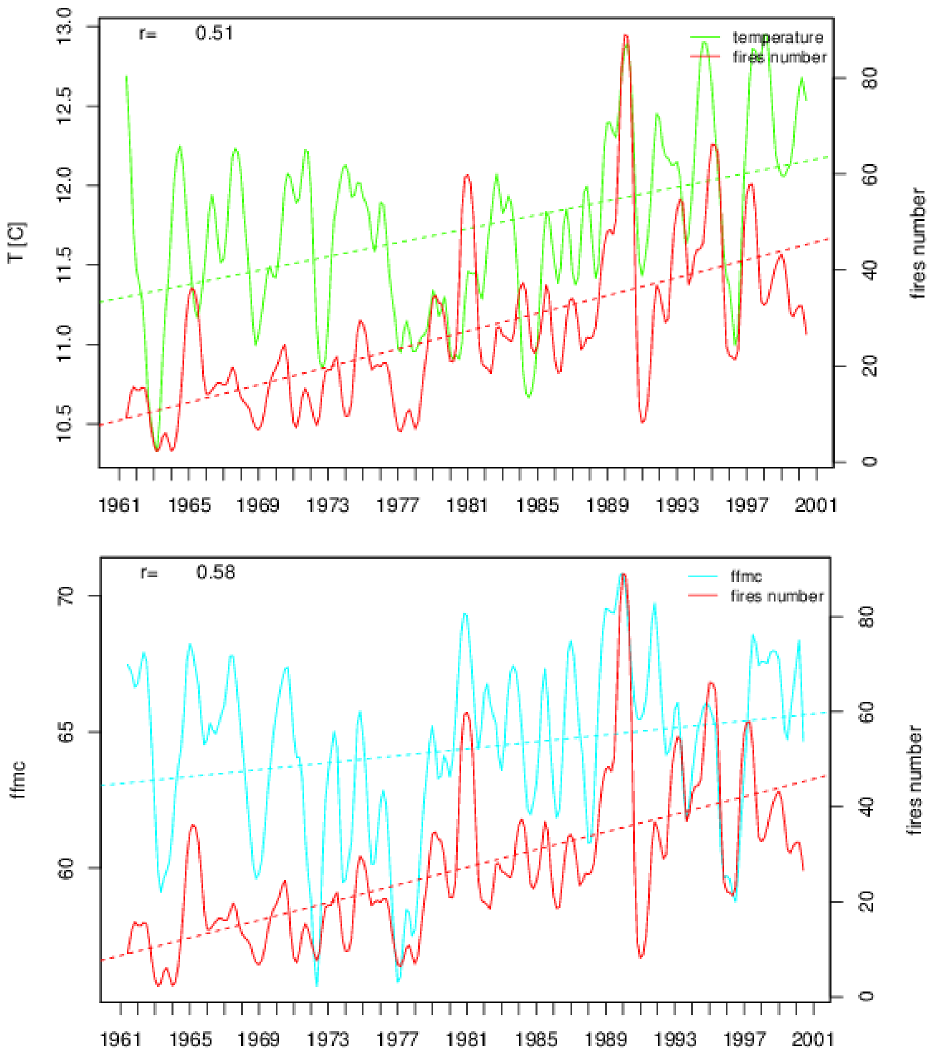

Figure 2. Comparison of trends of observed total fire number with temperature (top) and FFMC (bottom) over Piedmont gridpoints

3.2. Future scenario

Even if a correlation among physical parameters and fires was found, the projection of this to the future would lead to an error, because in this case we would project linearly the present climate features to the future, without taking into account the possible changes in the parameter distributions. To take into account these factors, we applied the technique described in Figure 3: in the control period (1981-2000) we extracted from the FFMC distribution of all the events only the days with fires and from this distribution we calculated two threshold, one for a “median fire condition” (50th percentile) and one for a “severe fire condition” (90th percentile). We calculated the number of days exceeding these thresholds in the scenario data in the control period and in the future interval (2031-2050) and we evaluated the increase of occurrence of values above the thresholds.

The procedure was repeated on the whole Piedmont and on climatic homogeneous macro-regions (Figure 1), on annual data and seasonal data (DJF: winter; MAM: spring; JJA: summer; SON: autumn). The results are listed in Table 2.

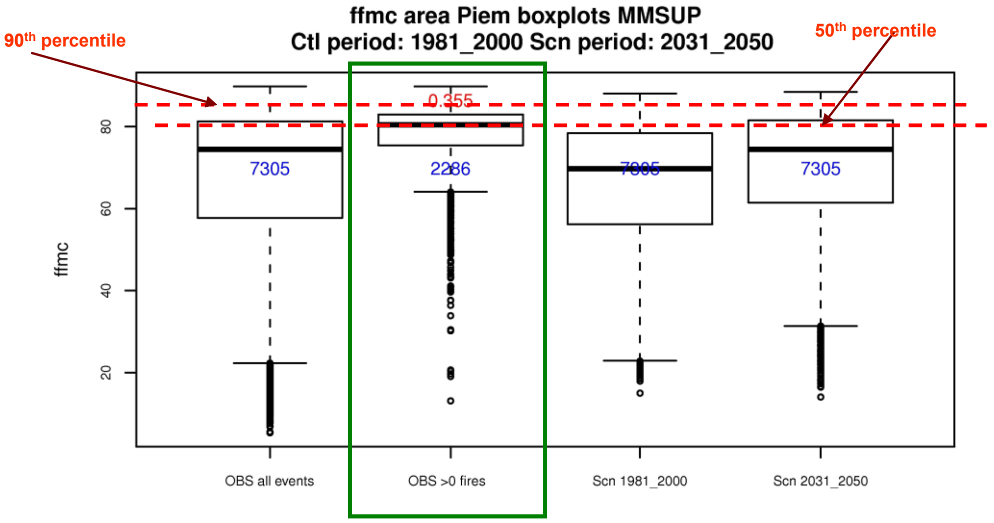

Figure 3. Boxplots of FFMC distribution on observed data, on observed data in cases of fires, for the scenario in the control period and for the scenario in the future interval

Table 2. Variation of the frequency of the 50th and 90th percentile threshold on 1981-2000 observed fires FWI distribution in the scenario, period 2031-2050.

Area	**Annual**		**DJF**		**MAM**		**JJA**		**SON**	
	50th	90th	50th	90th	50th	90th	50th	90th	50th	90th
Piedmont	+31%	+107%	+17%	+67%	+47%	+89%	+41%	+114%	+30%	+91%
North	+26%	+103%	+17%	+67%	+31%	+77%	+36%	+102%	+24%	+93%
NorthWest	+28%	+101%	+17%	+67%	+31%	+69%	+37%	+83%	+23%	+91%
SouthWest	+31%	+105%	+17%	+67%	+31%	+64%	+37%	+117%	+37%	+94%
South	+29%	+69%	+17%	+73%	+45%	+91%	+41%	+70%	+24%	+48%
Plain	+30%	+87%	+17%	+66%	+45%	+83%	+21%	+27%	+18%	+20%

All the variations are positive, indicating an increasing fire potential in the future scenario. The non-parametric statistics applied permit to see big differences among the behaviour of the median of distribution and its extremes: the “median fire potential condition” is projected to increase by 20-40% everywhere, but the “severe” conditions is almost doubling in the scenario everywhere but in the South and on the plains.

Looking at seasonal differences, the larger increase is expected during summer, indicating an extension of the fire season, which is presently mainly limited to the non-growing season (December - April).

4. CONCLUSION

The Fire Weather Index and sub-indices are able to capture part of the climatic variability of the fire potential in the past at the scale of the Multimodel fields.

The fire weather indices projection in Piedmont to the mid XXI century shows a significant increase in median fire potential conditions, and a dramatic increase in extreme conditions, with an extension of the fire season from winter/early spring towards the warmer months.

The extension of this study to the whole Alpine Area is under evaluation and a paper on this topic is in an advanced state of preparation.

5. ACKNOWLEDGEMENTS

This work was conducted under the European Project ALP FFIRS, funded by the European Regional Development fund of the Alpine Space Program, reference number 15-2-3-IT.
The ENSEMBLES data used in this work was funded by the EU FP6 Integrated Project ENSEMBLES (Contract number 505539) whose support is gratefully acknowledged.

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Potential changes in fire probability and severity under climate change scenarios in Mediterranean areas

Arca B.[1], Pellizzaro G.[1], Duce P.[1], Salis M.[2,3], Bacciu V.[2,3], Spano D.[2,3], Ager A.[4], Scoccimarro E.[3]

[1]Institute of Biometeorology (IBIMET), National Research Council, Sassari, Italy; [2]Department of Science for Nature and Environmental Resources (DIPNET), University of Sassari, Italy;[3]Euro Mediterranean Center for Climate Change; [4]WWETAC, USDA Forest Service, Pacific Northwest Research Station, Prineville

B.Arca@ibimet.cnr.it

Abstract

Complex and non-linear relationships among vegetation, weather patterns, and topography are responsible for wildfire probability and severity at landscape scales. Consequently, the study of potential climate change impacts on wildfire probability can be expected to have additional sources of error and uncertainty respect to the uncertainties in the future climate projections. The aim of this work is to estimate burn probability and fire severity under different weather scenarios, and to assess the future changes in burn probability and severity at Mediterranean area. The climatic data used in this study were generated by the Regional Climate Model (RCM) EBU-POM developed by the Belgrade University in cooperation with the Euro-Mediterranean Center for Climate Change (CMCC). The study was realized considering a baseline climate scenario in order to simulate the current Mediterranean climate (1961-1990), and a future climate scenario generated in order to produce a simulated climate for the period 2071-2100. The experimental results showed significant variations on the main variables affecting the fire weather and a significant increase in the burn probability in a fire-prone area of the Mediterranean basin.

Keywords: regional climate models, extreme fire days, fire weather index

1. INTRODUCTION

The fourth Assessment Report of the Intergovernmental Panel on Climate Change, and a large number of recent works (Alcamo et al. 2007), showed the expected future variations in climate and the large range of effects in terms of impacts and vulnerability, including the effects on wildland fires. A large spatial variability of the potential effects can be observed inside the Europe, moving from Northern Countries to the Mediterranean basin. In particular, the generalised increase in the annual mean temperature is expected to be more affected by the increase in winter temperatures in northern Europe, and in summer temperatures in the Mediterranean area. A similar pattern can be observed considering the range of variation in temperatures, where the minimum temperatures are expected to increase mainly in northern Europe, and the maximum temperatures are expected to increase in particular in southern areas. The precipitations, in terms of annual sum and number of days with rain, are expected to decrease in the Mediterranean area, and this fact could increase the risk of summer drought. The association of the above described conditions could increase the fire danger in areas characterised by differences in fire regime and vegetation types.

Considering the heterogeneity of geographic and climatic conditions, the use of regional climate models may improve the accuracy of the simulations at the different spatial domains, and the availability of increasing resolutions could improve the accuracy of the studies. Another way to account for the spatial heterogeneity of both climatic conditions and vegetation characteristics can be the use of a modelistic approach based on fire behaviour simulators, that are able to provide the integrated effect of topography, weather and fuel conditions on fire probability and severity (Farris et. al 2000; Ager et al. 2007; Finney et al. 2007; Ager and Finney 2009).

In this work we described the results of a study carried out at national (Italy) and local scale (Sardinia island), which estimated the changes in fire weather conditions under different climate scenarios, and assessed the future changes in burn probability and severity under several climate change scenarios using a fire simulator and a probabilistic approach.

2. MATERIALS AND METHODS

The Regional Climate Model (RCM) EBU-POM developed by the Belgrade University in cooperation with the Euro-Mediterranean Center for Climate Change (CMCC) was used in this study. The RCM furnished two climate projections: the baseline climate scenario forced by the 20C3M greenhouse gas scenario in order to simulate the current Mediterranean climate for the reference period 1961-1990, and a future climate scenario, generated using the forcing agents defined by the A1B SRES greenhouse gas emission scenario, in order to produce a simulated climate for the period 2071-2100. The RCM data used in this study were characterized by a 6 hours time step, a spatial resolution of 25 km, and a simulation domain covering the Mediterranean region. The accuracy of the baseline reference data was evaluated comparing such data with a set of weather data summarized at different temporal scales: daily, monthly, and yearly. A bias correction factor was used in order to modify the amount of precipitations provided by the RCM that was characterized by a systematic underestimation of the actual data. The spatial and temporal variations of the weather parameters affecting the propagation danger were evaluated in order to calculate the main descriptive statistics and the anomaly between A1B and baseline data on three different geographic areas (north, centre and south Italy), and on seasonal basis, partitioning the data in autumn (October-December, OND), winter (January-March, JFM), spring (April-June, AMJ) and summer (July-September, JAS). The Fire Weather Index (FWI) was used as an integrated indicator of the weather conditions associated with the fire danger, and was calculated for the different locations and for both baseline and future climate scenario. The percentile analysis was applied on the FWI values in order to select a set of weather streams data for extreme conditions that was used for the modelling applications. The Sardinia Island was the test site for the modelling applications, due to both the representativeness of the Mediterranean conditions, and the availability of accurate data on fuel models. The integrated effect of topography, weather and fuel conditions on fire probability and severity for both the baseline and the A1B scenario was assessed by a command line version of the FlamMap simulator (Finney et al. 2003; Finney 2006). The model allowed the simulation of 100,000 fires from a set of ignition points obtained by a Monte Carlo approach from the historical ignition points. All the themes used to feed the simulator were developed using a grid resolution of 250 m. Fuel and canopy cover maps were produced using the 1:25,000 land cover map of Sardinia from the CORINE project (EEA ETC/TE 2002), and combining the fuel information to obtain a broad classification of the main vegetation types and land uses for the study areas. A set of custom fuel models were used for shrubland and pasture vegetation types, whereas the standard fuel models were used for the other vegetation types. Regarding the wind conditions, we used a set of data representing the prevailing wind conditions obtained from a frequency analysis performed on the baseline and scenario data. The following output themes were obtained from each simulation and summarized in order to describe the fire behaviour on the study area: rate of spread (ROS), fireline intensity (FLI), and flame length (FL).

3. RESULTS

The comparison between baseline and the A1B scenario showed an increase of the mean annual temperature of 2.8 °C at national level (Table 1). Similar results were provided by the analysis performed on the three different geographic areas (north, centre, south), with a slightly greater increase in the central area (3 °C). The analysis performed at seasonal scale (Table 2) showed that the highest increase in mean temperature (3.6 °C) is concentrated in summer (JAS) and therefore could affect the characteristics of the fire season, mainly concentrated in this period in the Mediterranean basin. A significant increase (3.3 °C) in the mean temperature was observed even in the northern spring (AMJ), and this fact could anticipate the beginning and the extension of the fire season. The analysis conducted on the relative humidity showed a similar geographic and seasonal pattern, with a decrease of the mean annual value ranging from 2.4-3.7%, and the highest decrease concentrated respectively in northern and centre (Table 1). On seasonal basis the analysis (Table 2) showed a decrease mainly concentrated in autumn (OND), and northern spring (AMJ). The analysis of the anomalies in the annual mean of wind speed showed a lower increase (0.3-0.4 ms^{-1}) equally distributed in the different geographic areas and, on seasonal basis, mainly concentrated in the northern autumn. Since the above mentioned weather factors are the main responsible for the progress of the fire season in the Mediterranean basis, an integrated effect was estimated by calculating the FWI on seasonal basis by using the regional climate model data (T, RH, WS) delivered at 12:00 AM and the rainfall cumulated over the previously 24 hours. The analysis of the seasonal variations of the FWI (Table 2) showed the higher increases respectively concentrated in the spring (5.4, 39%) and summer season (5.2, 20%), with mean values of FWI for the A1B scenario ranging from 13 to 31%. The analysis of the extreme conditions was realised by calculating the 99° percentile on annual basis for the three different geographic areas, and selecting a subset of data in order to calculate the variation in the number of extreme days. The analysis showed an increase of 174 days with extreme conditions mainly concentrated in the summer season (135 days).

The above data on weather conditions, together with the data on fuel models and topography were used to prepare the input data to feed the fire behaviour simulator. Regarding the burn probability, the analysis of the simulation results (Figure 2) showed an increasing burn probability with increasing frequencies of fire per day and duration of the simulated fires (from 2 to 8 hours); a clear difference between baseline and a1b scenario was also observed. In Figure 2a we can observe the spatial distribution of the differences in burn probability, with the higher values concentrated in the western agricultural areas characterised by the higher values of historical ignition frequencies. The greatest differences between baseline and A1B scenario (26%) (Figure 2b) were observed in these areas.

Table 1. Annual average of temperature (T), relative humidity (RH), and wind speed (WS) calculated for baseline and A1B scenario on different geographic areas.

Area	Variable	Baseline	A1B scenario	Difference
Centre	T (°C)	17.4	20.4	3.0
	RH (%)	50.0	46.3	-3.7
	WS (m s^{-1})	6.3	6.0	-0.3
North	T (°C)	13.1	16.0	2.9
	RH (%)	54.3	50.5	-3.8
	WS (m s^{-1})	6.0	5.7	-0.3
South	T (°C)	19.1	21.9	2.8
	RH (%)	46.8	44.4	-2.4
	WS (m s^{-1})	7.8	7.4	-0.4
All	T (°C)	16.4	19.2	2.8
	RH (%)	50.4	47.3	-3.1
	WS (m s^{-1})	6.8	6.4	-0.4

Table 2. Annual average of temperature (T), relative humidity (RH), wind speed (WS), fire weather index (FWI), and number of Extreme fire days calculated for baseline and A1B scenario at seasonal basis.

Season	Variable	Baseline	A1B scenario	Difference
OND	T (°C)	13.1	10.8	2.3
	RH (%)	59.1	62.7	-3.6
	WS (m s^{-1})	6.9	7.7	-0.8
	FWI	7.0	4.4	2.6
	Extreme (days)	0	1.0	1
JFM	T (°C)	10.2	8.0	2.2
	RH (%)	58.8	61.5	-2.7
	WS (m s^{-1})	8.1	8.3	-0.2
	FWI	3.3	1.9	1.4
	Extreme (days)	0	0	0
AMJ	T (°C)	23.4	20.1	3.3
	RH (%)	39.0	42.3	-3.3
	WS (m s^{-1})	6.0	6.3	-0.3
	FWI	19.3	13.9	5.4
	Extreme (days)	10	48	38
JAS	T (°C)	30.2	26.6	3.6
	RH (%)	32.1	35.1	-3
	WS (m s^{-1})	4.6	4.9	-0.3
	FWI	31.2	26.0	5.2
	Extreme (days)	61	196	135

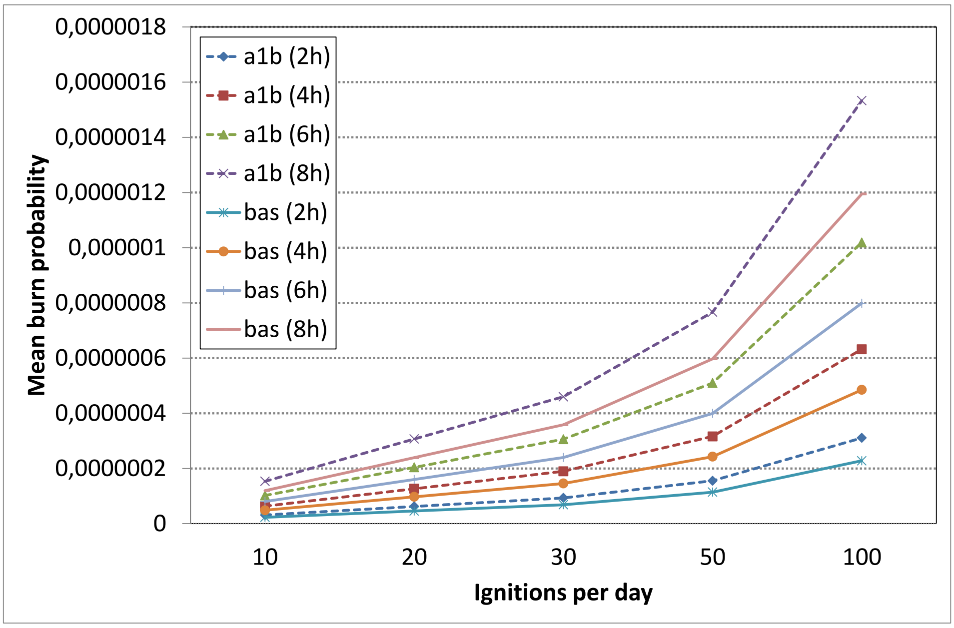

Figure 1. Mean value of burn probability provided by the simulator for baseline and A1B scenario at different levels of ignitions per day.

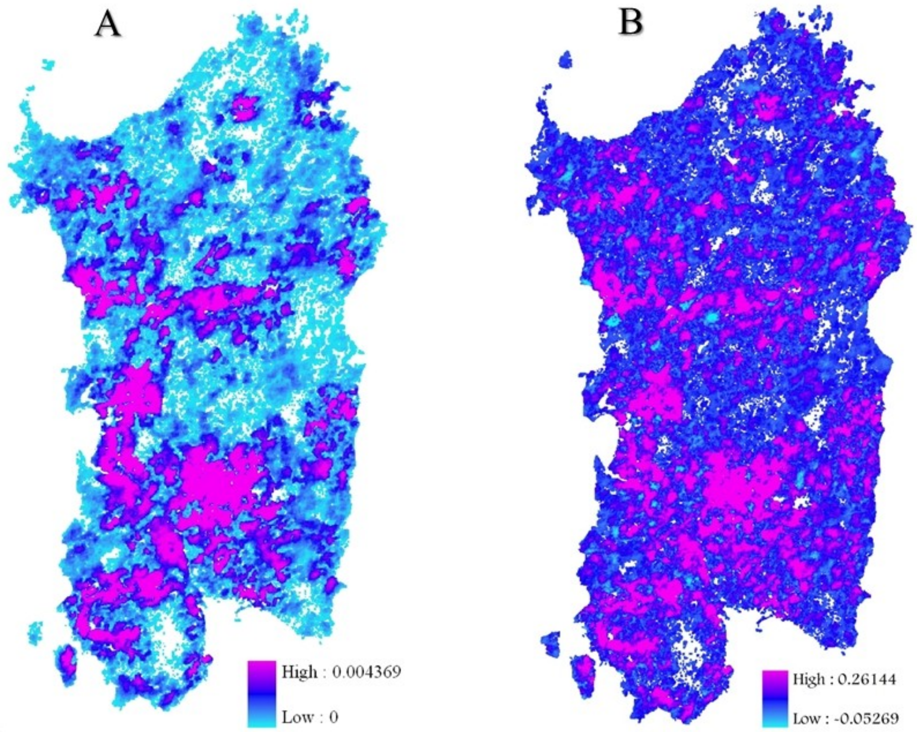

Figure 2. (A) Map of the burn probability for the A1B future climate scenario, and (B) anomaly respect to the baseline data.

4. CONCLUSIONS

The work presents an analysis of the potential impact of the climatic changes on a Mediterranean area based on the use of a fire behaviour simulator approach that allows obtaining probabilistic maps of burn probability and severity at landscape scale. The work highlights the increase of the annual mean values of the main weather parameters associated with the fire danger, as confirmed by the increase of the FWI; an increase in the number of days with extreme conditions was also observed. The combined effect of the above mentioned phenomena may cause an increase in the burn probability mainly associated with large fires and concentrated in the areas with the highest frequencies of observed ignitions. The work suggests that FlamMap simulator can be used as a valuable component of decision support systems for fire danger and fire risk assessment in the Mediterranean areas, with actual and future environmental conditions.

5. ACKNOWLEDGEMENTS

This work was partially funded by the European Union ITALIA-FRANCIA Marittimo (2007-2013) Project “Proterina-C” (A system to forecast and prevent the impacts of the variability of climatic conditions on the risk for natural and anthropic environment) and by the European Union Seventh Framework Programme (FP7/2007-2013) under Grant Agreement 243888 (“FUME” Project - Forest fires under climate, social and economic changes in Europe, the Mediterranean and other fire-affected areas of the world)

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Extreme events as represented by high resolution CMCC climate models at global and regional (Euro-Mediterranean) scale

Sanna A.[1], Scoccimarro E.[2], Gualdi S.[1,2], Bellucci A.[1], Montesarchio M.[1,3], Bucchignani E.[1,3]

[1]Euro-Mediterranean Center for Climate Changes, Italy; [2]National Institute for Geophysics and Volcanology (INGV), Bologna, Italy; [3]CIRA - Centro Italiano Ricerche Aerospaziali, Capua, Italy

Antonella.sanna@cmcc.it

Abstract

Within the framework of the FUME EU project, a set of climate projections covering the period 1970-2100 has been performed using a global and a regional climate model. Simulation outputs have been analyzed in order to investigate extreme events, with a special focus on heatwaves and wildfires. Several indexes have been computed and verified over Spain, comparing results from the regional model with an observational dataset. The projected trends in a future scenario A1B have been examined both for the global and regional model.

Keywords: heatwaves, wildfires, climate change, global climate model, regional climate model, Euro-Mediterranean region

1. INTRODUCTION

Wildfires and heat waves are hard to study and predict because they are extreme events and obey different statistical laws than averages (Naveau et al. 2005). The availability of climate simulations covering long periods gives the possibility to investigate climatic extremes in terms of their spatial and temporal evolution. In this work we want to analyze extreme conditions favoring fire and heatwaves, with a special focus on the Euro-Mediterranean region, using the results of one global and one regional climate simulation.

The characteristics of the model data and the observational dataset used for verification are described in Section 2. In Section 3 we define several indexes useful in determining fire development and heat waves conditions. Section 4 is devoted to the analysis and verification of the model simulations. In Section 5 we illustrate trends at global and regional scale in future scenario simulations. Section 6 summarizes the main results.

2. CLIMATE MODELS AND OBSERVATIONS

Within the framework of FP7 FUME project (*Forest fires under climate, social and economic changes in Europe, the Mediterranean and other fire-affected areas of the world*), CMCC implemented a set of climate simulations at global and regional scale.

2.1. The CMCC models

The global climate simulations are performed using the CMCC-MED global coupled model (Scoccimarro et al. 2011a). CMCC-MED represents an evolution of the SXG (Gualdi et al. 2008, Bellucci et al. 2008) and of the EOL (Fogli et al. 2009) models. The model includes an interacting very high-resolution model of the Mediterranean Sea (Oddo et al. 2009), to improve the representation of the fine-structure dynamical processes of this basin.

The global simulations have been downscaled with the limited area CMCC-CLM model (Rockel 2008; Bucchignani et al. 2011). The CMCC-CLM model is implemented over the Euro-Mediterranean region at a horizontal resolution of 14km, with boundary conditions from the CMCC-MED simulations every 6 hours.

The climate simulation and the dynamical downscaling have been performed for the period 1970-2100, following the IPCC 20C3M protocol for the 20th century part of the integration and the A1B scenario for the 21st century.

Model results were compared with a high-resolution observational data set over Spain.

2.2. The observational dataset Spain02

Spain is a very interesting region from the point of view of extreme weather conditions, both for its complex topography and for being particularly prone to wildfires. Moreover a high-resolution observational dataset is available over the region, making this area particularly suitable for a detailed model validation. Spain02 is a daily precipitation and maximum and minimum temperatures gridded database, with a regular 0.2° horizontal resolution spanning the period from 1950 to 2008 (Herrera et al. 2012).

3. INDEXES FOR EXTREME EVENTS CHARACTERIZATION

The proposed investigation focuses on: maximum and minimum 2m temperature (hereafter Tmax and Tmin, respectively), precipitation and 10m-wind velocity. These parameters have been used, within the framework of FUME project, for the definition and computation of several indexes of extreme conditions (Scoccimarro et al. 2011b).

In the following, we will examine the10th percentile of summer (JJA) daily Tmin, the 90th percentile of the daily Tmax (TN10P and TX90P, respectively), the 95th percentile of summer (JJA) and winter (DJF) total daily precipitation (PREC95P) and the 90th percentile of the JJA 10m-wind speed (WI90P).

The interest on TX90P, when computing heat waves or fire risk, is rather obvious (Beniston et al. 2007). On the other hand, TN10P becomes important when possible impacts on human health are considered. People vulnerable to heat need a recovery period (a relatively cool night) to limit harm (Poumadere et al. 2005).

PREC95P is analyzed both for winter and summer seasons. In fact, the amount of precipitation occurred in winter is extremely important to determine the evolution of soil moisture in the following months and the latter, in turn, has been proved to be a major factor in the onset of heat waves and droughts (Vautard et al. 2007).

As for wind speed, we will focus on JJA, because we are mainly concerned on events favoring fire and fire risk (Beer 1990). For this field, however, no verification is presented in this work because of the lack of reliable observations.

4. CMCC-CLM EXTREME VERIFICATION

In this Section, the CMCC-CLM results are verified against the SPAIN02 dataset. Figure 1 shows TX90P computed from the observations (left panel) and from the model (right panel) for the summer season. The model realistically reproduces the main features of the observed field, with maxima over central and southern Spain and minima in the North. Despite some overestimation over the southern plains, CMCC-CLM captures the main features of the field, mostly related to the orography. Also in summer, the simulated TN10P (not shown) reproduces well the main features of the observed results, except for some underestimation over central Spain.

Figure 2 shows PREC95P during JJA. Summer precipitation is clearly underestimated, especially over northern mountains. In winter (not shown), the model performs better, tough some overestimation of the PREC95P is found over western Spain. These results suggest that the model resolution is not fine enough to correctly reproduce the typical summer convection, while it permits a reasonably good representation of climate and circulation features related to the orographic complexity of the region.

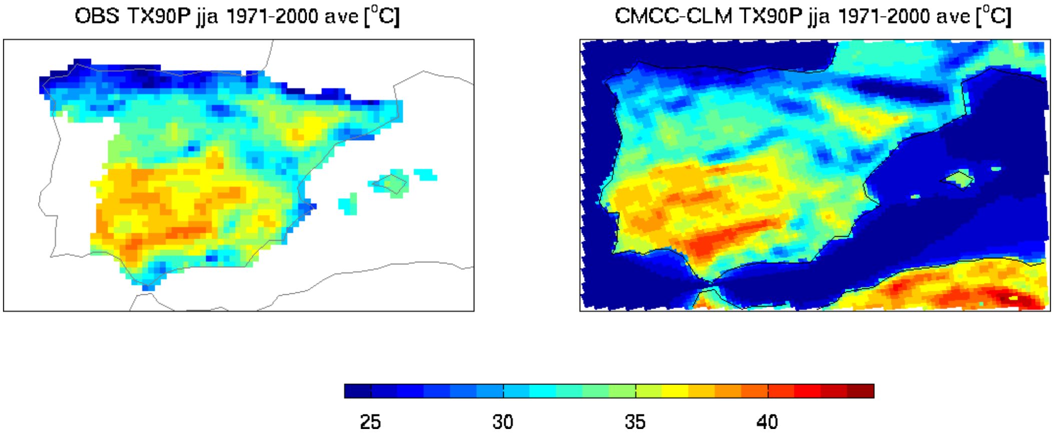

Figure 1. Summer TX90P: Spain2 (left panel) and model results (right panel).

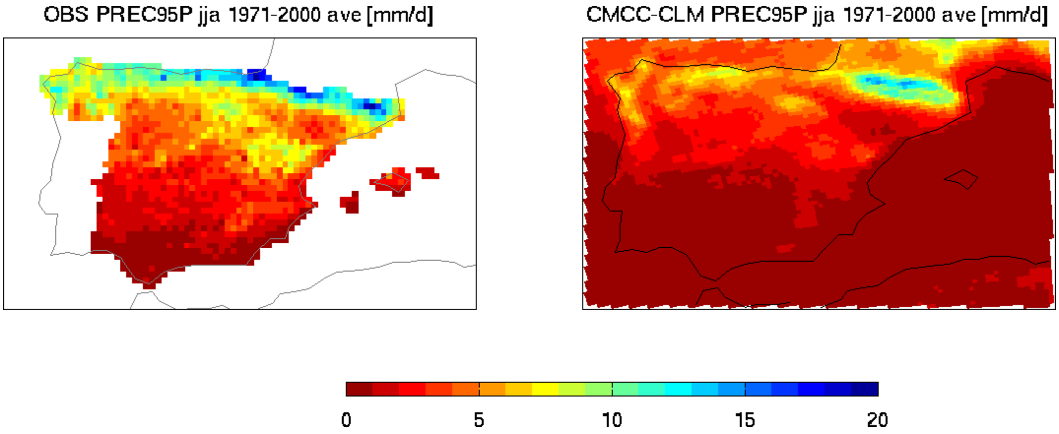

Figure 2. Summer PREC95P: Spain02 (left panel) and model results (right panel).

5. TRENDS AT REGIONAL AND GLOBAL SCALE

Trends of TN10P, TX90P, PRECIP95P and WI90P are computed over two periods of 65 years (1971-2035 and 2036-2100, in the following DT1 and DT2) both for the regional and global models.

5.2. Temperature

The summer TX90P is presented in Figure 3, left panels. The trend over the period DT1 (top panel) shows increasing values over west, whereas a decreasing trend characterizes the north-east. Bottom panel shows the trend over the period DT2. The trend is positive over the whole domain, with higher values compared to DT1 and a large maximum over France. At global scale (not shown) TX90P shows trends toward intensification, in particular over N Canada, N-E Russia and Antarctica in DT1. In DT2, the trend becomes everywhere positive, especially over continents. Trends of TN10P are show in Figure 3, right panels. In the period DT1, the trend is very similar to the TX90P case. The trend over the period DT2 (bottom right panel) is positive everywhere, with maxima over northwestern Africa and Spain. From the global point of view, TN10P (not shown) shows patterns very similar to what obtained for TX90P.

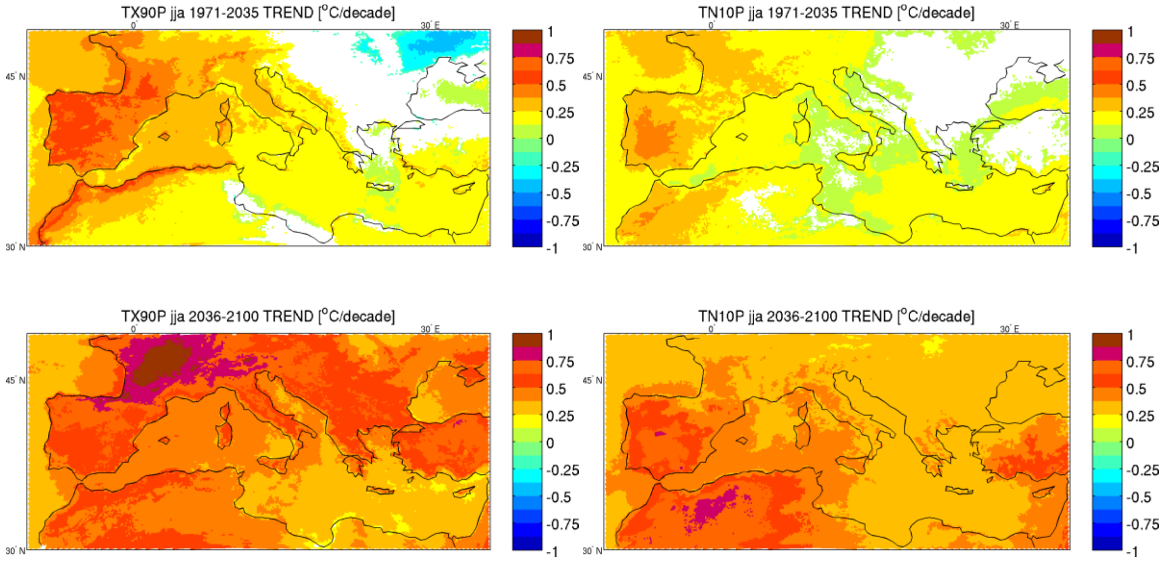

Figure 3. Summer TX90P (left) and TN10P (right) trends:DT1 (top panel) and DT2 (bottom panel). Areas where no statistical significance is found are in white.

5.3. Precipitation

Trends in extremely high precipitation events (PREC95P) are shown in Figure 4 for JJA (left panels) and DJF (right panels). During the period DT1 (top panels), both seasons are characterized by a positive trend over the eastern part of the domain, more evident in JJA. During DT2, DJF shows a positive trend almost everywhere over continents, whereas an overall negative trend characterizes JJA. At global scale (not shown), positive trends over central equatorial Pacific, more intense for period DT2, are opposed to negative tendencies over the extra tropical Oceans.

5.4. Wind

The trend in the summer 90th percentile of wind speed at 10 meter is shown in Figure 5. In the period DT1 (top panel), trends are mainly positive over the Eastern Mediterranean basin and negative over the Atlantic sector and the northern continental part of the domain.

In the period DT2, trends are significant only in restricted areas, increasing in the southern part of the domain and decreasing to the North. From the global perspective (not shown) the main result is a decreasing tendency over the oceans almost everywhere with the exception of the Barents Sea, especially in DT2. No clear trends are found for the continental areas.

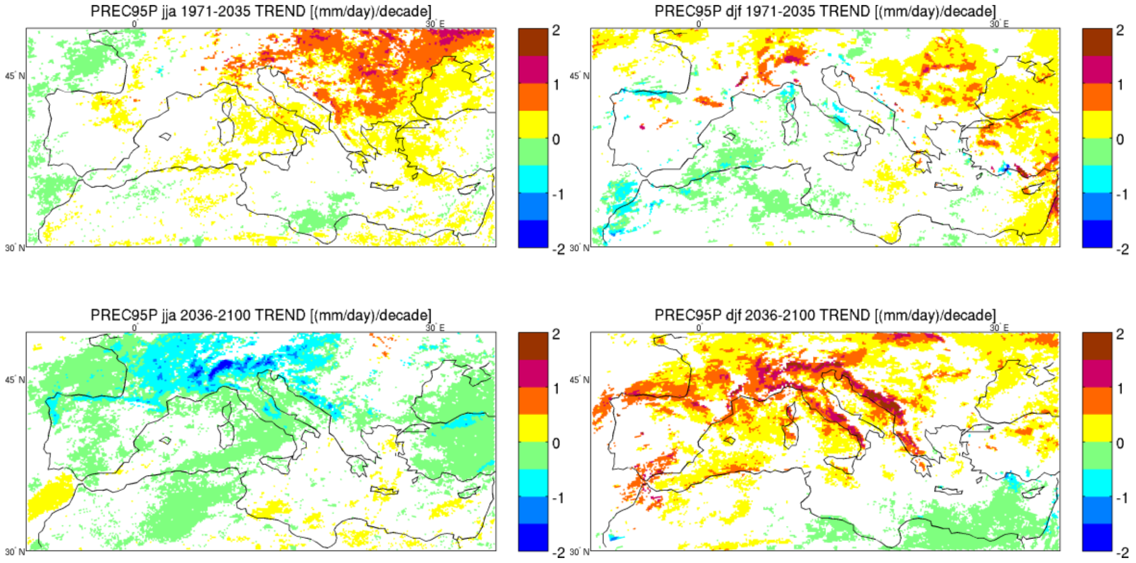

Figure 4. PREC95P trends for JJA (left) and DJF (right):DT1 (top panel) and DT2 (bottom panel). Areas where no statistical significance is found are in white.

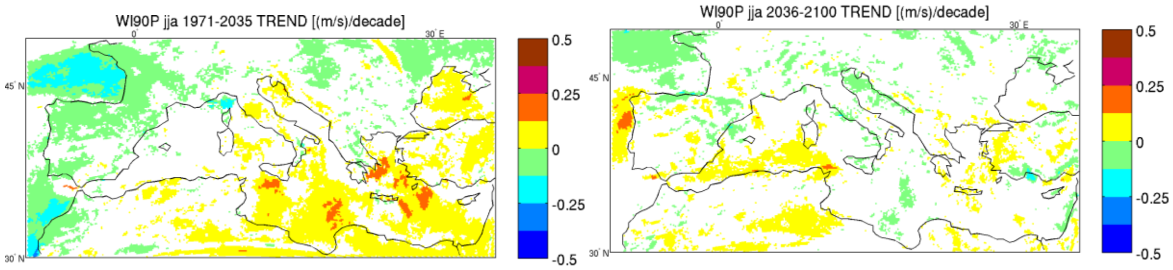

Figure 5. WI90P trends for JJA:DT1 (top panel) and DT2 (bottom panel). Areas where no statistical significance is found are in white.

6. SUMMARY AND CONCLUSIONS

We presented an analysis of a global and a regional climate model aimed at investigating heatwaves and wildfires conditions in the Mediterranean area.

A comparison between model results and a high-resolution observational data set suggests that the CMCC climate models might represent a reliable and useful tool for the investigation of the occurrence of extreme events and their possible changes in future climate scenarios.

Trends over two futures periods (DT1 and DT2) were computed for both global and limited area models, showing a clear tendency toward increasing temperatures, while the behavior of extreme precipitations and wind differ between seasons and periods considered.

7. ACKNOWLEDGEMENTS

This work was partially funded by GEMINA Project- MIUR/MATTM n. 232/2011 and by FUME Project- FP7/2007-2013, Grant Agreement 243888.

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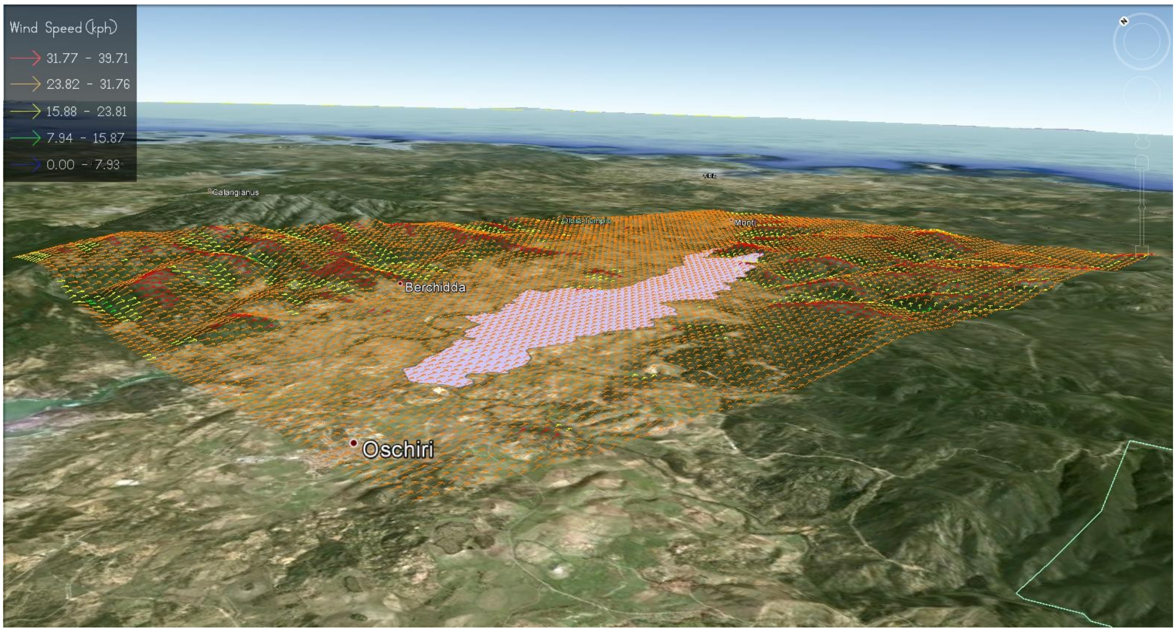

Simulated windfield and observed fire perimeter of the Lochiri wildfire (Sardinia, Italy). July 2011.

MODELING FIRE BEHAVIOUR AND RISK

Analyzing the spatial transmission of wildfire risk from large fires

Ager A.[1], Finney M.A.[2], Vaillant N.M.[1]

[1]USDA Forest Service, Pacific Northwest Research Station, Western Wildland Environmental Threat Assessment Center, 3160 NE 3rd Street, Prineville, OR, 97754. U.S.A.; [2]USDA Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory, 5775 Hwy. 10 West, Missoula, MT, 59808. U.S.A.

aager@fs.fed.us

Abstract

Large wildfires in the US and elsewhere burn over long distances and typically cross many ecological and anthropogenic boundaries. These boundaries often delineate land parcels that have diverse conditions with respect to fuel and fire management (e.g., wilderness versus private forestry), yet it is the collective status of the fuels in concert with weather that ultimately determine containment and the resulting fire perimeter. When conditions in one parcel strongly affect risk factors (likelihood, intensity) in an adjacent parcel, risk is potentially transmitted from the former to the latter. The idea of risk transmission on heterogeneous, fire-prone landscapes has yet to be explored. In this paper, we first describe a quantitative framework for the transmission of risk as the expected loss in a given parcel from fires ignited elsewhere. We then present an experiment to begin applying the framework to an example landscape using simulation modeling.

Keywords: wildfire simulation, wildfire risk, conservation biology, graph theory

1. INTRODUCTION

A growing body of work concerning methods for quantifying wildfire risk and exposure has emerged in the last several years (Finney et al. 2011, Miller and Ager, in press). A key part of this work is identifying and mapping the causal factors that contribute to overall risk, and integrating these data to develop risk management strategies. The challenge with wildfire risk assessment and management is that most of the damage results from relatively few large wildfires that spread over long distances (e.g. 5 – 50 km) relative to the ignition point (FAO 2007). These large fires burn through mosaics of different ownerships and fuel conditions on a typical wildland landscape, and the collective conditions influence the final perimeter. Thus the risk from large fires can be *transmitted* across land parcels since the likelihood of a fire arriving in one parcel is a function of the conditions in the other.

A quantitative definition of transmitted risk can be stated as follows:

$$E(L) = \sum_{j \notin A} \sum_{i=1}^{n} RF_{ij}(P_{ij}) \qquad (1)$$

Where:

$E(L)$ is the expected loss,
RF_{ij} is the loss from fire intensity class i in pixel j,
A is the set of all pixels of a given land parcel,

P_{ij} is the probability of a fire of intensity i from an ignition from outside A.

Local risk can be calculated and compared to transmitted risk by substituting $j \in A$ into the first term. Current wildfire simulation methods limit the practicality of estimating transmitted E(L) primarily because processing pixel-specific intensity maps for a large number of fires would be overwhelming. Estimating transmitted P is, however, possible using recent modeling enhancements that allow efficient calculation and storage of simulated wildfire perimeters (Finney et al. 2011).

In this paper we describe initial work to quantify the transmission of wildfire risk, focusing on the *exposure* (likelihood) component of risk. We used a 0.6 million ha fire-prone study area in the western US that is partitioned into a large number of land designations for the purpose of providing specific ecosystem services (e.g., biodiversity, recreation, wood products, urban interface). We used wildfire simulation outputs from a previous study (Ager et al. 2012) to estimate burn probabilities for transmitted fires. We then built an exposure network that described transmission among all possible land designations, and characterized the network with selected network statistics derived from graph theory (Minor and Urban 2008).

2. METHODS

The study area encompasses the 653,035 ha Deschutes National Forest near Bend, Oregon (Figure 1). The physiographic gradients, diversity of vegetation, climate, and management resemble many national forests throughout the western US. The forest contains extensive stands of lodgepole pine (*Pinus contorta*), ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*), Shasta fir (*Abies concolor*), and mountain hemlock. The Forest has experienced over 8,400 wildland fire ignitions since 1949, with 99% caused by lightning. Wildfire activity has seen a major jump in the past decade, with 1,950 ignitions and 10 large fire events that combined burned 61,500 ha. The forest is partitioned into about 15 primary land management designations (Figure 1B) as specified in the Deschutes National Forest Land and Resource Management and elsewhere. The land management designations are intended to provide a broad mix of ecosystem services including timber, wildlife, waters, recreation, and biodiversity. We included land surrounding the Forest, including wildland urban interfaces, other national forests, private industrial land, and Native American reservations.

We used wildfire simulation outputs from a previous study (Ager et al. 2012) where 50,000 wildfires were simulated using the minimum travel time (MTT) fire spread algorithm (Finney et al. 2011). Calibration and validation for the simulations in the study were described elsewhere (Ager et al. 2012). Ignitions were assumed to be lightning caused and randomly located. Simulation parameters were patterned after escaped wildfires within the study area and surrounding national forest lands (Figure 1B). The simulation model generates output data on the ignition location and perimeter for each fire. We intersected these outputs with the land designation map and calculated: 1) the proportional contribution of fire burning from ignitions on other designations, and 2) the proportional area that ignitions in a given designation burns other designations. The former measures the transmission of fire and associated risk from each designation to the others, while the latter measured the source of incoming fires. We also calculated total average burn probability of each land designation defined as the likelihood of a pixel given one random ignition within the study area.

We used graph theory and network analysis tools to examine wildfire risk transmission among the land designations (Carley and Columbus 2011, Igraph R library). Network analysis tools detect risks or vulnerabilities of an organization's design structure. In this case, the vulnerability in the design was the exposure of fire sensitive land designations to fire. We attributed the nodes (land designations) of the network with burn probability, and weighted the links by the proportion of total area burned either from or to other land designations. For space considerations we were limited to a few network statistics, including three measures of centrality (degree, betweeness, closeness) and one measure of clustering (Table 1, see results). We used these statistics to rank nodes in terms of their routing of fire to and from other land designations.

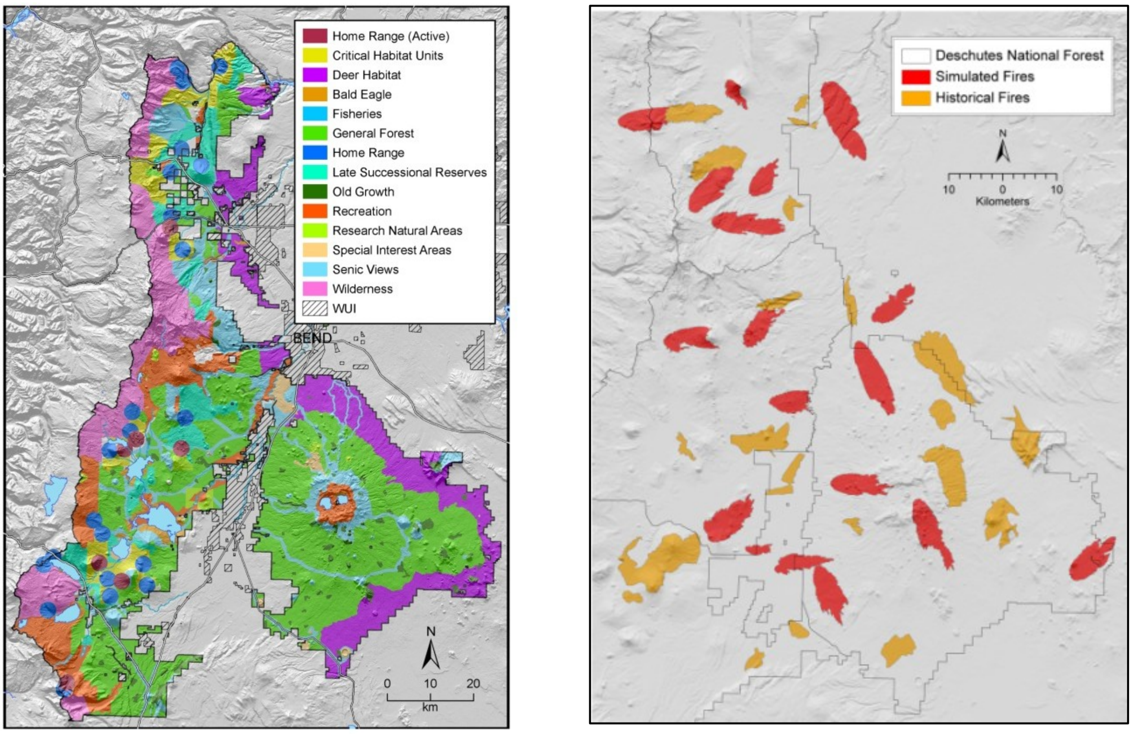

Figure 1. (Left) Study area with land designations and recent wildfire perimeters. Only major land designations are shown in the key for space purposes. (Right) Example fire perimeters, historical perimeters, and the boundary of the Deschutes National Forest in central Oregon.

3. RESULTS

Simulated fire size ranged from about two to 10,821 ha with a mean of 4,512 ha. On average, fires burned across the boundaries of 3.3 different land designations. A few fires burned a maximum of 12 other land designations. In general, the total area burned by transmitted fires into land designations averaged 61%. The general pattern of transmission across land designations was related to their shape and size; designations that were relatively small and imbedded within a matrix of other designations were the recipients of fire from the surrounding matrix. These included small old growth patches (Figure 1A, Figure 2, OLD_E) imbedded in the general forest matrix where 68% of the area burned was from fires originating in primarily the surrounding general forest. Long, narrow visual and riparian habitat corridors were also the recipients of a relatively high number of fires from other areas. The highest level of exposure (area burned) from ignitions outside the designation was about 0.94 (visual and old growth designations), meaning that 94% of the total area burned in the designation was from fires that started elsewhere.

The network diagram of wildfire exposure (Figure 2) clearly showed the major transmission linkages among the land designations. Note that for clarity, linkages that had values less than 0.1 were not shown. Of most interest were the linkages to the fire sensitive wildland urban interface (WUI) and conservation reserves (FSH, CHU). Network statistics revealed wide variation in the land designations, but were difficult to interpret. For instance, the triad count, which measures the number of triangles for a given node, varied from 561 for visual corridors in the western portion of the forest (VIS_W), to 38 for the recreation areas in the eastern portion (REC_S). Centrality degree, which is defined as the number of total ties for a network node, was highest for the general forest in the southern portion of the Forest (GFM_S), and thus these areas potentially interact (transmit and receive) fire to the largest number of other designations. The Centrality closeness measures the sum of the linkages (proportion burned) to all other nodes, and was largest for the national forest lands adjacent to the Deschutes (FS_W), and the general forest in the eastern portion (GFM_E).

Table 1. Rankings of land designations for selected network descriptor variables. See text for definitions and the methods for their calculation.

Rank	Triad count	Centrality- closeness	Centrality-degree
1	VIS_W	FS_W	GFM_S
2	REC_W	GFM_E	GFM_E
3	PVT_IN	WUI_S	PVT_IN
4	FSH	WUI_BND	PVT_OUT
5	WILD_DES	OCRA_DES	DHB_S

4. DISCUSSION

We presented a formal quantitative framework for measuring the transmission of risk and exposure from large fires, and defined the necessary information to partition risk from large fires into local versus transmitted. Applying this framework will be a challenging problem with current simulation methods since fire intensity footprints will be required for the large number of fires (e.g., >50,000) used to estimate wildfire risk factors. In spite of these technical issues, we were able to quantify the transmission of exposure (likelihood) with existing fire simulation models. We also introduced graph theory as a tool to interpret wildfire transmission networks. Graph theory facilitates the study of disturbance flows through networks and may have the potential to quantify the direct (local) and indirect effect (transmitted) risk in the system. Graph theory is being widely applied to study landscape connectivity of habitats (e.g., Minor and Urban 2008). In this study, the primary interest was the connectivity of fire among the land designation parcels, especially with respect for biodiversity reserves and the urban interface. Understanding how connectivity facilitates the transmission of risk is important in the context of designing strategic fuel management activities.

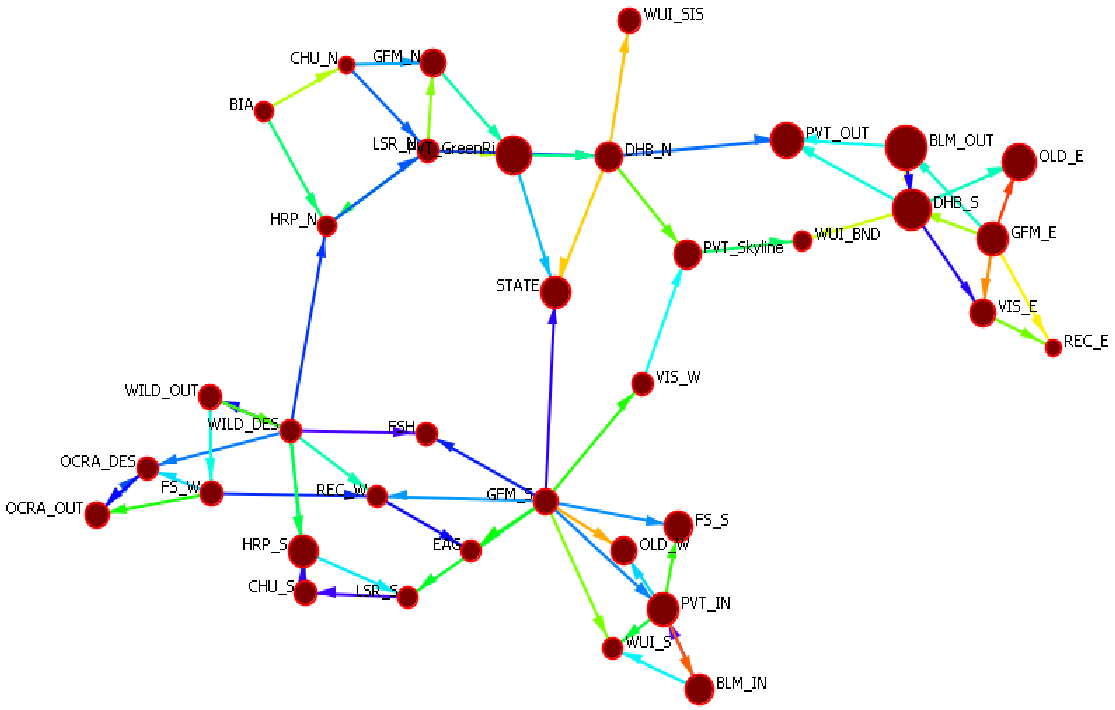

Figure 2. Network diagram of fire transmission among land designations on the Deschutes National Forest and surrounding lands. Nodes are sized by the burn probability, and linkages are colored by the contribution of fire to other nodes (see Figure 1). Selected codes: GFM = general forest matrix, REC = recreation sites, WUI = wildland urban interface, VIS = scenic areas, wildlife habitat (DHB = deer habitat, FSH = aquatic reserves, HRA and HRP are owl home range sites), OLD = old growth areas, WIL = wilderness areas, LSR = late successional reserves, RNA = research natural areas. Suffix of S and N indicate southern and northern portions of the forest. Suffix of IN and OUT indicate inside and outside the Forest boundary. FS indicates adjacent national forests.

The network diagram (Figure 2) provided a new way to characterize landscape fire behavior from simulation outputs, especially in the context of multi-owner landscapes, and federal forests that are partitioned into parcels for specific ecosystem services. These parcels can have divergent fire and fuel management goals that contribute to the larger landscape fire behavior. Network statistics can be used to develop wildfire mitigation strategies for fire sensitive ecosystem services by identifying the source nodes of fire. The network diagram and statistics for the study area suggest disturbance linkages between disparate ecosystem services both on and adjacent to the Forest. Moreover, it is evident that transmission is a function of the shape and spatial grain of specific land designations relative to others.

In the future we expect that processing the voluminous outputs on fire intensity for many simulated fires will become practical for risk assessment, thereby advancing the study of wildfire risk transmission. In the interim, estimating exposure networks in additional case studies will help inform landscape design questions and help build sustainable landscapes to provide for a wide variety of sustainable ecosystems services on landscapes prone to large fires. Network analyses will be useful to better understand how to manage fire risk in the context of both restoring fire adapted ecosystems, and protecting fire sensitive assets from wildfire. A number of graph theory concepts and network analysis tools not explored here will likely offer many new ways to understand fire transmission networks. These tools will be particularly useful for studying wildfire risk in the urban interface where current risk assessment procedures do not consider large fire spread, and thus do not measure the *ex situ* risk at the landscape scale.

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Fire behavior modeling in laboratory experiments

Beutling A.[1]**, Batista A.C.**[2]**, Viana Soares R.**[2]

[1]*Federal University of Mato Grosso do Sul Chapadão do Sul, MS, Brazil;* [2]*Forest Fire Laboratory, Federal University of Paraná Curitiba, PR, Brazil*

beutling.a@gmail.com, batistaufpr@ufpr.br, rvsoares@ufpr.br

Abstract

The objective of this research was to develop and adjust fire behavior models in laboratory experiments. The work was carried out in two locations: the University of Paraná Forest Fire Research Laboratory and the Rio Sagrado Industrial Chemistry Fire Control Laboratory, located in Curitiba and Quatro Barras Municipalities, Paraná State, Brazil, respectively. The dependent variables rate of spread and fire intensity were estimated through the following independent and predetermined variables: fuel load, fuel depth, flame height, and slope degree. Results showed that, in slopes lower than 15º, fuel load was the main explanatory variable in the rate of spread estimation, whereas the inclination became the main factor in slopes higher than 15º. Second order polynomial models presented best fit to estimate fire spread based on the slope degree ($R^2 = 0.76$). Flame height presented good results to estimate rate of spread ($R^2 = 0.81$) and fire intensity ($R^2 = 0.83$).

Keywords: Fire behavior, Fire intensity, Rate of spread, Flame height

1. INTRODUCTION

In fire suppression activities the rate of spread, the fire line intensity, and the flames height are the most important information for the fire brigades. On the other hand, these variables are dependent on other variables like terrain slope, fuel load, wind speed, relative humidity, and air temperature. Several authors have tried to estimate the main fire behavior variables through field and laboratory experiments (McArthur 1967; Rothermel 1972; Rothermel 1983; Botelho and Ventura 1990; Andrews and Bevins 1999; Julio 1996; Andrews et al. 2004). Different from field conditions, laboratory experiments allows the control of most independent variables, favoring the development of mathematic models to estimate or predict the fire behavior components with more accuracy.

The objective of this research was the development of models to predict fire behavior components based on the following controlled variables: fuel load, fuel bed thickness, and fuel bed inclination.

2. METHODOLOGY

The research was carried out in two laboratories, the Federal University of Paraná (UFPR) Fire Lab and the Rio Sagrado Industrial Chemistry Fire Control Laboratory (LPCI-Rio Sagrado), located in Curitiba and Quatro Barras Municipalities, Paraná State, Brazil, respectively. The UFPR Fire Lab has a combustion chamber with a 1.20 x 0.70 m fuel bed that can be inclined in five levels, and lateral pins spaced 10 cm from each other to monitor the fire rate of spread. A vertical rule allows the flame height measurement (Figure 1).

Figure 1. The UFPR Fire Lab combustion chamber and the fuel bed.

The LPCI-Rio Sagrado Fire Lab presents several combustion beds but only the main one, measuring 5.0 x 3.0 m was used in this research (Beutling 2009). The combustion bed has horizontal pins spaced 20 cm from each other to monitor the fire rate of spread and two vertical rules with marks every 10 cm to facilitate the flames height measurements (Figure 2).

2.1. Methodological procedures

Pine needles oven dried at 75ºC during 48 hours were used as fuel material for the burnings in the UFPR Fire Lab tests. Two fuel loads were used, 0.2 kg m^{-2} and 0.4 kg m^{-2}, homogeneously distributed over the fuel bed. The fuel density remained the same, varying only the fuel layer thickness. A randomized design with two fuel loads, five inclinations (0, 5, 10, 15, and 20º) and five replications was used, totalizing 50 burnings. During the burnings the rate of spread and the flames height were measured every 10 cm of fire propagation. The data were submitted to the analysis of variance and the differences between the averages compared by the SNK test (Steel and Torrie 1960). The statistic software used was the Statgraphics plus 4.1.

In the LPCI-Rio Sagrado Fire Lab the burnings the fuel material was “tifton hay” oven dried at 75 ºC for 48 hours. The fuel moisture content ranged from 7 to 15%, the fuel density was 11.11 kg m^{-3} and the fuel layer thickness 9.0 cm. Flames height and rate of spread were measured every 20 cm of propagation interval. Air temperature and relative humidity were also measured at one minute intervals through a portable weather station. A total of 188 burnings were done during the tests. The statistic analysis was similar to the ones used in the UFPR Fire Lab tests.

Figure 2. The LCI –Rio Sagrado Fire Lab showing the main combustion bed.

3. RESULTS AND DISCUSSION

3.1. UFPR Forest Fire Laboratory

In the 0.2 kg m^{-2} fuel load burnings the rate of spread ranged from 0.00503836 m s^{-1} in the 0° slope to 0.0139211 m s^{-1} in the 20º slope. No statistic difference was detected between the rates of spread in the 0º and 5º slope. However, the average rate of spread increased 1.21 times in the 10º slope, 1.79 in the 15º slope, and 2.83 in the 20º slope. McArthur (1962) stated that the rate of spread doubled at every 10º slope, but Chandler et al. (1983) said that it only doubles every 15º slope. In the 0.4 kg m^{-2} fuel load burnings the rate of spread ranged from 0.00579103 m s^{-1} to 0.01915 m s^{-1} in the 0º and 20º slope, respectively. No statistic difference between the rate of spread in the 0º slope and 5º slope was detected also in these burnings. However, the rate of spread increased 1.46 times in the 10º slope, 2.11 times in the 15º slope (very similar to that observed by Chandler et al. (1983)), and 3.12 times in the 20º slope (Figure 3).

Statistic analysis showed that in slopes up to 10º fuel load was the main factor in the rate of spread estimation, whereas in slopes higher than 15º inclination became the main factor. From 10º to 15º slopes no difference between fuel load and inclination as main factor was observed. The tests run in the UFPR Fire Lab permitted the development of mathematical models to estimate the rate of spread (r) based on the slope level (d), as follows:

i) Mathematic model to estimate rate of spread in burnings with 0.2 kg m^{-2} fuel load and different slope levels (degrees):

$$\boldsymbol{r_{0,2} = 0{,}00511284 - 0{,}00026972\, d + 0{,}0000352957\, d^2} \quad (R^2=0.79);\ (S_{yx}=45.92)$$

ii) Mathematic model to estimate rate of spread in burnings with 0.4 kg.m^{-2} fuel load and different slope levels (degrees):

$$\boldsymbol{r_{0,4} = 0{,}00581917 - 0{,}0000528598\, d + 0{,}0000358139\, d^2} \quad (R^2=0.77);\ (S_{yx}=25.15)$$

The average fire line intensity values observed in the UFPR Fire Lab burnings were quite low, ranging from 3.93 kcal $m^{-1}s^{-1}$ in the 0.2 kg m^{-2} fuel load and flat surface (0º slope) to 30.64 kcal $m^{-1}s^{-1}$ in the 0.4 kg m^{-2} fuel load and 20º slope (Figure 4).

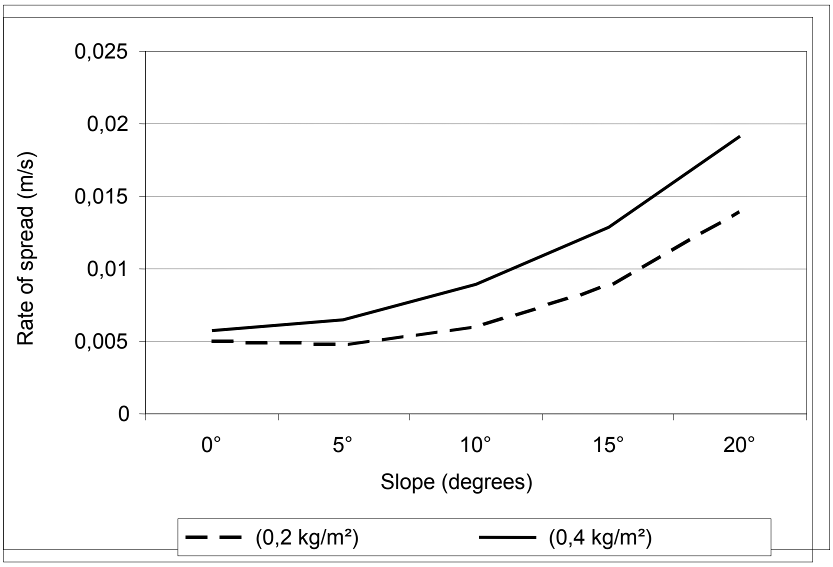

Figure 3. Rate of spread according to the slope degree in laboratory experiments with two different fuel loads.

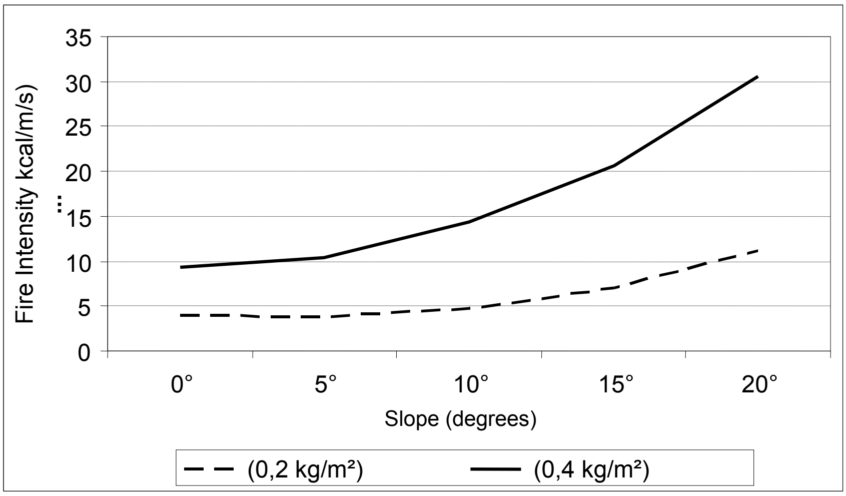

Figure 4. Fire intensity variation according to the slope degree in laboratory experiments with two different fuel loads.

3.2. LPCI-Rio Sagrado Fire Laboratory

The tests run in this laboratory were conducted without variation in the fuel load (1 kg/m^2) and the fuel layer thickness (9.0 cm). Therefore, the fire behavior was only influenced by the air temperature and relative humidity in the laboratory environment. The air temperature recorded in the laboratory during the burnings ranged from 15.05 to 32.85 ºC, and the relative humidity ranged from 34.90 to 82.05%.

Table 1. Maximum, medium and minimum values of rate of spread, flames height, and fire intensity observed in the LPCI-Rio Sagrado laboratory burnings

	Rate of spread ($m\ s^{-1}$)	Flames height (m)	Fire intensity ($kcal\ m^{-1}s^{-1}$)
Minimum	0.0016667	0.28	13.72
Medium	0.0075769	0.72	30.06
Maximum	0.0200000	1.10	46.40

The statistic analysis showed no significant correlation between air temperature and fire behavior variables. However, significant correlation was observed between:

Rate of spread and relative humidity (-0.4914);
Flames height and relative humidity (-0.3682);
Flames height and rate of spread (0.8905);
Flames height and fire line intensity (0.9048);
Fire line intensity and relative humidity (-0.4796);
Fire line intensity and rate of spread (0.9899).

The association between the measured variables permitted the development of mathematical models to estimate rate of spread (*r*) and fire line intensity (*I*) based on relative humidity (*UR*) and average flames height (*hc*):

i) Mathematical model to estimate rate of spread ($m\ s^{-1}$) based on the flames height (m):

$$\boldsymbol{r = 0.00286971 - 0.00153305hc + 0.0108964hc^2} \quad (R^2 = 0.81); \quad (S_{yx} = 12.03)$$

ii) Mathematic model to estimate rate of spread ($m\ s^{-1}$) based on the flames height (m) and relative humidity (%):

$$\boldsymbol{r = 0.00131575 + 0.0118399hc - 0.0000377575UR} \quad (R^2 = 0.82); \quad (S_{yx} = 11.42)$$

iii) Mathematic model to estimate fire line intensity ($kcal\ m^{-1}s^{-1}$) based on flames height (m):

$$\boldsymbol{I = \exp(2.01271 + 1.89883hc} \quad (R^2 = 0.83); \quad (S_{yx} = 0.41)$$

iv) Mathematic model to estimate fire line intensity ($kcal\ m^{-1}s^{-1}$) based on flames height (h) and relative humidity (%):

$$\boldsymbol{I = 3.88372 + 47.6523hc - 0.130531UR} \quad (R^2 = 0.84); \quad (S_{yx} = 10.80)$$

4. CONCLUSIONS

i) No statistical difference was detected in the rate of spread between the burnings carried out in flat surfaces and 5º slope.

ii) For the 0.2 kg m^{-2} fuel load the rate of spread increased 1.21 times in the 10º slope, 1.79 times in the 15° slope, and 2.83 times in the 20º slope when compared to the flat surface.

iii) For the 0.4 kg m^{-2} fuel load the rate of spread increased 1.46 times in the 10º slope, 2.11 times in the 15° slope, and 3.12 times in the 20º slope when compared to the flat surface.

iv) In slopes up to 10º fuel load was the main factor in the rate of spread estimation, whereas in slopes higher than 15º inclination became the main factor; from 10º to 15º slopes no difference between fuel load and inclination as main factor was observed.

v) Second order polynomial models presented best fit to estimate fire spread based on the slope degree ($R^2 = 0.76$).

vi) Flame height presented good results to estimate rate of spread ($R^2 = 0.81$) and fire intensity ($R^2 = 0.83$).

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An Application of the Level-set Method to Fire Front Propagation

Ghisu T., Arca B., Pellizzaro G., Duce P.

National Research Council, Institute of Biometeorology (CNR-IBIMET), Sassari, Italy

t.ghisu@ibimet.cnr.it

Abstract

Wildland fire models and simulators developed in the last two decades are increasingly applied in different ecosystems and countries of the world to predict fire behavior and effects. Fire models range from empirical formulas, such as the ones defined by Rothermel and applied in spatially and temporally explicit fire simulators (i.e. Farsite), to complex three-dimensional CFD approaches solving the partial differential equation of continuity, momentum and energy. The wide range of length and time scales governing wildland fire (from the millimeter scale of combustion processes to the hundreds of meters scale of synoptic wind flow) complicates the use of a full-3D numerical approach, at least for operational forecasting purposes. At the same time, there is an important two-way influence between weather and fire: wind determines fire propagation and, conversely, the buoyancy effects generated by fire heat modify the local wind field, "creating their own weather". A possible solution to this problem is the use of a simpler (and thus computationally cheaper) model to describe fire propagation, while maintaining a CFD approach to model wind behavior and, more importantly, the two-way interaction due to fire heat release. A number of studies applied this approach in the last few years [1]. This work describes the initial steps in the development of a model for fire-front propagation based on a level-set methodology and its integration into a CFD model.

Keywords: fire propagation, level-set, CFD

1. INTRODUCTION

The majority of wildfire simulation codes make use of empirical formulas to predict fire propagation. With the relentless increase in computational resources, there is a need for improved reliability by capturing more of the physics of the fire propagation process. While a full 3D approach is still too heavy (at least for operational purposes), a number of studies have demonstrated improved accuracy by means of coupled atmosphere-fire propagation modeling, which combines a CFD approach for the wind behavior with empirical models to predict the displacement of the fire front. The objective of this work is to develop a coupled atmosphere-fire propagation model by expanding the capabilities of available CFD software.

2. METHODOLOGY

2.1. A level-set method for fire propagation

Level-set methods are Eulerian schemes for tracking fronts that propagate with a given speed function (which can depend on position, time and other local properties such as normal direction and local curvature [2]). The basic idea is to use an implicit definition of the front $\Gamma(t)$ by means of a function $\psi : \Re^n \times [0, T_f] \rightarrow \Re$ such that:

$$\forall t \in [0, T_f] \; \Gamma(t) = \{x \in \mathbb{R}^n | \psi(x, t) = 0\} \tag{1}$$

The partial differential equation defining the evolution of the front can be obtained by differentiating the equation for the fire front with respect to time:

$$\frac{\partial \psi}{\partial t} + R \cdot \nabla \psi = 0 \tag{2}$$

where R is the front propagation speed, generally assumed perpendicular to the fire front [3]. With this assumption, equation (2) becomes:

$$\frac{\partial \psi}{\partial t} + ||R||||\nabla \psi|| = 0 \tag{3}$$

where || . || represents the Euclidean norm operator.

On Cartesian grids, equation (3) can be solved using a Finite Difference approach. To preserve stability, special care needs to be placed in the approximation of spatial derivatives. The simplest stable scheme is a first-order upwind. For the x-derivative it reads:

$$\frac{\partial \psi}{\partial x} = \begin{cases} \frac{\psi_{i,j} - \psi_{i-1,j}}{\Delta x} & \text{if } R_x > 0 \\ \frac{\psi_{i,j} - \psi_{i-1,j}}{\Delta x} & \text{otherwise} \end{cases} \tag{4}$$

Similarly, the time derivative in equation (3) can be approximated with a first-order explicit scheme (Euler's method):

$$\frac{\partial \psi}{\partial t} = \frac{\psi_{i,j}^{n+1} - \psi_{i,j}^{n}}{\Delta t} \tag{5}$$

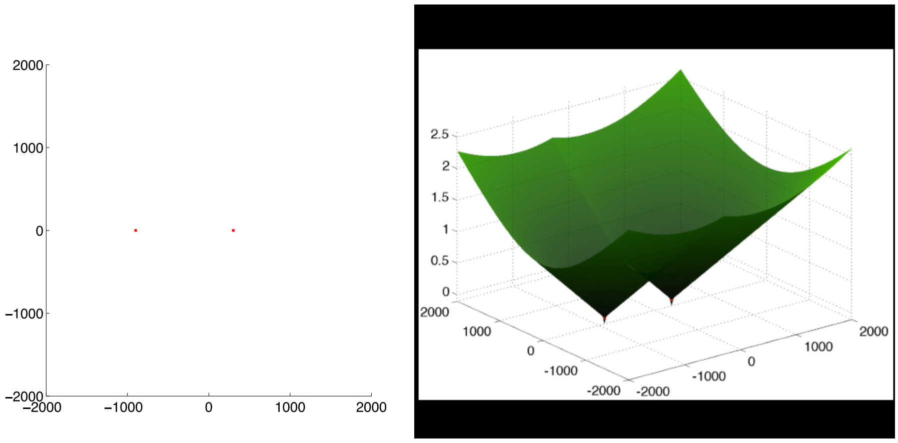
where the superscripts represent the time step. This approach is first-order accurate in both time and space: higher-order discretization can be used, but are not considered in this study due to the uncertainties in the estimation of the fire propagation rate. For an explicit scheme, the maximum stable time step is related to the grid spacing by the Courant-Friedrichs-Lewy (CFL) condition:

$$\max\left(\frac{R \Delta t}{\Delta x}\right) \leq 1 \tag{6}$$

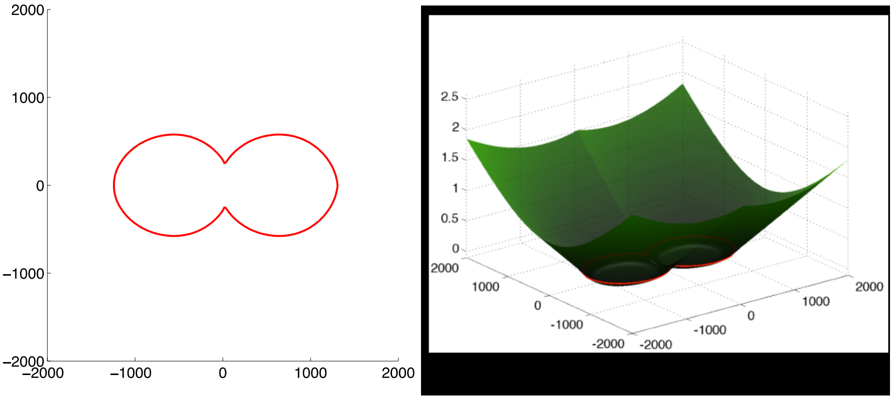
Von Neumann boundary conditions are used at the boundaries of the physical domain. To approximate the fire front at time $t = 0$, the initial value of the level-set function can be chosen as the signed distance from the fire-line:

$$\psi(x, t) = \begin{cases} d_{\Gamma(t)}(x) \text{if } x \text{ lies outside } \Gamma(x) \\ -d_{\Gamma(t)}(x) \text{if } x \text{ lies outside } \Gamma(x) \end{cases} \tag{7}$$

Figure 1 shows the evolution of a fire from two separate ignition points. The level-set function is shown on the right, the fire perimeter on the left, in the presence a low intensity wind (corresponding to an ellipse eccentricity of 0.5). Fire-spread rate has been calculated using Rothermel’s formulation. The level-set approach is able to deal with fire-front merging without additional complexities.



(a) Initial fire



(b) Final fire

Figure 1. Evolution of fire perimeter (left) and corresponding level-set function (right)

2.2. Wind-field predictions

To compute the atmospheric flow, we make use of the CFD solver Fluent from Ansys, which provides a wide range of well-validated solvers and models. A body-fitted numerical grid is generated efficiently via a free-form-deformation of a Cartesian grid (an example of the deformed ground-mesh is shown in Figure 2). The grid in this case is structured (evenly- spaced in x- and y-directions), but any other type of grids could be used without any additional requirements.

Fluent allows a generic wind field to be predicted, given boundary conditions at the extremes of the computational domain. At vertical boundaries, inlet-velocity, pressure-outlet or symmetry boundary conditions are used (depending on the wind direction), a symmetry boundary condition is used at the top of the computational domain and a no-slip boundary condition at the bottom, with a roughness wall-function to account for the large frictional forces exerted by the vegetation on the atmospheric boundary layer. A renormalization group $k-\varepsilon$ model is used for turbulence closure.

For generality, equation (2) has been rewritten in Finite Volume formulation:

$$\frac{d}{dt}\int_V \psi dV + \int_\Omega R\psi \cdot n dS \tag{8}$$

where V is a generic control volume and Ω the corresponding boundary surface. The same approximation of Section 2.1 is obtained using the upstream value of ψ to calculate the surface integrals in equation (7). For simplicity, the mesh used to solve the level-set problem corresponds to the ground mesh in the fluid problem.

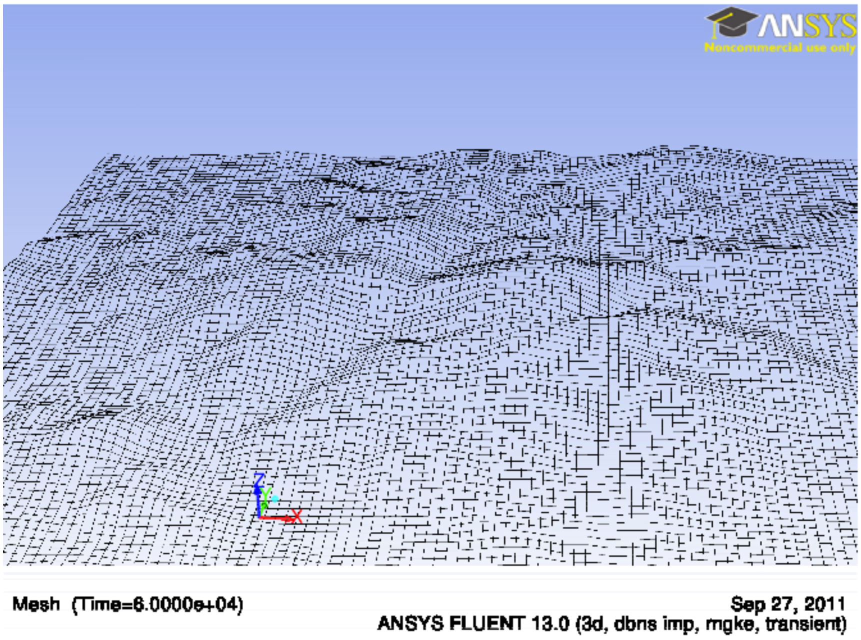


Figure 2. Ground mesh in Fluent

Fluent allows a generic wind field to be predicted, given boundary conditions at the extremes of the computational domain. At vertical boundaries, inlet-velocity, pressure-outlet or symmetry boundary conditions are used (depending on the wind direction), a symmetry boundary condition is used at the top of the computational domain and a no-slip boundary condition at the bottom, with a roughness wall-function to account for the large frictional forces exerted by the vegetation on the atmospheric boundary layer. A renormalization group $k-\varepsilon$ model is used for turbulence closure.

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The fire propagation solver has been linked to Fluent by means of user-defined-functions (UDFs) written in C. To simplify the integration, we have defined a *cell* structure containing a number of information required to solve equation (7), mostly calculated during the initialization process -- e.g. number of neighboring cells and their IDs, cell volume and boundary areas, ID of fluid cell for wind velocity, current and old values of level-set function (if needed), fire propagation parameters (vegetation, slope, etc.) and fire-front rate of spread -- to reduce run times.

2.3. Wind-fire interaction

To resolve the interaction between the heat generated in the combustion process and the wind flow, the heat has been introduced at the ground boundary. The reaction intensity from Rothermel's formulation gives the heat generated per unit surface. The surface has been assumed to start burning when the level-set function assumes a negative value and to continue burning until all the fuel is consumed (the burning time can be calculated as the product of the reaction intensity and the inverse of fuel load and fuel heat content).

3. RESULTS

Figure 3 presents a comparison between the evolution of a line fire without (left) and with (right) wind-fire interaction, in the presence of a 5 m/s intensity wind coming from the left boundary. Figure 4 shows the complex vortical structures generated the buoyant flow.

Figure 5 demonstrates the application of the solver in a real case (note the formation of an unburned island due to the combined effect of terrain morphology and wind).

4. CONCLUSIONS

This work presents the first steps in the development of a tool to predict wildland fire propagation, capable to account for wind-fire interaction. Future plans include extensive testing and further development of available capabilities

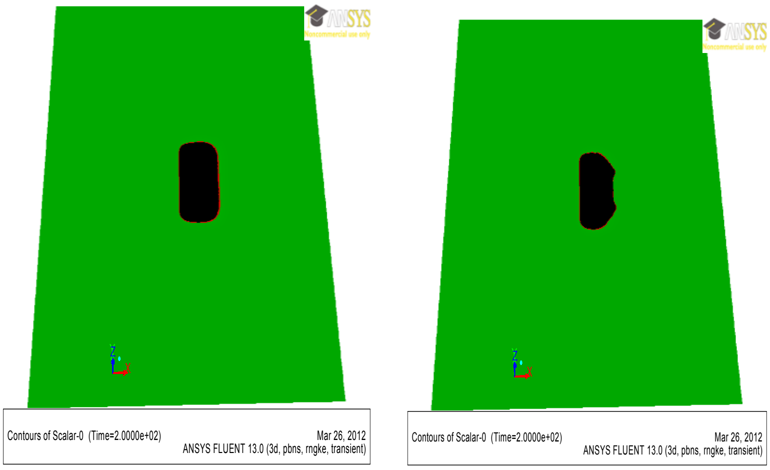

Figure 3. Effects of buoyancy on the fire perimeter

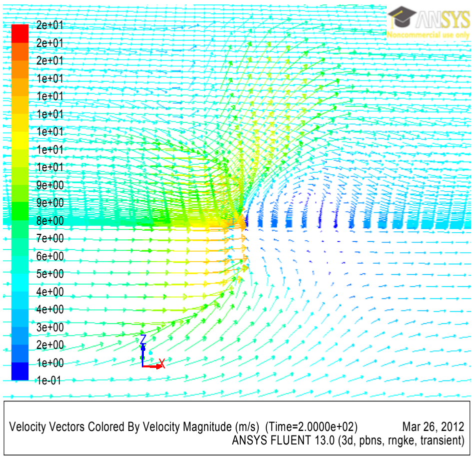

Figure 4. Wind-fire interaction

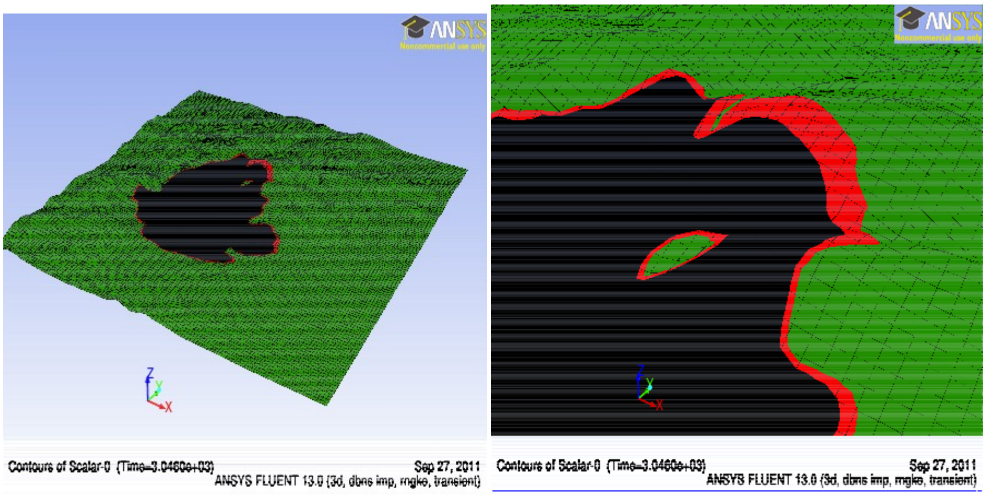

Figure 5. Application in a real case

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The randomized level-set method to model turbulence effects in wildland fire propagation

Pagnini G., Massidda L.

CRS4, Polaris Bldg. 1, 09010 Pula (CA), Italy

pagnini@crs4.it

Abstract

The wildland fire propagates at the ground level and then strongly depends on the dynamics of the Atmospheric Boundary Layer, whose flow is turbulent in nature. Turbulence is amplified by the forcing due to the fire-atmosphere coupling and by the appearing of the fire-induced flow. Turbulence randomly transports the hot air mass that can pre-heat and then ignite the area around and ahead the fire. The fire front position gets therefore a random character. The level-set method for tracking fire line contour is randomized according to the probability density function of the turbulent displacement of the hot air particles. The proposed model emerges to be suitable to simulate a moving fire front displaced by the pre-heating action of the hot air mass itself diffused by the turbulence. This mechanism allows the simulation of the fire overcoming a firebreak zone, a situation that the level-set method can not resolve.

Keywords: fire front propagation, level-set method, randomized level-set method, fire-atmosphere coupling, fire-induced flow, turbulence

1. INTRODUCTION

The wildland fire propagation is a multi-scale, as well as a multi-physics, process strongly influenced by the atmospheric wind. Since the fire front propagates at the ground level it is driven by the dynamics of the Atmospheric Boundary Layer (ABL), whose large scale motion influences the fire front velocity while the small scale motion is related to turbulent flows that play a fundamental role in wildfire spread as demonstrated in [1]. Actually, when a wildland fire occurs, the ABL emerges to be forced also by the fire-atmosphere coupling and turbulence increases. Close to the fire front, turbulence is increased also by the fire-induced flow. To model the effects of turbulence on the fire front propagation, the suitability of a recent approach based on the statistical distribution of the level-set contour [2] is here investigated.

The level-set is a method to track moving interfaces [3] that has been recently applied to study the fire front contour in wildland fire propagation [4], [5], [6]. It allows the representation of the burning region on a simple cartesian grid and the flexible implementation of various ignition modes. Moreover, this method is particularly appropriate to handle problems that arise from propagation of wildfires since leads to an accurate calculation of the front normal vector, which is necessary to compute the burning velocity. The level-set method can automatically deal with topological changes that can occur during the fire spreading, as the merging of separate flame fronts or the formation of unburned “islands”.

The level-set method for tracking fire line contour is randomized by considering a distribution of the contour according to the probability density function (PDF) of the turbulent displacement of the hot air particles. The accounting for the effect of turbulence on the fire propagation improves the usefulness of the operational models and thereby increases the firefighting safety and in general the efficiency of the efforts for the fire suppression and control.

The paper is organized as follows. In paragraph 2, the random level-set method is introduced and the proposed model described. In paragraph 3, the model is applied to predict the fire front motion when the pre-heating induced by the hot turbulent flow is taken into account and also to successfully tackle the realistic situation when the ordinary level-set method fails: fire overcoming of firebreaks. Finally in paragraph 4 some conclusions on the performance of the model are given.

2. MODEL DESCRIPTION

The concept of the *randomized level-set method* is founded on the idea that, due to the turbulence, the fire front contour cannot be assumed to be deterministic, so that the resulting *effective* fire front propagates according to the statistical distribution of a random trajectory. Hence, a statistically distributed fire line follows.

Let $\bar{x}(t,\bar{x}_0)$be a deterministic trajectory with initial condition $\bar{x}_0$, i.e., $\bar{x}(0,\bar{x}_0)=\bar{x}_0$, and driven solely by the rate of spread $V(\bar{x},t)$. Moreover, let $\phi(\bar{x},t)$be the function with values $1$and 0such that$\phi(\bar{x},t)=1$ marks the burned area $\Omega(t)$, i.e., $\Omega(t)=\{\bar{x},t\colon\phi(\bar{x},t)=1\}$, and $\phi(\bar{x},t)=0$marks the unburned area, i.e., $x\notin\Omega(t)$. Let $X^\omega(t,\bar{x}_0)=\bar{x}(t,\bar{x}_0)+\sigma^\omega$be the ω-realization of a random trajectory driven by the noise σ, with average value $\langle X^\omega(t,\bar{x}_0)\rangle=\bar{x}(t,\bar{x}_0)$and the same fixed initial condition $X^\omega(0,\bar{x}_0)=\bar{x}_0$in all realizations. Hence, the ω-realization of the fire line contour follows to be

$$\phi^\omega(x,t)=\int\phi(\bar{x}_0,0)\delta(x-X^\omega(t,\bar{x}_0))d\bar{x}_0. \tag{1}$$

Since the trajectory $\bar{x}(t,\bar{x}_0)$is time-reversible, i.e., the Jacobian of its transformation $\bar{x}(t,\bar{x}_0)=F_t(\bar{x}_0)$is $\frac{d\bar{x}_0}{d\bar{x}}=1$, then Formula (1) becomes

$$\phi^\omega(x,t)=\int\phi(\bar{x},t)\delta(x-X^\omega(t,\bar{x}))d\bar{x}. \tag{2}$$

Finally, after averaging, the effective fire front contour emerges to be determined as

$$\begin{aligned}\langle\phi^\omega(x,t)\rangle=\langle\int\phi(\bar{x},t)\delta(x-X^\omega(t,\bar{x}))d\bar{x}\rangle&=\int\phi(\bar{x},t)\langle\delta(x-\bar{X}^\omega(t,\bar{x}))\rangle d\bar{x}\\&=\int\phi(\bar{x},t)p(x;t\mid\bar{x})d\bar{x}\\&=\int_{\Omega(t)}p(x;t\mid\bar{x})d\bar{x}=\phi_{eff}(x,t),\end{aligned} \tag{3}$$

where $p(x;t\mid\bar{x})=p(x-\bar{x};t)$is the PDF of the turbulent dispersion of the hot flow particles with average position $\bar{x}$.

Formula (1) has been originally proposed to model the progress variable in turbulent premixed combustion [2]. The evolution equation of the effective fire front $\phi_{eff}(x,t)$is [2]

$$\frac{\partial\phi_{eff}}{\partial t}=\int_{\Omega(t)}\frac{\partial p}{\partial t}d\bar{x}+\int_{\Omega(t)}\nabla_{\bar{x}}\cdot[V(\bar{x},t)p(x-\bar{x};t)]d\bar{x}, \tag{4}$$

that for a deterministic motion, i.e., $p(x-\bar{x};t)=\delta(x-\bar{x})$, reduces to the ordinary level-set front propagation [2]. This fire line distribution permits to model the pre-heating of the area ahead the flame front. Points x such that $\phi_{eff}(x,t)>0.5$ are marked as burnt.

The model is completed by a law for the ignition due to the pre-heating induced by the hot turbulent flow. Let $T(x,t)$ be the temperature field, then the superposition of hot air in an unburned point x, i.e., $\phi_{eff}(x,t)\leq 0.5$, for a temporal interval $\varDelta t$ makes the temperature rise up to the ignition value $T(x,\varDelta t)=T_{ign}$.

Assuming that the temperature grows according to

$$\frac{\partial T(x,t)}{\partial t}=\phi_{eff}(x,t)\frac{T_{ign}-T(x,0)}{\tau}, T\leq T_{ign}, \tag{5}$$

then, for a given characteristic ignition delay τ, it holds

$$\tau=\int_0^{\varDelta t}\phi_{eff}(x,\xi)d\xi. \tag{6}$$

3. NUMERICAL SIMULATIONS

3.1. Numerical simulation set-up

Simulations are performed assuming an isotropic bi-variate Gaussian PDF

$$p(x-\bar{x};t)=\frac{1}{2\pi\sigma^2}\exp\left\{-\frac{(x-\bar{x})^2+(y-\bar{y})^2}{2\sigma^2}\right\} \tag{7}$$

where σ^2 is the particle displacement variance related to the turbulent diffusion coefficient D, i.e., $\langle(x-x)^2\rangle=\langle(y-\bar{y})^2\rangle=\sigma^2=2Dt$.

The rate of spread $V(\bar{x},t)=V(\bar{x},t)\hat{n}$, where $\hat{n}=-\nabla\phi/\|\nabla\phi\|$ is the outcoming normal, is calculated from the well known Rothermel semi-empirical formula [7]

$$V(\bar{x},t)=V_0(1+f_W+f_S) \tag{8}$$

where V_0 is the spread rate in the absence of wind, f_W is the wind factor and f_S is the slope factor. The reader is referred to fireLib and Fire Behaviour SDK documentation (http://fire.org/) and to [6] for a full description of V_0, f_W and f_S.

However, to best highlight the model performance, the simulations are performed in the most simple case with no wind, no slope and short grass fuel, i.e., NFFL (Northern Forest Fire Laboratory) Model 1, and with a unique dead fuel moisture of the type 1-hour dead fuel moisture (i.e., those fuels whose moisture content reaches equilibrium with the surrounding atmosphere within one hour) that is stated equal to 0.1[lb water / lb fuel]. Lenght and elapsed time are expressed in feets [ft] and minutes [min], respectively.

3.2. Pre-heating effects on the fire-front propagation

Two competing ignition mechanisms for fire front propagation are considered: the flame reaching a certain place, or the hot air mass heating an area so much that it burns after an ignition delay $\varDelta t$. Then, if the ignition delay $\varDelta t$ is short enough, places heated by the hot air can burn before than the fire flame is arrived and the effective fire front velocity results to be increased. The stronger is the turbulence, the more distant from the fire flame the hot air is diffused.

Figures 1 and 2 show that strong turbulence and short ignition time delay generate a faster fire front propagation whereas for long ignition delay the effects of the pre-heating are negligible. In the plots, the strong or weak effect of pre-heating is embodied by the time that the fire needs to reach the boundaries of the considered domain.

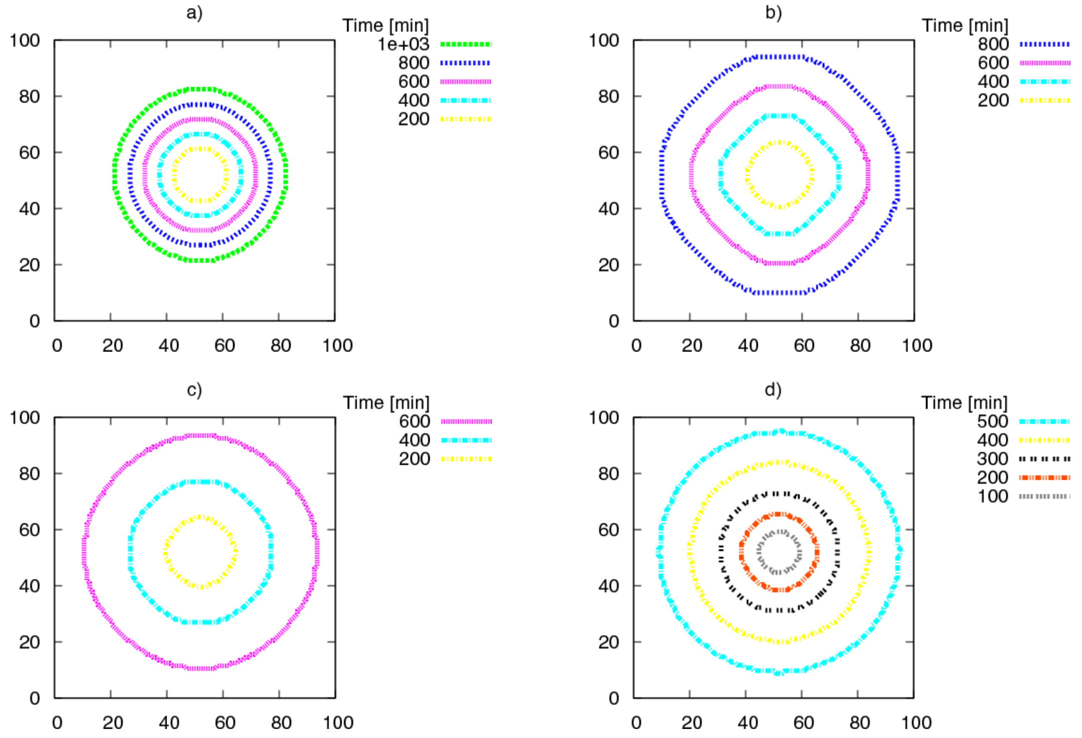

Figure 1. Evolution in time of the fire line contour, when $\tau = 10[\mathrm{min}]$, *for the level-set method a) and for the random level-set method with increasing turbulence: b)* $D = 25[\mathrm{ft}]^2[\mathrm{min}]^{-1}$, *c)* $D = 100[\mathrm{ft}]^2[\mathrm{min}]^{-1}$, *d)* $D = 225[\mathrm{ft}]^2[\mathrm{min}]^{-1}$. *The domain axes are expressed in feets and the colors refer to the elapsed time in minutes according to the column on the right*

3.3. Fire front overcoming firebreaks

The realistic situation in which the level-set method fails is the simulation of a fire that overcomes a firebreak. In fact, the firebreak is a zone without fuel and is modeled as an area in which the rate of spread of the fire is $V(x, t) = 0$, causing the fire to stop. However, the hot air mass can overcome the firebreak and ignite an area over it, so that a new fire front starts. In Figure 3 it is shown the suitability of the proposed model to simulate the hot air that overcomes a firebreak so that the fire front passes on. The stronger is the turbulence, the earlier is the ignition behind the firebreak. The spotting phenomenon can be modeled with a similar technique.

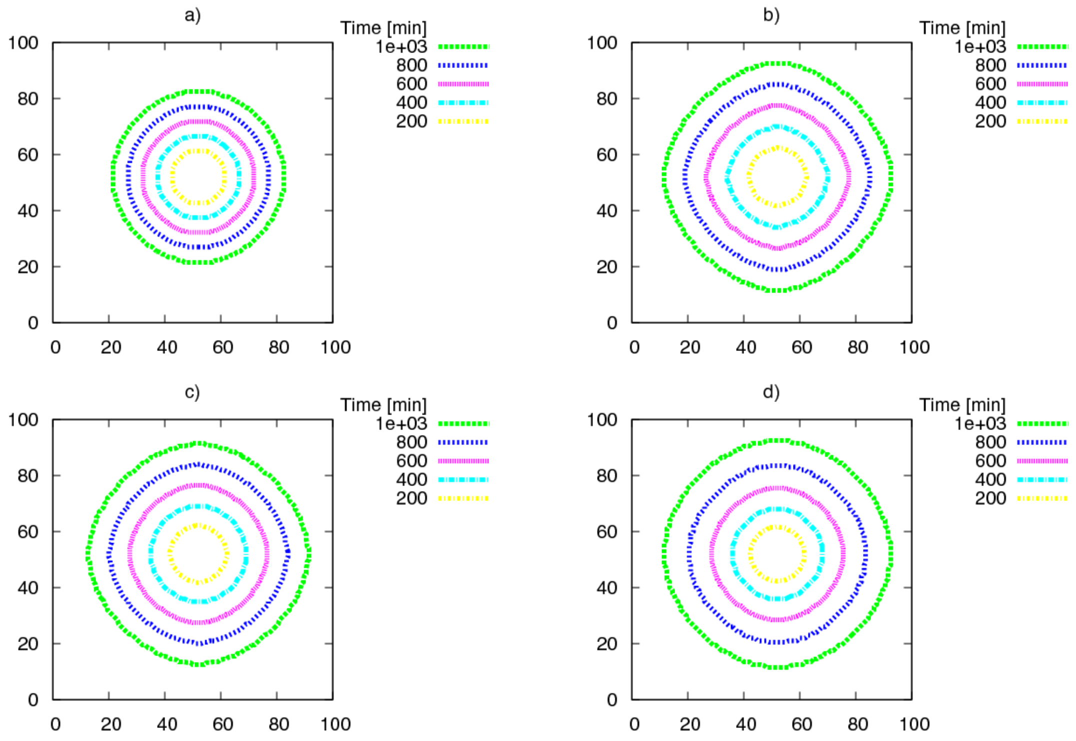

Figure 2. The same as in Figure 1 but when $\tau = 50[\mathrm{min}]$.

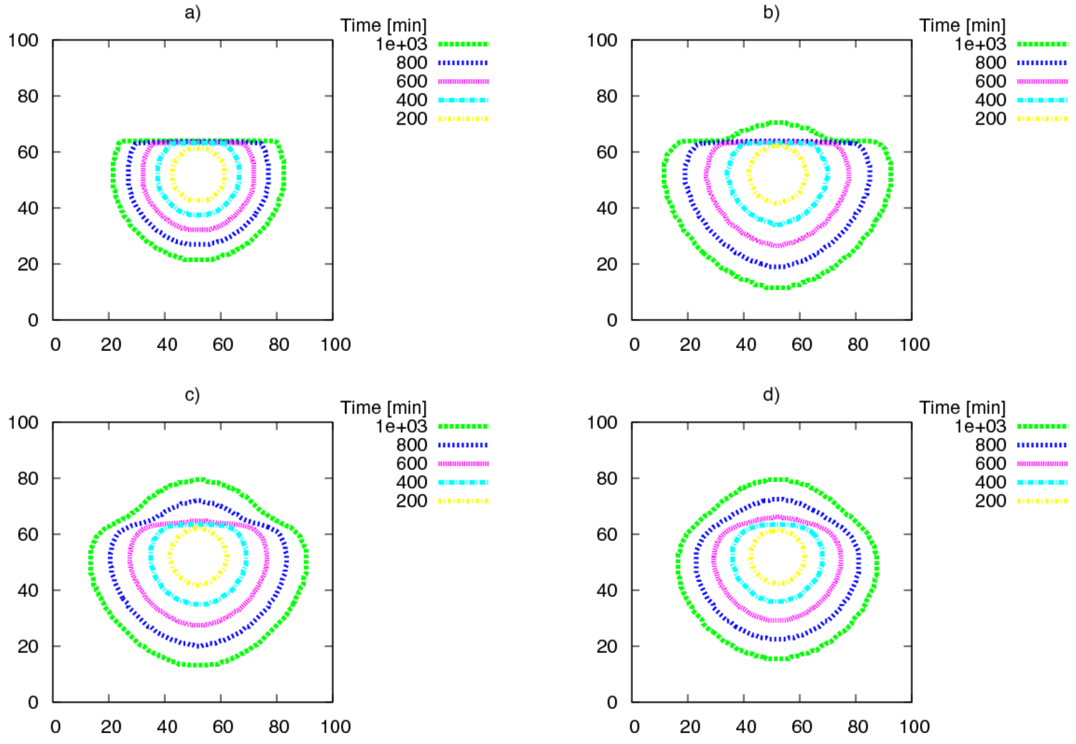

Figure 3. The same as in Figure 1 but in the presence of a firebreak and when $\tau = 100[\mathrm{min}]$.

4. CONCLUSION

A new formulation for modeling the wildland fire front propagation is proposed. It includes small scale processes driven by the turbulence generated by the ABL dynamics, which is increased by the fire-atmosphere coupling, and by the fire-induced flow. It is based on the randomization of the level-set method for tracking fire line contour by considering a distribution of the contour according to the PDF of the turbulent displacement of hot air particles.

This formulation is emerged to be suitable, more than the ordinary level-set approach, to model the following two dangerous situations: i) the faster propagation of the fire line as a consequence of the pre-heating action by the hot air mass and ii) the overcoming of a break-fire by the fire because of the diffusion of the hot air behind it.

5. ACKNOWLEDGEMENT

G. Pagnini is funded by Regione Autonoma della Sardegna (PO Sardegna FSE 2007-2013 sulla L.R. 7/2007 “Promozione della ricerca scientifica e dell'innovazione tecnologica in Sardegna”).

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Fire behavior analysis of the Anela wildfire (Sardinia, 1945)

Fois C.[1], Casula F.[1], Salis M.[1,2], Dessy C.[3], Falchi S.[4], Mavuli S.[4], Piga A.[4], Sanna S.[4], Spano D.[1,2]

[1]Department of Science for Nature and Environmetal Resources (DipNeT), University of Sassari, Italy; [2]Euro-Mediterranean Center for Climate Changes, IAFENT Division, Sassari, Italy: [3]ARPAS, Dip. Spec. Reg. Idrometeoclimatico, v. P. Torres 119, 07100 Sassari; [4]Corpo Forestale e di Vigilanza Ambientale, STIR Sassari

cfois@uniss.it, miksalis@uniss.it

Abstract

Wildfires are a major problem in Europe as in several other regions of the world. This issue is particularly relevant in the Mediterranean area, where wildfires are responsible for thousands of hectares burned each year. Commonly, a limited number of fires with extreme behaviour can account for the widest impacts on forest ecosystems and for the hugest damage to properties, together with loss of human lives. These extreme events are the result of the combination of severe weather conditions, very dry fuels and topography effects. This study investigates a historical extreme wildfire which took place in Sardinia on July 31st, 1945. Seven people of the Sardinia Forest Service lost their life during the fire-fight operations. The fire burned about 700 hectares of oak forests and high Mediterranean maquis. The distinctive feature of this work lies in its historical value and in the difficulties encountered in collecting data about vegetation, final fire perimeter, spatio-temporal spread of the fire front, and weather conditions.

Keywords: Mediterranean ecosystems, extreme wildfire, historical case studies, fire behaviour analysis

1. INTRODUCTION

Worldwide, wildfires represent a threat for the ecosystems and the environment. The effects of fires are commonly quantified at large scales, considering the hectares burned, the number of events, the costs associated to firefighting and properties losses, the loss of human lives. From this point of view, the huge and dramatic fires that affected Greece in 2007 (78 casualties in about one week) represent an emblematic case. Commonly, the loss of lives during wildfires is associated to a combination of extreme weather conditions, dry fuel conditions and complex topography.

Several wildfires have been analyzed and deeply investigated in the US, Canada and Australia (Butler et al. 1998, Rothermel 1993). The lessons learned in these Countries have strongly influenced and improved training methods and rules in order to reduce risks during the fire fighting operations and to strengthen fire crew safety (Viegas 2009). At European level, the most relevant contribution was given by Viegas et al. (2009), that analyzed and investigated a set of wildfires associated with loss of lives.

In several fatal accidents, as for example the fire entrapments, the accidents are the results of the relations between fire behaviour and potential dangerous human behaviours or risk underestimation. This is a key point, because we need to update and improve continuously the knowledge and the training of the fire crew and management, together with the awareness of population and politicians about the risk associated with fires (Viegas 2009, Alexander et al. 2003).

The analysis of historical fires represents, from this point of view, one of the strongest elements that we can pursue. This represents also a way to learn from the past events and to avoid potential errors or risk underestimations.

We will describe and analyze the case study of Anela, a fire that was ignited at the end of July 1945 and affected about 700 ha of forests. In general, the reconstruction of a wildfire is a challenging task: in this case, considering that the event occurred 66 years ago, the difficulties are greater.

2. MATERIAL AND METHODS

As shown in Figure 1, the study area is located in the municipality of Anela (40°27'09''N, 9°00'01''E) (Sardinia, Italy), in an area characterised by a complex topography. The vegetation (Figures 2 and 3) is mainly represented by *Quercus ilex* L. woods. In the humid and north facing slopes, it is associated with *Quercus pubescens* Willd. and above 800 m a.s.l. *Ilex aquifolium* L. is also present. The bottom part of the valley is covered by *Q. ilex* and high and dense Mediterranean maquis. Nowadays the vegetation is continuous, the canopy cover is close to 100% and the forest height ranges from 8 to 16 m.

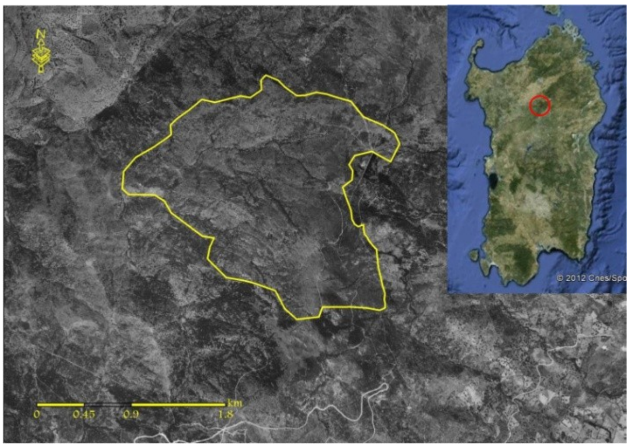

Figure 1. Estimated fire perimeter (aerial photo of 1954). The wooded vegetation was not able to recover 9 years after the fire

The vegetation distribution and characteristics before the fire has been reconstructed using the information gathered through interviews with local people and the use of the 1954 aerial photographs. From the interviews, the photos and other information gathered it looks very likely that, in 1945, the vegetation characteristics were similar to the present-day situation.

The climate is typically Mediterranean, characterized by moderately cold and wet winters and hot and dry summers. The coldest months are January and February, while the highest values of temperature are recorded in July and August. The total rainfall is quite high (about 900-1000 mm), and it is mainly distributed in autumn-winter; snowfalls are also frequent. The year 1945 was particularly dry in Sardinia, with very low values of rainfall in the period February – July (Figure 3 - Annali Idrologici 1945, Servizio Idrografico Ministero Lavori Pubblici). Almost no rainfall was recorded in May, June and July. The last days of July were characterised by temperatures higher than the average values and were particularly hot: peaks of 40 °C were observed in the whole island. A synoptic analysis (Figures 7) of troposphere meteorological conditions during July 1945 was carried out at European scale, inferring the local tendencies for Sardinia (data from www.wetterzentrale.de). The weather in July 1945 remained constantly stable with no rainfalls, high atmospheric pressure and temperature values above the monthly average. In particular, two severe heat waves were responsible for important anomalies in temperatures from the 17th to the 23rd and from the 27th to the 31st.

Figure 2. Pictures describing the study area (April 2011)

The wildfire was ignited in the late morning of July 31st, 1945, in the bottom part of the valet called Badu Edras. A well-trained and experienced fire-fighter team composed of 7 members moved downslope towards the fire that did not look too intense. The weather was hot and dry but not too windy. Driven by the slope, the fire behaviour changed, growing in rate of spread and intensity, and an active production of firebrands was observed. The wind speed increased abruptly, probably empowered by the fire itself. At this point, the fire assumed an extreme behaviour, forced by the convection effects. The members of the fire-fighter crew tried to escape and run back upslope but the fire was very fast and too intense. They were at first dazed and then killed by smoke and gases. Their corpses were found dispersed (Figures 4 and 5). The fire was completely extinguished at 6 p.m. of the same day, while the hill had entirely burned down 2 hours after the ignition. The final fire perimeter was defined by interviewing local people and analysing historical aerial photographs.

FARSITE semi-empirical fire spread model (Finney 2004) was used to simulate propagation and behaviour of the Anela wildfire. Wherever possible, the simulated fire perimeters and the fire behaviour charts were compared with observed data and information collected in the interviews.

In order to provide the input data needed for the run of the simulator, the values of daily temperature and precipitation from the nearest weather stations were collected (Annali Idrologici); furthermore, the historical synoptic weather charts were analysed in order to estimate reference wind speed and direction and relative humidity. Vegetation type, height and structure were broadly appraised with interviews and old pictures. Fuel data collected in the framework of the Proterina-C Project in areas with similar vegetation types were used for the simulations.

A high margin of error remains in the description of the fire dynamic and behaviour. This because it was not possible to univocally reconstruct the real and entire course of events. In spite of the uncertainty of some input data and of the degree of approximation of the fire, the study resulted in a likely reconstruction of the event.

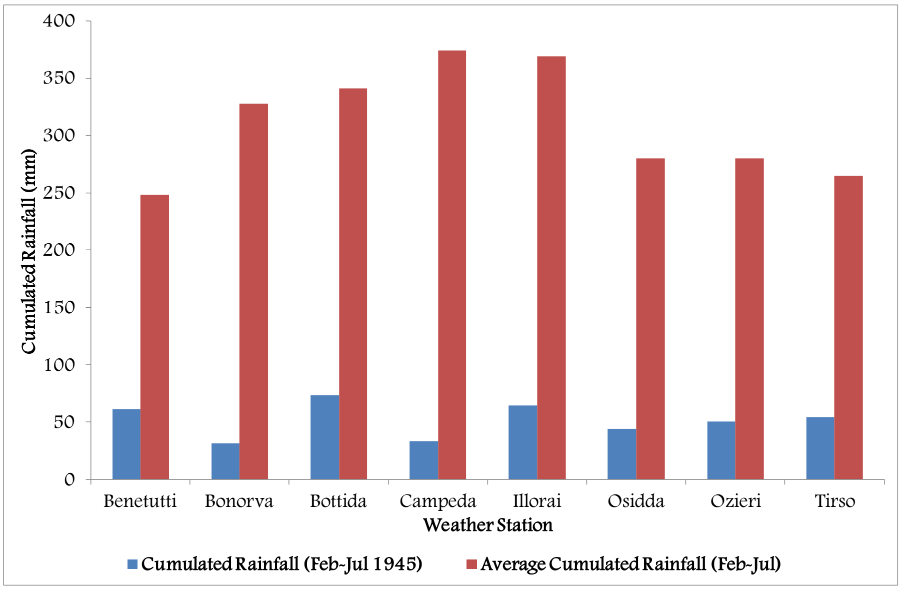

Figure 3. Comparison between cumulated rainfall from February to July 1945 and average cumulate rainfall from February to July (Annali Idrologici – 1945, Servizio Idrografico Ministero Lavori Pubblici)

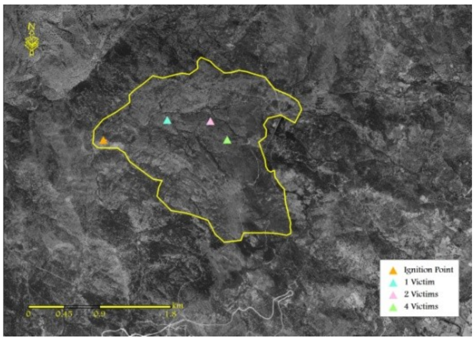

Figure 5. Localization of the ignition point and of the victims

Sette morti

in un disastroso incendio

ANELA, 7. — Alle ore 12 del 31 luglio u. s. nella regione «Badhedras» del comune di Anela, per cause non ancora precisate, ma che si ritengono fortuite, si sviluppava un violento incendio che si propagava in breve tempo alle foreste demaniali.

Una squadra di operai antincendio, organizzata dal Comune e composta da Sanna Giovanni, Satta Antonio, Farina Settimio, Virdis Silvestro, Paoni Salvatore, Loi Antonio e Sini Giovanni, recatasi per prima sul posto, iniziava l'opera di spegnimento, ma veniva investita subito dalle fiamme. Tutti i componenti morirono. Essi furono più tardi rinvenuti carbonizzati quando, verso le ore 21, con l'intervento di tutta la popolazione del luogo, l'incendio potè essere finalmente domato.

I danni prodotti dall'incendio ai boschi ed ai pascoli non sono stati ancora calcolati, ma sono ingenti. Tutta la popolazione di Anela è costernata dal luttuoso avvenimento, e si adopera come può per esprimere alle famiglie delle generose vittime la sua solidarietà e il suo cordoglio.

Figure 6. Left: the monument erected in honour of the Sardinia Forest Service crew; Right: the original article appeared in the newspaper "L'Isola", August 7, 1945

3. RESULTS AND DISCUSSION

The flame length (FL) and rate of spread (ROS) maps (Figures 7 and 8) obtained by FARSITE highlight the very dangerous conditions that the fire crew faced, in particular in a second explosive phase of the fire. The maps indicate that in the first 30-60 minutes the fire was probably not intense, and that the spread rate was moderate. The FL map shows how the fire at first was characterised by a low intensity, then gradually grew until it exploded in all its power. FL ranged from 8 to 25 m. The areas with a low fuel load show lower value of FL. The higher FL values are recorded in the areas where the vegetation was characterised by oak forests, with estimated average height ranging between12 and 15 meters. The most relevant FLs have occurred in the areas where wind direction, exposure and slope were aligned.

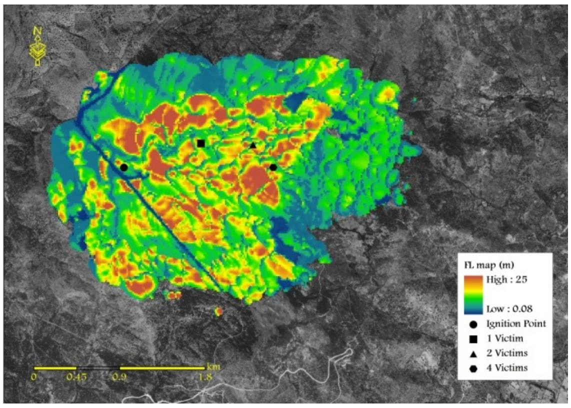

Figure 7. Simulated Flame Length

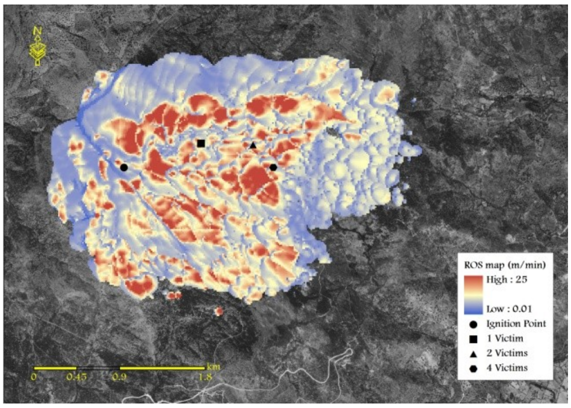

Figure 8. Simulated Rate of Spread

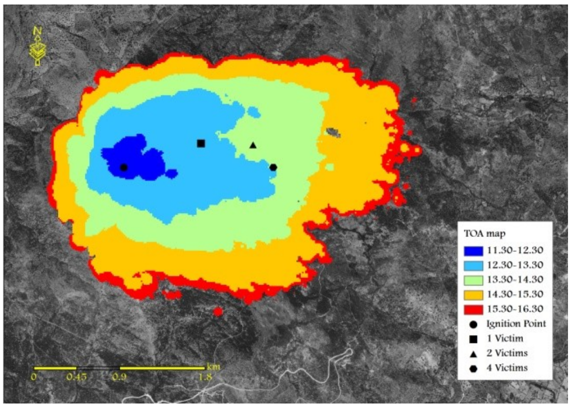

Figure 9. Simulated Time of Arrival

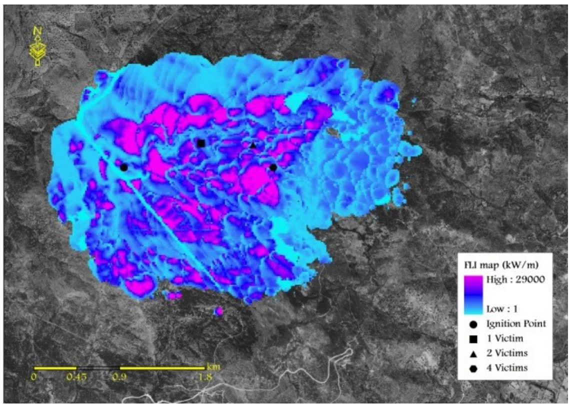

Figure 10. Simulated Fireline Intensity

As the wind conditions where not too strong, the ROS was not high and therefore the fire initially has grown very slowly. The spread rate has increased to values of 25 m min^{-1} in the slope areas. Due to FARSITE limitations in modelling the fire propagation in very steep topography conditions, the ROS values could be underestimated.

As interviews and documents suggested, the maps (Figures 2, 9 and 10) can explain why after the fire ignition the fire crew team has tried to attack the fire moving down slope: they probably underestimated the fire potential, considering the initial low fire spread and intensity. When the fire-fighting crew realized how critical the situation was, they moved upslope, but their retreat was made very difficult by the smoke, the slope and the heat. The fire behaviour maps revealed that the 4 guys that lost their lives in the point C were very close to a safer area, that was flat, rocky and with low load vegetation. The other 3 components of the fire crew died in areas where the fire was estimated as very intense.

On the whole, this fire was characterised by an abrupt change of fire behaviour. The main driver of this behaviour change seems to be the topography; the influence of the wind, which was empowered by the fire itself, reinforced the slope effect. Although the general wind speed was probably moderate, the local wind grew in intensity. Furthermore, it is important to notice the strong fire behaviour differences between slopes and plateau.

In conclusion, the analysis of an historical fire has a high margin of error due to input data uncertainty. Then the output must be interpreted taking into account such limitations. The usefulness of this work lies in the analysis of fire behaviour and in the comprehension of the complex mechanisms that are associated with extreme wildfires. The goal of this work is to investigate a very important historical wildfire in order to evaluate critical and strong points of the fire, to provide information to fire fighters and improve understanding of fire propagation dynamics.

4. ACKNOWLEDGMENTS

This work was partially funded by the European Union ITALIA-FRANCIA Marittimo (2007- 2013) Project “Proterina-C” and by the European Union Seventh Framework Programme (FP7/2007-2013) under Grant Agreement 243888 (“FUME” Project)

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Extreme wildfire spread and behavior: a case study from North Sardinia

Salis M.[1,2], Mavuli S.[3], Falchi S.[3], Piga A.[3], Desole G.[3], Montesu G.P.[3], Spano D.[1,2]

[1]Department of Science for Nature and Environmental Resources (DipNeT), University of Sassari, Italy; [2]Euro Mediterranean Center for Climate Change (CMCC IAFENT), Sassari, Italy; [3]Corpo Forestale e di Vigilanza Ambientale, STIR Sassari, Italy

miksalis@uniss.it

Abstract

The more critical fire seasons are usually characterized by the occurrence of one or more days with extreme environmental conditions. On these days, fires can burn hotter and can quickly get out of hand originating large and severe wildfires. In these situations containment and extinguishment of wildfires are critical for fire managers, that also have the imperative goal to keep their fire crews, people and animals safe. The Oschiri wildfire we will present in this paper is an example of a large and severe wildfire occurred with extreme environmental conditions. The fire was ignited on July 13, 2011 in the Oschiri municipality (North Sardinia), and burned about 2,500 ha of wooded and herbaceous pastures and oakwoods in few hours, from 12:45 to 19:15. The fire day was characterized by hot temperatures, related to the effect of air masses moving from inland North Africa to the Mediterranean Basin, and strong winds from west-south west; this is a typical weather pattern associated with large fires in North Sardinia (e.g.: 23 July 2007, 23 July 2009). Weather conditions, fuels and topography factors that strongly affected the fire will be accurately analyzed. Fire spread and behavior data collected during the event will be also compared with the results obtained by FARSITE (Finney 2004) model. The main goal of this paper is to thoroughly study the fire behavior of a relevant and recent case study, in order to learn from it and lessen the chance of making potential mistakes or hazardous fire-fighting operations in similar environmental conditions. Furthermore, a crucial point is to teach and prepare the fire crews not to be surprised by severe or abrupt fire behavior under extreme environmental conditions. For these reasons, the combination of analysis, knowledge and awareness of historical case studies, field experience and computer modeling represent a key learning technique

Keywords: extreme fire behaviour; FARSITE; historical fires; Mediterranean areas

1. INTRODUCTION

The importance of weather conditions on fire behavior and spread is well-documented (Burgan et al. 1997; Flannigan and Wotton 2001; Flannigan 2011). The spatio-temporal variability of fire behavior and spread is often related to short-term weather conditions (i.e. wind speed and direction, relative humidity, temperature), that represent the most variable environmental component (Pyne et al 1996); on the other hand, fire ignition is basically linked to a set of long-term factors such as drought, rainfall amount and period, fuel load and live/dead fuel ratios (Mouillot et al. 2002). Several studies have shown that climate changes in the Mediterranean Basin will lead to greater weather variability and to an increase in extreme weather events, together with higher cumulated precipitation in winter, hotter summers and longer and more frequent heat waves (Alcamo et al. 2007). Another important issue is represented by the progressive abandonment of agriculture and farming activities, which is gradually resulting in fuel build-up, natural recovery of shrublands and forests, and fuel management problems in several Mediterranean ecosystems (Castellnou et al. 2010). The potential results of these changes will be the increase in fire number and in the occurrence of fires with extreme behavior, particularly with strong winds and heat waves (Brown et al. 2004; Alcamo et al. 2007). Several studies have shown that wildland fire activity has increased during the last decades, in many parts of the world (Brown et al. 2004; Pausas 2004; Viegas et al. 2006; Riano et al. 2007). In fact, the catastrophic fires that affected Portugal (2003, 2005), Greece (2007, 2011), Italy (2007, 2011), and Sardinia (2009), were characterized by extremely severe weather conditions and represent a wake-up call for fire managers, considering the future scenarios of climate changes and socio-economic conditions. For this reason, education and training of fire crews on fire behavior and spread understanding and prediction, as well as the definition of the best strategies to prevent, mitigate and fight fires, are crucial for improving fire crews potential and efficiency. These aspects are key-points when fire spread and behavior are driven by extreme weather conditions.

From this point of view, a great support on studying and understanding fire behavior and spread of historical fires, and for assessing strategies, operations and potential mistakes during the fire, can be obtained by the use of fire simulation systems: Farsite (Fire Area Simulator, Finney 2004) represents one of the most used fire simulators, and is based on the semi-empirical surface fire prediction model of Rothermel (1972), and on the elliptical wave propagation technique (Richards 1990, Finney 2004) for the spatial fire growth. FARSITE was developed in the U.S., but several studies validated the simulator in Mediterranean areas (Arca et al. 2007; Duguy et al. 2007). Since Farsite is a spatially and temporally explicit model, it can produce detailed analysis of fire behavior and fire effects.

The main goals of this study were (i) to describe propagation and behavior of a fire spreading with extreme weather conditions, analyzing the effect of fuels, weather conditions and topography on the fire; ii) to evaluate the capabilities of FARSITE for accurately modelling the fire spread and behavior; iii) to provide useful information for the post-fire analysis, in order to evaluate fire-fight strategies, operations and potential errors.

2. MATERIAL AND METHODS

The case study is represented by a fire ignited in Lochiri (Oschiri municipality, Sardinia, Italy; coord. 40°43’50’’ N; 9°07’50’’ E) (Figure 1) on July 13, 2011. The fire burned about 2,500 ha in 6.30 hours, from 12.45 to 19.15; the flanks were definitively blocked at 10.30 p.m. The fire was not intense, with low observed flame lengths, but it was very fast in the first 2 hours of spread, when it mainly interested herbaceous areas and sparse wooded pastures. After 6 p.m., when the fire front reached a thick area of *Pinus radiata* L. and *Quercus suber* L., its spread rate slowed down but burned hotter; the forward spread was definitively stopped by the aerial forces, together with a slight mitigation of the weather conditions (increase of relative humidity, decrease of wind speed and temperatures).

The vegetation burned was represented by a mosaic of herbaceous and wooded pastures, *Quercus suber* L. oakwoods, *Pinus radiata* L. woods, agricultural areas (vineyards and olive trees) (Figure 2, left). The first part of the fire interested an area mostly represented by herbaceous pastures, while in the last hours of propagation some wooded areas were affected. The vegetation characteristics were modelled in 13 fuel models, using both standard (Anderson 1982; Scott and Burgan 2005) and custom (Arca et al. 2007) fuel models.

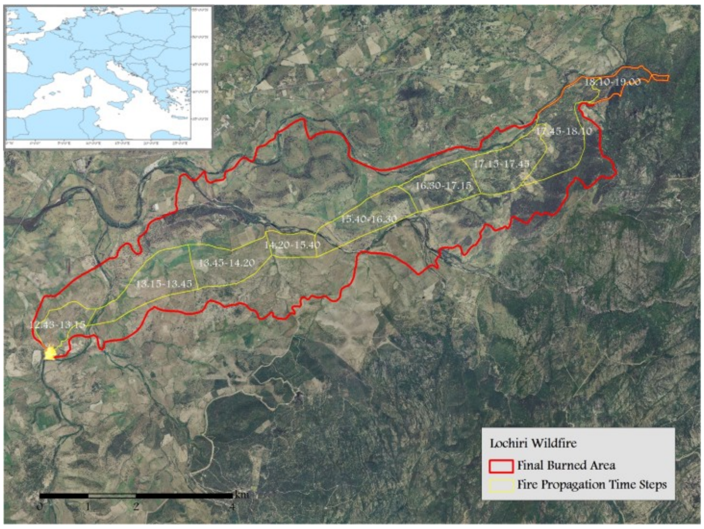

Figure 1. Map of the study area, fire perimeter and observed spatio-temporal fire propagation

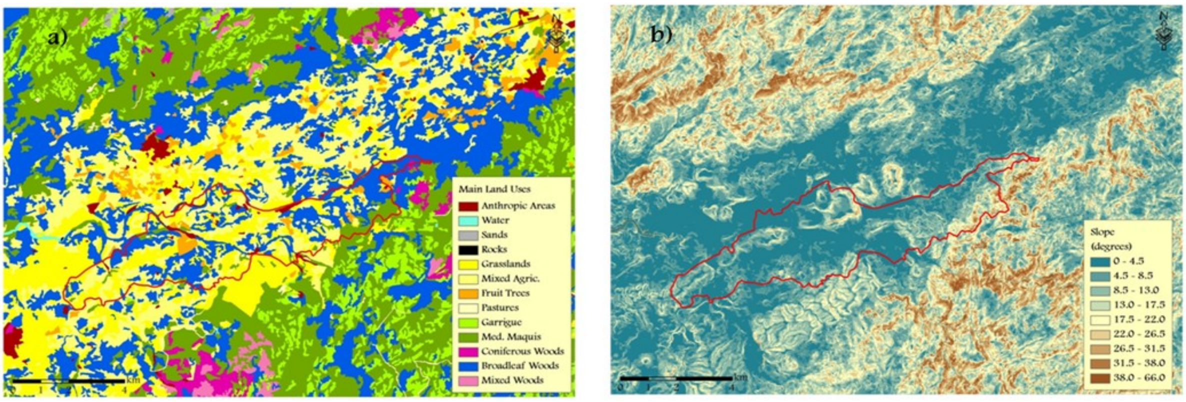

Figure 2. Main land use (left) and slope (right) maps of the study area. The red line represents the fire perimeter

Most of the fire propagated in a plateau with limited slopes (Figure 2, right). This plateau is surrounded by important hills and mountains, that were not affected by the fire (except in the east boundary of the fire perimeter) because of the massive attacks of the Sardinia Forest Service crews in the fire flanks.

Regarding the weather conditions, the day of the fire was characterized by hot temperatures, related to the effect of air masses moving from inland North Africa to the Mediterranean Basin, and strong winds from west-south west (Figure 4). This is one of the typical weather pattern associated with large fires in North Sardinia (e.g.: 23 July 2007, 23 July 2009). In the closest ARPAS weather station high temperatures registered were associated with low relative humidity, conditions that drove the 1hr fuel moisture to very low values (Figure 5). These factors, together with strong winds, can explain the very high rate of spread observed during the fire.

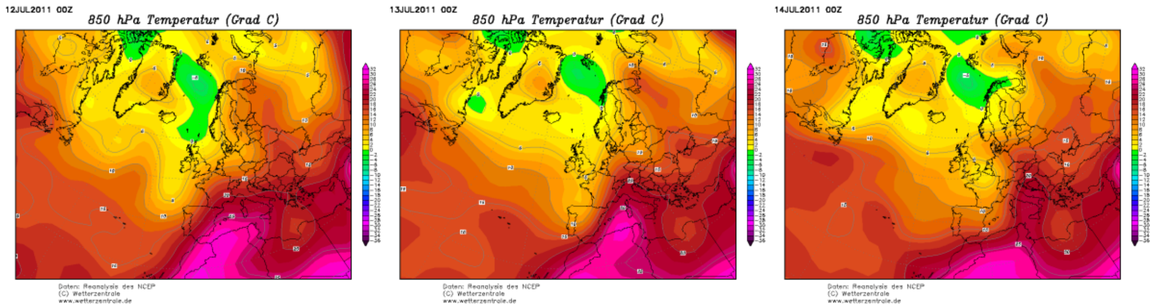

Figure 4. Synoptical weather conditions in the Euro-Mediterranean area (from Wetterzentrale, www.wetterzentrale.de) on July 12-13-14, 2011

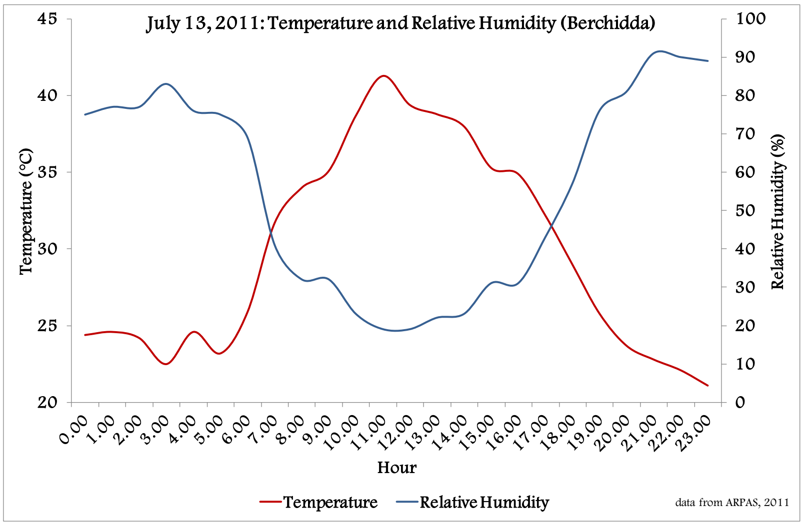

Figure 5. Observed temperatures and relative humidity in the weather station closest to the fire, on July 13, 2011.

To simulate the fire spread and behaviour, we used FARSITE as fire simulator system. As previously pointed out, FARSITE is a semi-empirical fire simulator, developed in the FireLab of Missoula by Mark Finney in the '90s. The simulator, based on the Rothermel's equation (1972) for surface fires, simulates the surface fire spread using the elliptical wave propagation technique (Huygens' principle): the fire perimeter is an elliptical polygon that spatially grows starting from an ignition point, after a defined number of time-steps. FARSITE incorporates other modules in order to simulate crown fires, spotting, post fire combustion, and fire acceleration. The input layers requested for the simulations are basically topography, weather conditions and fuel, provided as ASCII files. We used a Geographic Information System (GIS, ArcGIS 9, ESRI Inc.) to manage the spatial information of the study area and to obtain the input layers needed to run the model. The grid resolution of all layers was 25 m. The FARSITE outputs were compared with the observed values of fire behaviour, and a detailed postfire analysis was promoted with the fire crews in order to learn strength and weak points of the fire-fight operations.

3. RESULTS AND DISCUSSION

The Oschiri wildfire represented an example of large and severe wildfires that may affect North Sardinia when summer days are characterized by severe heat waves, strong winds from SW and very dry fuels. Other wildfires burning in similar weather conditions were historically responsible for several damages and problems in the northern part of the island (e.g. 23 July 2007; 23 July 2009; etc.). The main characteristic of this fire was represented by a high rate of spread in the front: this case study was clearly driven by the strong wind from SW. The highest rates of spread were observed in the herbaceous areas, where maximum values of about 40 m/min were reached. These values were confirmed in several points by observations and post fire interviews. The fire shape was stretched in the front, while fire rear and flanks were slowed down by the wind. In terms of intensity, this fire reached very high values in the wooded areas located in the eastern boundary of the fire perimeter, where the combined effect of slope and wind helped the fire. The highest fire intensity estimated by FARSITE was close to 45 m in terms of flame length. These values were confirmed by the post fire interviews by the crews. On the other hand, in he herbaceous areas, the intensity was relatively low (about 2 m in terms of flame length), although combined with very high rate of spread values. The time of arrival output (Figure 6a) was close to the observed fire propagation time steps of the Lochiri wildfire, and an overestimation of FARSITE was observed in the final hours of propagation, when the fire was heavily attacked with aerial forces and several terrestrial fire crews. The accuracy of the FARSITE simulation was evaluated with two statistical indicators, based on the definition of an error matrix, that are Sorensen and Kappa coefficients. Both of them were close to 70%. The main error of the simulation was represented by an overestimation of the eastern boundary of the fire perimeter. FARSITE confirmed the high severity of the fire in the eastern wooded boundaries, where fire spread rates and intensity were both high and therefore fire-fight was not possible without the aerial forces (Figure 6b, 6c, 6d). FARSITE highlighted the difficulty of stopping the fire in the herbaceous vegetation, where the low fire intensity was counterbalanced by a very high spread rate (Figure 6b, 6c, 6d). Other useful indications that FARSITE provided for this case study are related to the evaluation of potential limitation of the fire flanks linked with the fact that terrestrial attacks were concentrated in the flanks during the first hours of spread.

The re-analysis of historical fires, in particular of the most relevant fires, allows fire crews and managers to maintain an historical memory of the past situations, providing a huge amount of potential information and knowledge of the interactions fire-landscape-environmental conditions. This is even more important if we consider that, in some areas of the island, there are some recurrent ignition points, with potential recurrent fire spread and behaviour. Additionally, the use of fire spread and behaviour models could allow to monitor landscapes of interest and to evaluate the potential fire severity, at given fuel and weather scenarios. In the near future, the use of simulation models can provide high detail and basic guidelines for fire prevention and mitigation; this goal could be reached by coupling the fire simulators with updated databases of fuel types and moisture together with weather conditions. Furthermore, the future need to plan the development of urban centres and touristic areas taking into account also fire occurrence is gaining importance, considering that in the last decades the WUI fires are increasing, mainly near the coastal areas. From this point of view, FARSITE can provide information for the urban development concerning potential fire occurrence, recurrence and behaviour.

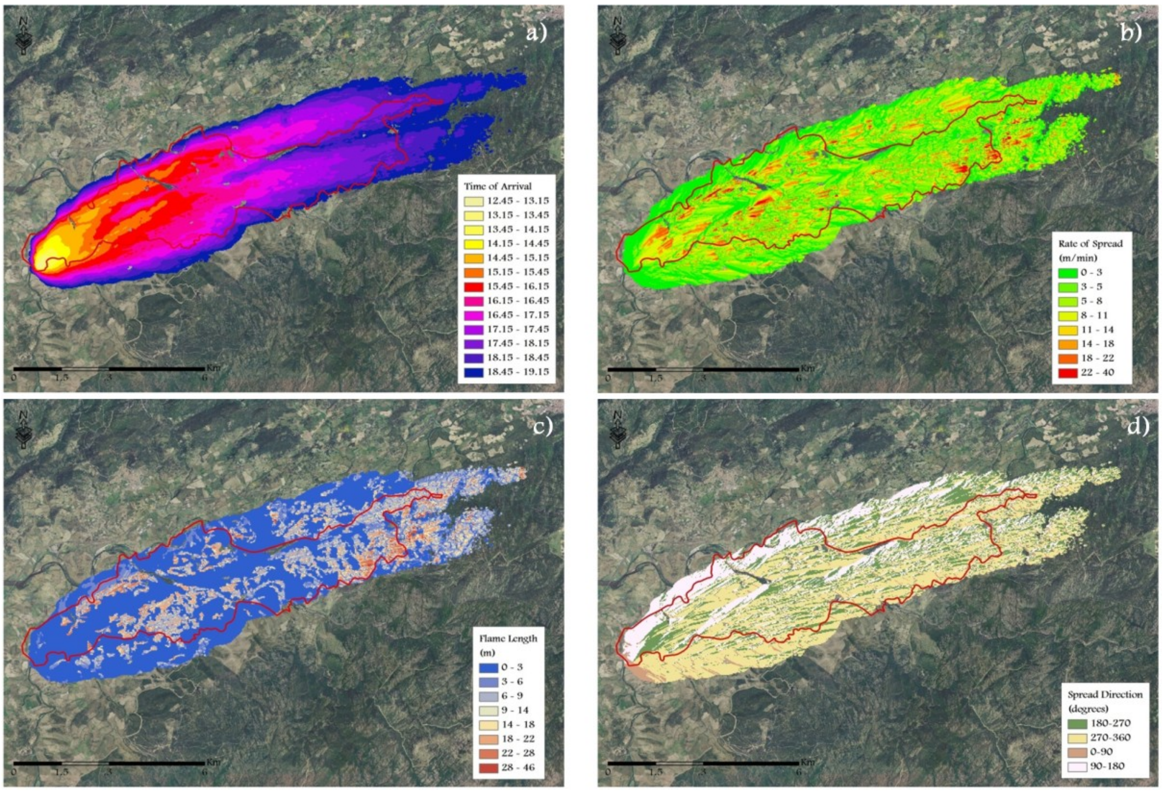

Figure 6. FARSITE outputs: a) Time of Arrival; b) Rate of Spread; c) Flame Length; d) Main Fire Spread Direction

4. ACKNOWLEDGEMENTS

This work was partially funded by the European Union Seventh Framework Programme (FP7/2007-2013) under Grant Agreement 243888 (“FUME” Project - Forest fires under climate, social and economic changes in Europe, the Mediterranean and other fire-affected areas of the world).

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Muravera 2010: analysis of an extreme wildfire

Delogu G.[1], Murranca S.[1], Deiana E.[1], Cabiddu S.[2]

[1]Corpo forestale e di V.A. Regione Sardegna, Via Biasi 9, 09131, Cagliari, Italy; [2]Corpo Forestale e di V.A. Regione Sardegna, Via Gennauara 08045, Lanusei, Italy

gdelogu@regione.sardegna.it, smurranca@regione.sardegna.it, edeiana@regione.sardegna.it, scabiddu@regione.sardegna.it

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Abstract

Large and extreme wildfires represent an issue that Forest Services and fire fighting Institutions in the Mediterranean areas and worldwide have to face. Usually extreme wildfires are associated with environmental conditions that overcome the extinguishing efforts and capacity. Fuel accumulation, frequently linked to land abandonment and socio-economic changes, and extreme weather conditions, in a context of expected climate changes for the future, can lead to mega-fires characterized by very high rate of spread and severe intensity, in more dangerous conditions with respect to the past decades. In these cases, it is common to have to deal with problems of civil protection and strong limitations to fire crews operations; these extreme fire behaviors are often responsible for accidents and entrapments. The Muravera case study (24 July 2010) represented an example of extreme fire behavior. The fire, favored by strong winds and complex topography, burned intensively for 4 hours and was able to burn 461 hectares of grasslands, Mediterranean maquis, *Quercus ilex* woods and Eucalyptus and Pinus stands. The fire behavior analysis of this case study, carried out with reports, interviews, videos and observed weather data, highlighted the very high values of fire spread and intensity, in particular in some WUI areas, together with several difficulties for the fire crews to extinguish or slow down the fire spread. Moreover, it was observed the need to define correct plans of fuel reduction and management, in particular in the WUI, to limit potential damages to houses and people. The analysis of historical fires with extreme behavior could give useful guides to future planning of landscapes and urban areas, in order to take into account the observed pathways, shape and behavior of the most dangerous fires.

Keywords: large fires, extreme fire behavior, analysis of case studies, fire fighting

1. INTRODUCTION

Fire has always been part of nature, because of its connection with traditional human activities and the natural sources of ignition (lightning) (Pyne et al. 1996; Pyne 1997). Only recently, by its wilder explosion, wildfires have become a problem for the society, especially when it can't be managed and deals with human settlements (Castellnou et al. 2011). This pathological display (large and extreme wildfires) has not a unique definition. This report refers to the definition proposed by Castellnou et al. (2010) in the framework of the European Project Fire Paradox. They paid attention to the "generations" of those wide and extreme fires that can hardly be extinguished because of a huge amount of combustible materials, a rapid growth, crown fires, huge intensity and the involvement of wildland urban interfaces.

2. DESCRIPTION

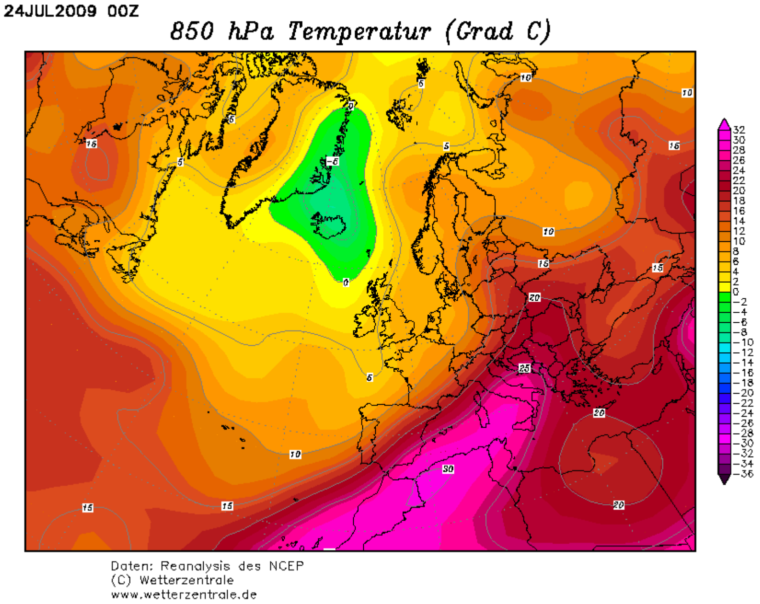

Figure 1. Synoptic representation of the meteorological conditions at 00Z hour on July 24, 2010. (www.wetterzentrale.de)

The Muravera wildfire started on July 24, 2010 at 14.15 and was extinguished at 20.30. That day was considered at high fire risk for the whole island: other 5 huge wildfires broke out in different parts of Sardinia (Palau, Torpè, Carbonia, S.Antioco, Quirra), all showing the typical signs of a 4th generation-fire. The synoptic general situation was characterized by a great instability in the air and by a rapid movement of air masses from North West (Figure1). Initially, the Muravera fire was driven by the mistral wind, which intensity was over 12 m sec^{-1}, with some gusts (17 m sec^{-1}) accentuated by the turbulence of the fire, as recorded by the ARPAS meteorological station in Muravera (Figure 2). The 24th of July was preceded by two days of warm moist advections from South-East, followed by a sudden drying up of fine vegetation with the arrival of the mistral. Later, the evolution of the fire was affected by the topography and the large supply of fuel. Figure 4 shows the general terms of the wildfire behavior at about 17.00.

The intervention of the first direct attack with water was immediate (within the first 5 minutes) with a 1500 liter tanker and a crew of two people. Several fire spots caused the rapid expansion of the flame upstream of the town of Muravera, transforming the wildfire in a wildland-urban interface fire. During this initial attack, the crew got almost trapped, but luckily this first part of the intervention concluded with no injuries.

During the first 30 minutes all the vehicles were displaced from the Quirra wildfire 15 km North from Muravera, including a drive unit of the Ente Foreste with 1800 liters, two motorized units of the National Fire Department, three regional helicopters and after an hour, three Canadairs of the air fleet of the National Civil Protection.

The extended attack was not successful. The rapid expansion of the flames (about 40 m min^{-1} of rate of spread) burned about 100 ha in the first hour, 200 ha in the second, and 400 ha in the third. When the fire was declared fully extinguished, at 20.10, about 461 ha were burned. The firefighting structures were placed as a barrier to protect houses, given that the flames propagated within unbuilt lots and condominium. On the other hand, the turbulence and violence of the wind gusts made impossible an effective control by the aircrafts, with drifts of throwing water and retardant over 200 meters. At the top of the explosive phase of the fire, the flames on ridges exposed to the wind were lowered by the mistral, diverted locally by the morphology of the interior valley (Figure 5).

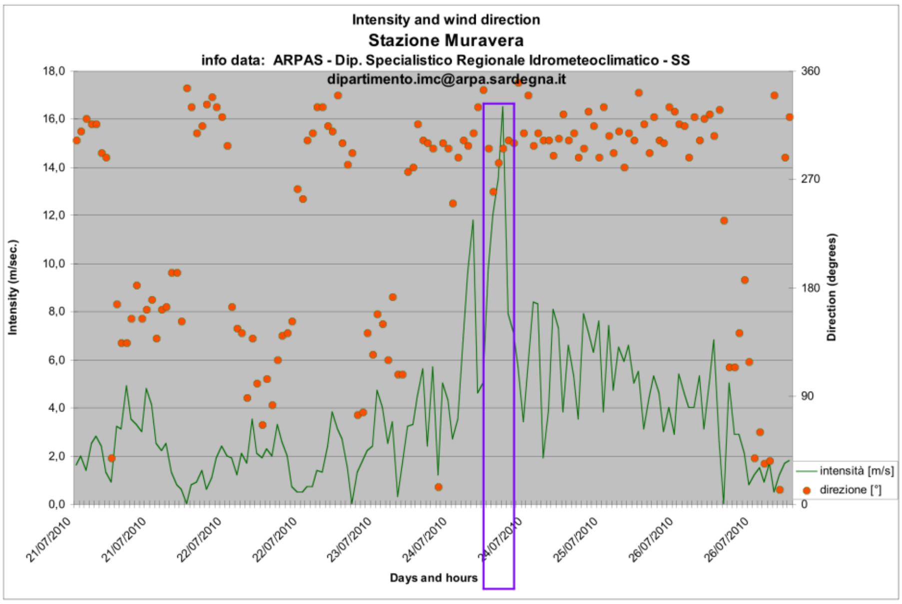

Figure 2. Intensity and direction of wind (www.arpas.it)

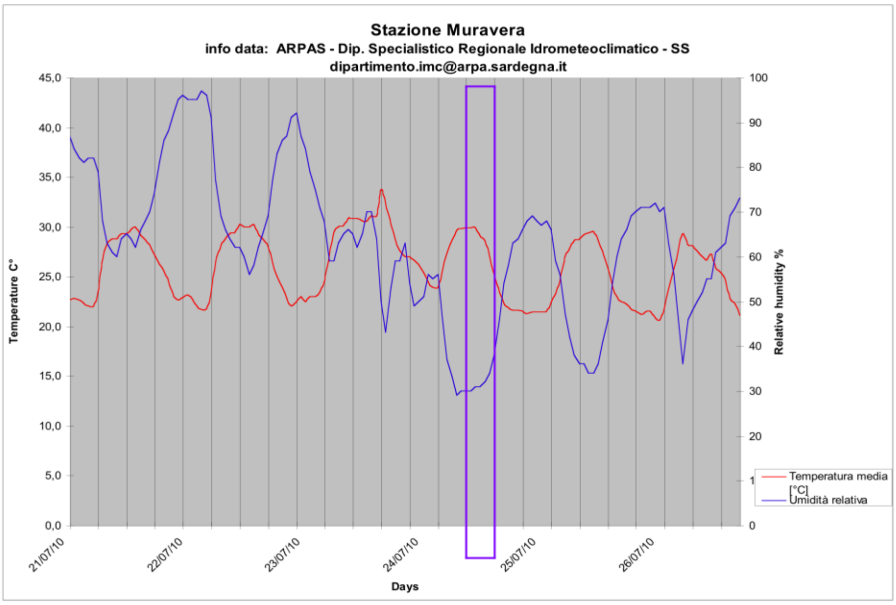

Figure 3. On the left of the blue box the situation of the two days preceding the wildfire, on the right the situation during and after the wildfire

Figure 4. This picture has been taken from the north of fire scenario

Figure 5. The arrow shows the drop in flames made by the wind

Several spot fires were observed. The smoke column assumed at first an "eruptive" shape, but its inclination wind driven and inversion located at about 1500 meters a.s.l. (Figure 6) push it away 15 km offshore. The operating conditions appeared immediately to be difficult and beyond the control threshold, as showed in Figure 7. The whole scenario representing the evolution of the wildfire is represented in Figure 8.

The wildland-urban interface was manifested in all its danger due to its dreadful status, the neglect in which the land behind the houses was held, the accumulation of garbage. In addition, the upper part of the town was damaged by frequent flooding processes, mainly due to the occluded drainage network and the frequency of heavy autumnal rain fall.

3. GENERAL CONSIDERATIONS

The great wildfire of Muravera burned in a day which was considered at high fire risk by the Regional System, and in conjunction with other big fires. Its characteristics, such as rapid expansion, high energies released by burning, frequent spotting fires and crown fire, forest-urban interface situations, led to the overcoming of the extinguishing capability of the regional and national suppression system. The fire, once the paroxysmal phases of expansion were over (h. about 14.15 to 18.00), was declared under control at 20.30 and closed with a mop-up at 20.10 the following day. The first day, 71 men were employed (it is not known how many volunteers), and 3 Canadair Department of Civil Protection National and 3 Regional helicopters were used; the second day 17 men and 1 helicopter completed the drainage.

Despite the commitment and the dedication of staff, the fire propagated freely, because the general conditions, and in particular the turbulence and wind speed did not allow effective launch of extinction. An adequate planning, developed through the analysis of fires that historically occurred in the affected area, would have allowed to create more effective lines of defense downstream the town, with the interruption of the spread of fire toward the mountain, creating conditions for a faster and effective extinction in order to prevent a new threat of erosion and hydrological instability for the future.

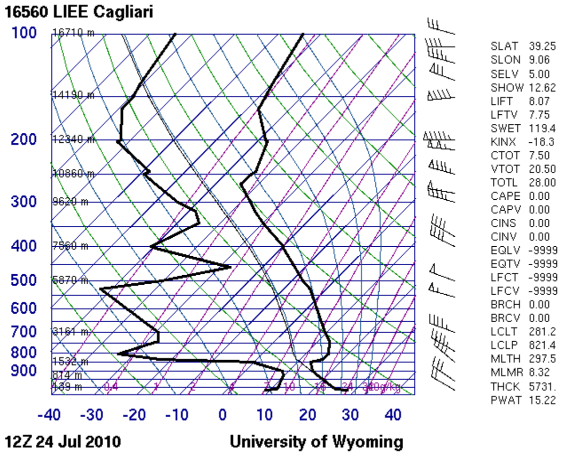

Figure 6. Radiosounding LIEE Cagliari, at 12.00, on July 24.

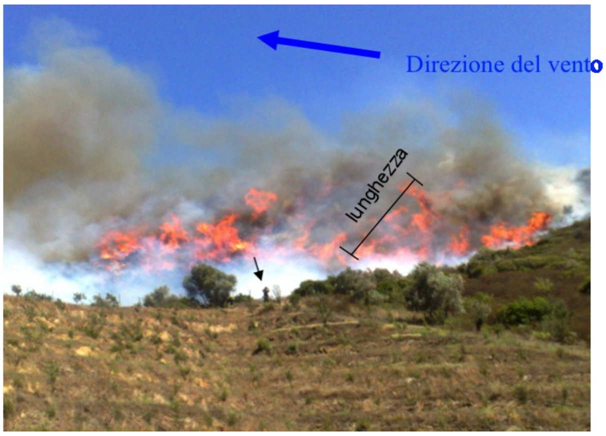

Figure 7. Flame length during the first 20 minutes (the black arrow indicates the CFVA operator)

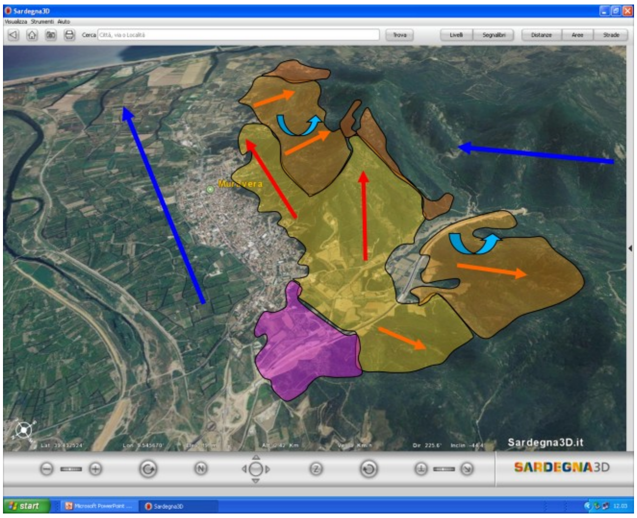

Figure 8. Purple color represents the perimeter of the fire in the first 15 minutes; in yellow the fire perimeter during the first hour; in orange the fire area in the second and third hour; The red arrows indicate the paths with a faster expansion, while orange arrows indicate fire growth resulting from the local wind (blue arrows twisted).

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The Curraggia wildfire, analysis of an entrapment (28 July 1983)

Cabiddu S., Brigaglia S., Congiu F., Delogu G., Lara G., Muntoni G., Usai L.

Corpo Forestale e di Vigilanza Ambientale

scabiddu@regione.sardegna.it

Abstract

Statistically, the 1983 summer is considered one of the hottest in Sardinia. The Mediterranean area was invested by a strong heat wave caming directly from Sahara desert (source www.wetterzentrale.com), with temperatures that gone over 40 °C. Despite these air masses picked up moisture as they cross the Mediterranean Sea, in some central areas of the island the RH dropped up to 5%. Because of the combination of these factors and moderate winds, the fire season was dramatic. This work is a contribution to the analysis of one of the most impressive extreme fire, Curraggia (Olbia-Tempio province, Sardinia), considering the experience and knowledge of the Sardinian Forest Service (C.F.V.A.) in this topic, in order to share these information with other fire crews, people involved in wildfires and the scientific community. The aim of this work is also to give cue for reflection about the wildfires problem that, considering changes on climate, land use, and socio-economic, is becoming more and more worrying in the last years.

The Curraggia wildfire started on July 23, 1983, at 12:30 AM and burned an estimated area of 18,000 ha (180 km^2) before the final full containment, on July 29. It was an arson-caused wildfire and resulted in the deaths of nine people (four firefighters and five volunteers) and several injured persons. Also a lot of properties and houses were destroyed by the fire. The damage caused by the fire was estimated more than 9 million of euros, and up to now is the worst wildfire/firefighters disaster occurred in Sardinia. The analysis of this event was concentrated on what happened in the hill of Curraggia, especially from the point of view of the fire behavior.

Keywords: extreme fire behavior; Mediterranean area; historical wildfire

1. INTRODUCTION

The importance of environmental factors on fire behavior is well documented in the scientific literature. On the other hand, the fire behavior can change rapidly in a short period of time, hours and minutes, generating potential extreme behaviors that can trap the firefighters, as happened in the Curraggia fire. In the last years, both environmental and socio-economic conditions are clearly changed with respect to 1983, and Sardinia faced a large increase of WUI and RUI, in particular along the cost. A marked reduction of fuel management activities in forest and rural areas, which is gradually resulting in fuel build-up (Castellnou et al. 2010), in combination with strong winds and heat waves, leads to the increasing of the potential development of fires with extreme characteristics. Over the last years we want to remind the catastrophic fires in Portugal (2003, 2005), Greece (2007, 2011), Italy (Peschici fire, 2007), Sardinia (2009), all of them with extreme characteristics of behavior. Nowadays we are perfectly aware that our territories could be the scenery of large fires, and that no suppression effort can control them, like other countries in the Mediterranean area.

Containment and extinguishment of a forest fire may be a hard and difficult task, requiring a significant commitment of trained firefighters and equipment. However, all our efforts to fight a fire, the strategy of containment and attack, could be nullified in the presence of buildings and human life to defend (WUI and WRI). In such background, which is the Sardinia ordinariness, the forest is the last thing to be defended. First of all, we have to save the human life. Understanding what really happened during a wildfire is very important, especially during catastrophic fires such as the Curraggia one. Moreover, the study of the historical fires can provide us the cognitive tools necessary to deal safely and more effectively with the new generation of fires (Castellnou et al. 2010). The main goal of this analysis was to understand why and how the people have been trapped in the Curraggia wildfire.

2. MATERIAL AND METHODS

The study area is located in North Sardinia (Figure1), and affected several villages throughout this area, with consequent problems of WUI and WRI. We focused primarily on the final stage of the fire, and more precisely on that which covered the hill of "Curraggia", South West outskirts of Tempio-Pausania. Nine people were killed, including colleagues of C.F.V.A., volunteers and civilians. This report is dedicated also to their memory.

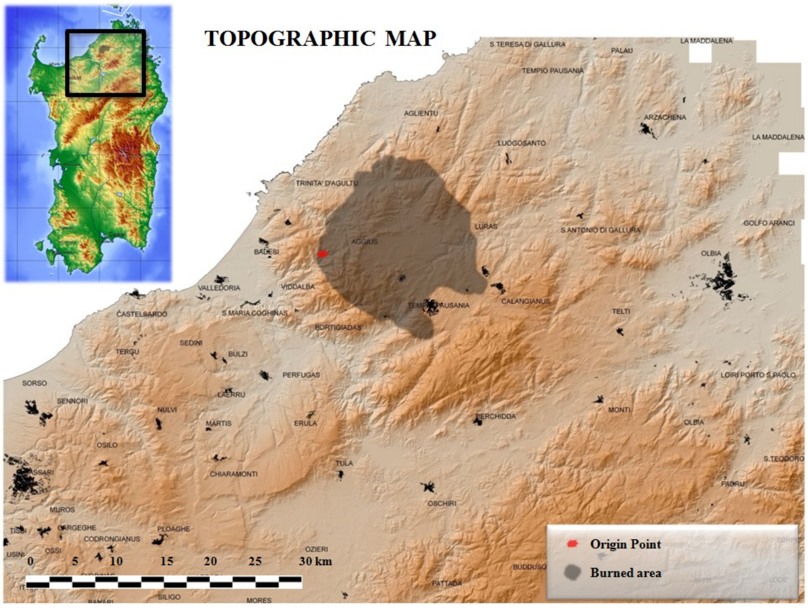

Figure1. The map shows the geographical area where the wildfire grew up and led to the tragedy of Curraggia (Tempio-Pausania)

The synoptic situation at that time (source Wetterzentrale, www.wetterzentrale.de) showed a strong and intense intrusion of warm air from Africa into the Mediterranean basin. The anomaly is that these seasonal weather conditions, which led hot air directly from the Sahara desert, remained for several days raising the temperature up to record values of 40 °C in the shade in different parts of the island territory. The relative humidity (RH, in %) reached the minimum of 5% in some areas of Sardinia (unofficial values). Overall, this weather situation significantly lowered the water content of the fuel, particularly of smaller size dead fuel, increasing its potential of flammability. This fact encouraged the fire spread (ROS): in some cases there were ROS changes equal to 70 times, and higher. Synoptic central Figure (Figure 2) refers to the 28th of July, 1983. A small cold dropping located in the north of the Iberian peninsula, tried to push and rub the massive high pressure system located at the center of the Mediterranean. On the border of these two systems, the main flows of hot air run, determining the general winds that affected Sardinia in those days. The erratic movement of the high pressure system also determined the main direction of the general winds, mainly coming from the South-Western quadrant.

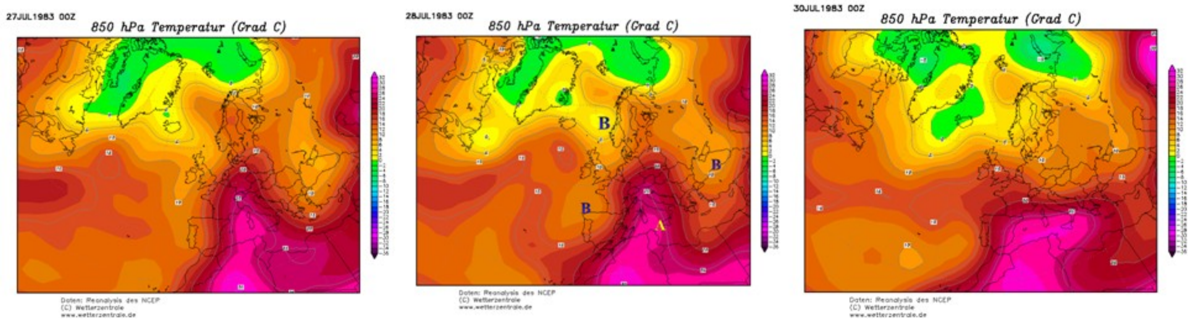

Figure 2. July 27-28-30, 1983. Synoptical weather conditions in the Euro-Mediterranean area (from Wetterzentrale, www.wetterzentrale.de)

Unfortunately, in the 80s the weather stations were not so widespread yet in the territory as they are today, then we have no objective weather data recorded near or at a distance "acceptable" of the fire scenario. The weather analysis, particularly the microclimate where the accident happened, is therefore the result of comparisons of general weather, measures of the meteorological stations (such as Alghero, although located about 75 km away the theater of the fire), as well as the evidences of the firefighters who have worked almost continuously for 7 days to put out the flames. The analysis of data collected from Alghero meteorological station showed that the general winds were not strong, ~15-25 km hr^{-1} and the direction was mainly from South, South-West. The temperatures were instead very high for several consecutive days, even above 40 °C. The Curraggia wildfire was divided in 4 phases, the later deals with the analysis of trapping (Figure 4).

The general weather conditions, after several days of domination of the African anticyclone, continued to be particularly favorable to the spread of fire. On July 28, at 13:40, a whirlwind (as defined by witnesses), originated in the air throwing incandescent material to about 70-100 m down the SS-127 road, creating a new fire ignition (Figure 5). In a short amount of time the fire expanded, producing a front of about 200 m, reaching and crossing the village of La Fumosa, and continuing its race to the bottom of the valley. In this initial juncture of the fourth phase, the flames were pushed by a westerly wind, although not very strong. At this juncture the ROS was about 26 m min^{-1}.

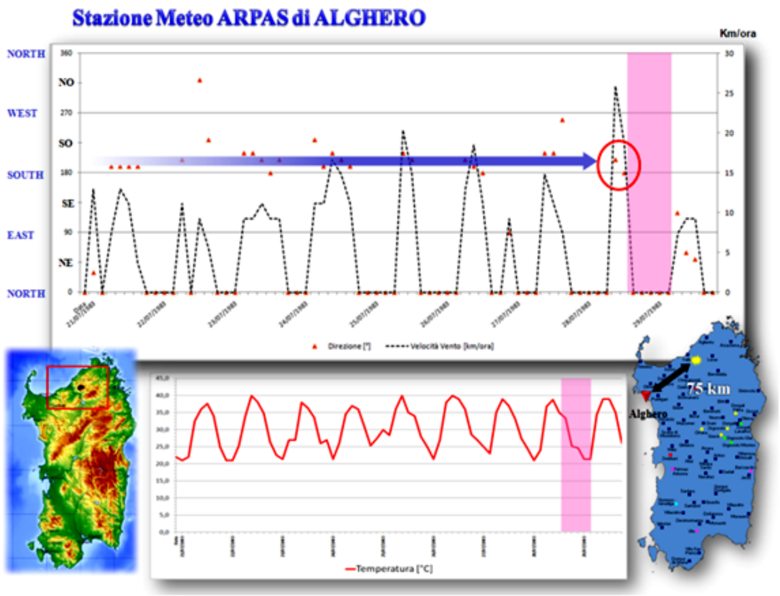

Figure 3. Changes in intensity, wind direction, and air temperature, during and after the wildfire (ARPAS meteorological station of Alghero). The colored rectangle shows the measure during the phase when the tragedy happened.

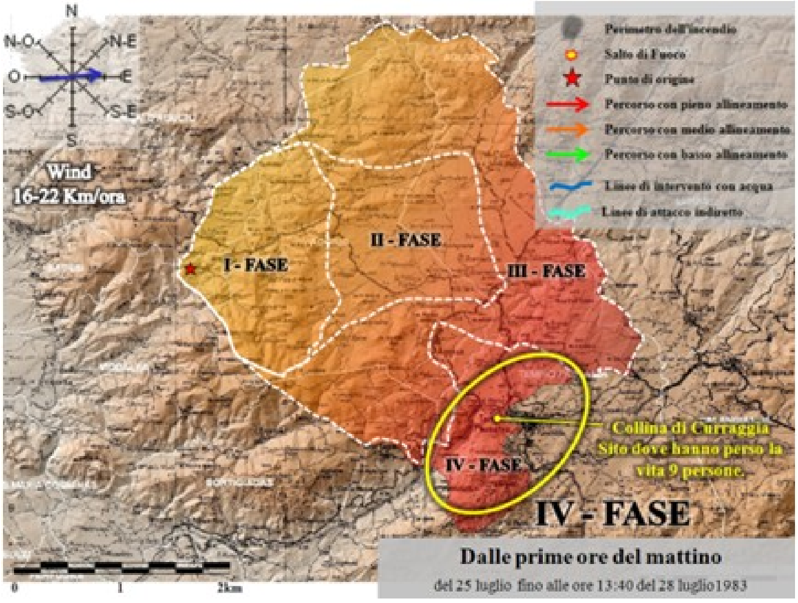

Figure 4. The map shows all the stages of the wildfire. The yellow circle shows the area where the accident happened.

Figure 5. The 3D image shows the exact point where it was observed the re-start of the fire, that was originated from a whirlwind above the SS-127 road.

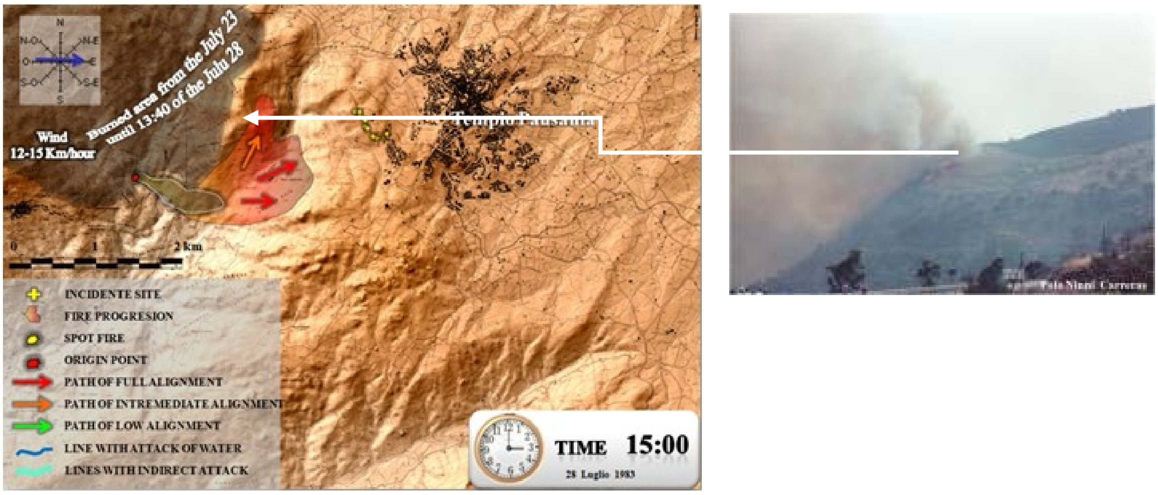

Figure 6. In this two pictures it is showed how the westerly wind intercepts and shifts the convective column while it approaches the ridge line of the east facing slope (Photo 1), located just across the hill of Curraggia.

Reached the bottom of the valley, the fire front was intercepted by the local winds in the valley, increasing both intensity and speed (Figure 6): at this juncture the ROS was about 42 m min^{-1}. The sides of the valley that exposed at west, given the hour of the afternoon, began to be perfectly aligned with the wind and slope, according to the CPSL-Campbell Prediction System Language (Campbell 1995). At 15:20 of that July 28, a new fire was reported near the country church of Santo Spirito (Figure 7), probably a spot fire advancing counter-slope with the wind in favor, which jumped the SS-127 road, and then started climbing the North, North-East face of the hill of Curraggia.

The Figure 6 on the right, in particular, shows the convective column at a time which is arched upwards, showing a strong activity of combustion: at this juncture the flames licked heavy fuel (chestnut wood). The Figure 6 also shows the development of a fire whirlwind (black arrow).

The tongue of fire that started to surround the hill of Curraggia, more exactly on the side North, North-East, continued its run, moving towards the outskirts of Tempio, creating serious problems of interface (Figure 8). The flames attacked light fuel.

These were the moments just before the tragedy, most likely estimated between 17.00 and 17.20, with the sad balance of 9 dead and 15 injured, more or less serious (Figure 9).

The Figure 10 shows the topography of the site where the entrapment occurred. The top of the hill (630 m above sea level) is surrounded by a gravel road where crews, volunteers and many other curious were placed. Other firefighters, along with numerous volunteers, tried to stop the front of the flames, which was slowly climbing the South-West side of the hill. Two huge tongues of fire, one from the North, North-East and one from the South-West slope, converged towards the top of the hill, climbing the slopes quickly. Not long after, other fire tongues quickly enveloped the entire hill of Curraggia, entrapping the fire crews (Figure 11).

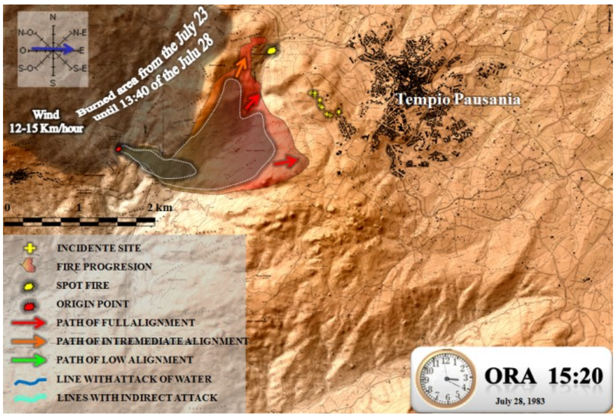

Figure 7. In this picture you can see the exact position of the new fire reported at 15:20 of July, 1983

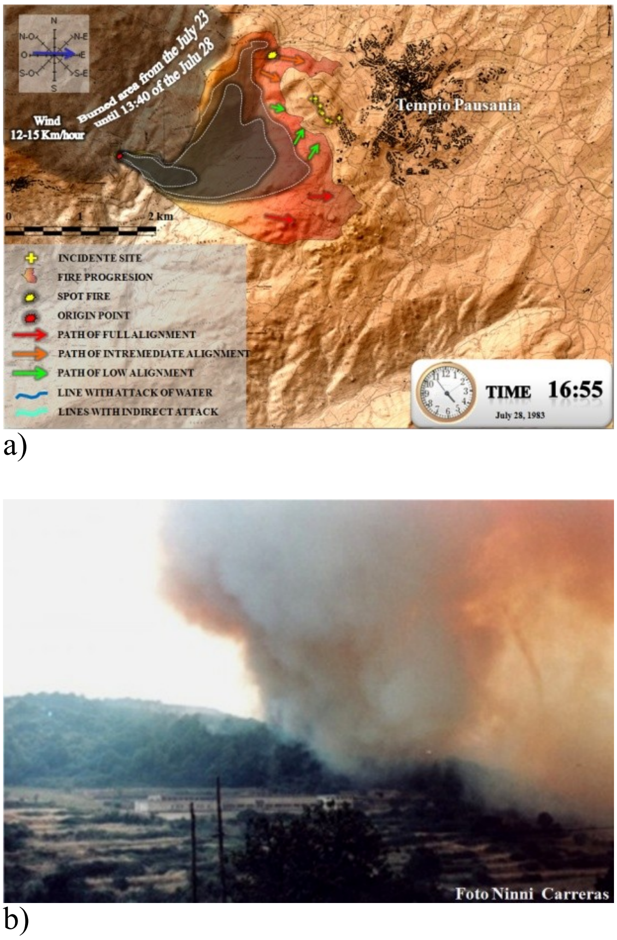

Figure 8 (a and b). Fire progress around 16:55 p.m. of July 28, 1983

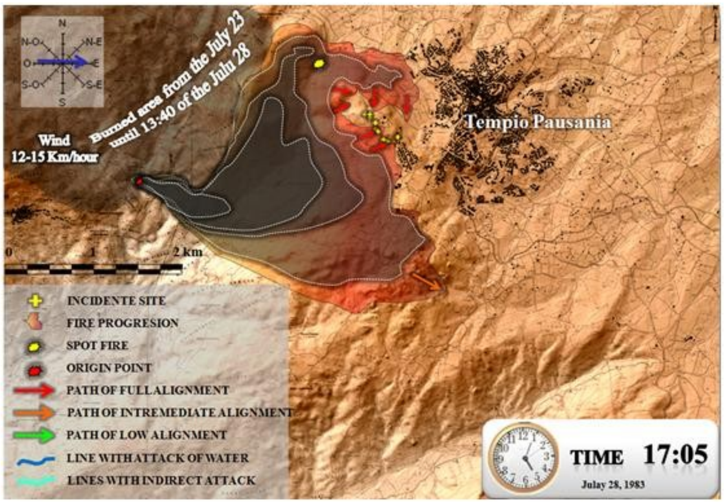

Figure 9. Fire progress around 17:05 p.m. of July 28, 1983

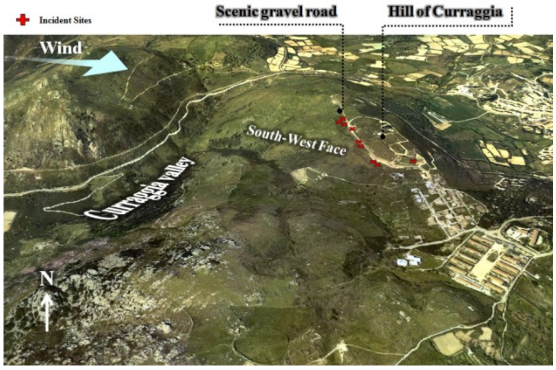

Figure 10. Fire progress around 17:05 p.m. of July 28, 1983

Figure 11. 3D image of the scenario of Curraggia.

3. RESULTS AND DISCUSSION

What really happened in that short time from a point of view of the fire behavior? The flames ranged from an average length between 1.10-1.30 m to 2.80 m, with a relative increase of linear intensity of the front equal to 507-2352 kW m^{-1} (Byram 1959). This change was very quick: the ROS (rate of spread) reached 350 m min^{-1}, with an estimated rate of change of about 75 times, calculated from images taken on the hill of Curraggia (ASS.FOR. ONLUS 2008). The flames, which initially could be extinguished with a direct attack, became too high and dangerous. The intense heat, due by both convection and radiation, and the smoke became unbearable for firefighters that were trying to extinguish the flames in the middle of the slope, forcing them to run away quickly upwards.

The escape route they were trying to achieve was ineffective. Six of nine men that lost their lives were attacked by both smoke and flames just before the roadway. It is very likely that the intense smoke had first choked the fire crew: because of very poor visibility, they have lost their bearings and senses, getting themselves caught among other obstacles, such as the presence of barbed wires and drywall. At this point we analyze more closely what happened in that July 28, 1983 from the point of view of the fire behavior. The people who died were reached and overwhelmed by the fire when the winds changed and blew the flames towards them, perfectly aligned along the slope. Many factors contributed a this tragedy, including their position at the head of the fire, in that moment perfectly aligned with the slope and wind, with an alignment 3/3, according to the CPSL-Campbell Prediction System Language (Campbell 1995). Coupled with the lack of risk awareness, there was another important factor that was determinant: the fuel type.

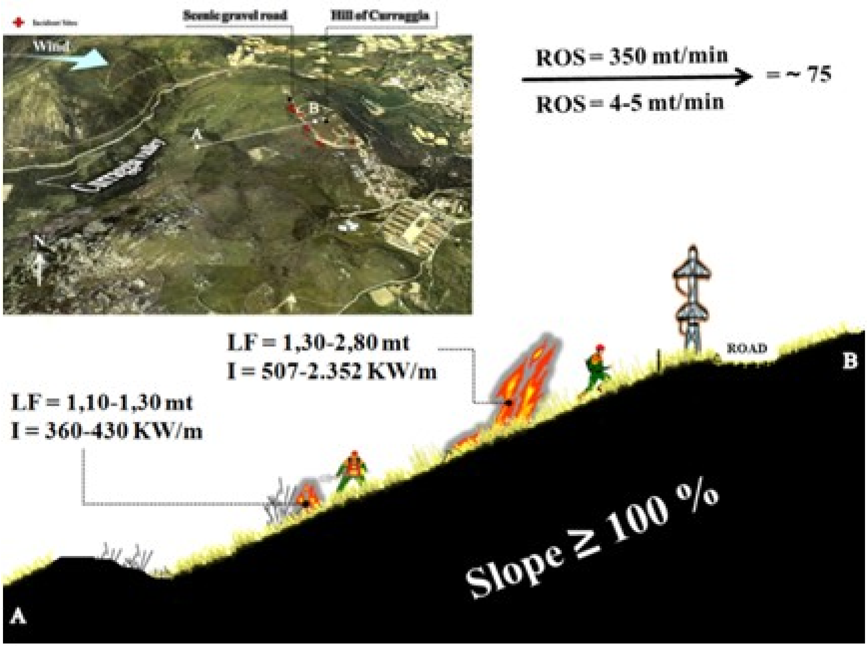

Figure 12. Representation of the accident on the hill of Curraggia

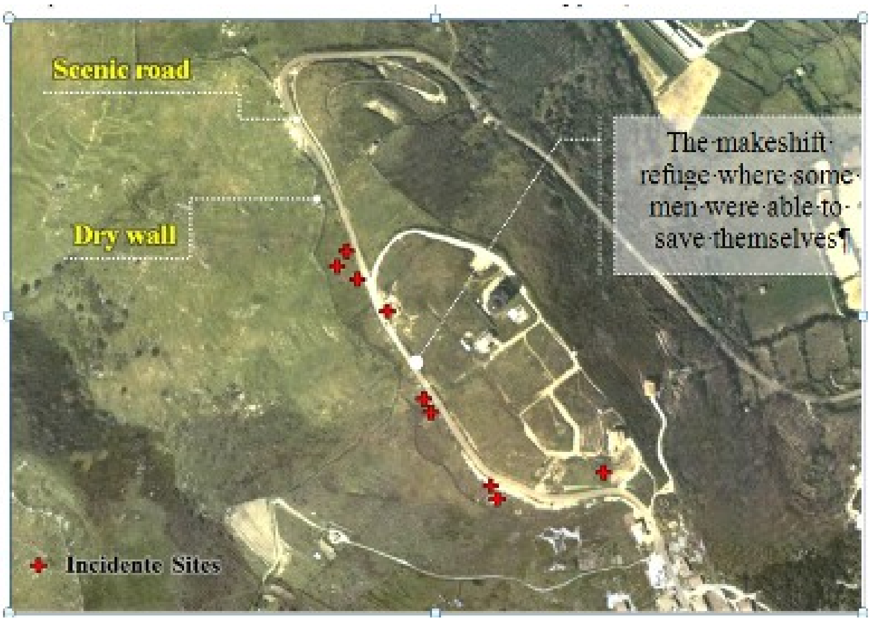

Figure 13. Representation of the accident on the hill of Curraggia

Meanwhile, someone succeeded to reach the road and other men who were already on the road quickly realized the impracticability of escape at the top of the hill because of the arrival of another well-developed tongue of fire on the opposite side. They found refuge in a small corner of the escarpment, right on the edge of the road. Here, because of the small space available, they created a pile. The flames crossed the makeshift shelter, touching their bodies, creating an effect similar to an oven, with temperatures around 500-600 °C, leaving indelible consequences to their bodies. One of them, the most exposed, died the day after. The desolating scenario of death left by the passage of the flames began to take shape between 17:20 and 17:30. Some of the survivors began to see the charred bodies of some colleagues, some of them still agonizing.

4. GENERAL CONSIDERATION

In the case of Curraggia incident, the change of ROS was fatal. This is a risk factor universally accepted in the international field. Many other factors contributed to the deaths of these men. For example, their positions at the head of the fire, perfectly aligned with the wind and the slope, according to the prediction system of Campbell (Campbell 1995). Another key element in this tragedy was the type of fuel. The flames that overwhelmed and killed the men of Curraggia were particularly aggressive, as they combusted the 1-hour and 10-hour fuel load with a fuel moisture content very low. This favoured a rapid process of combustion with a release of an impressive amount of heat in a very short time, resulting fateful for firefighters and volunteers who were trapped. Finally, the complete lack of "awareness of risk", is another factor leading to the entrapment of men who worked in the southwest side of the Curraggia, with the outcomes we all know. Referring to this, appears to be effective and meaningful the affirmation of a survivor who was working, along with many other men, on the southwest side of the hill of Curraggia, about 100-150 m downstream away from the scenic road: "*...Once we realized the danger and the speed at which the fire propagated, we decided to go away ...*". This statement emphasizes unequivocally that the behavior of the Fire was underestimated.

We learned a lot from this tragedy that deeply marked the history of fighting forest fires in Sardinia.

- We need to know very well the factors that determine the changes in fire behavior and try not to surprise us by them.
- We must develop an appropriate awareness of risk and identifying critical points where the fire has the potential to change his behavior, either positively or negatively.
- We must be aware that the conditions for the burning of Curraggia could be repeated.
- Turn off the fire is a difficult job.
- Every fire has its own dynamic and signs that must be read and understood.
- The technology is only a part of the problem
- The maintenance and cleaning of the territory are the best form of prevention.

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http://www.wetterzentrale.de

SardegnaARPAS, Dipartimento Specialistico Regionale Idrometeoclimatico

Crown fires in conifer forests of the world: Do you have something to contribute or would you like to know about something?

Alexander M.E.[1], Cruz M.G.[2], Vaillant N.M.[3]

[1]University of Alberta, Department of Renewable Resources and Alberta School of Forest Science and Management, Edmonton, AB, T6G 2H1, Canada; [2]CSIRO Ecosystem Sciences and CSIRO Climate Adaptation Flagship - Bushfire Dynamics and Applications, GPO Box 284, Canberra, ACT 2601, Australia; [3]USDA Forest Service, Pacific Northwest Research Station, Western Wildland Environmental Threat Assessment Center, 1200 Franklin Way, Sparks, NV, 89431, USA

mea2@telus.net

Abstract

This paper provides a brief overview and progress report of the U.S. Joint Fire Science Program (JFSP) sponsored project "Crown Fire Behavior Characteristics and Prediction in Conifer Forests: A State-of-Knowledge Synthesis" (JFSP 09-S-03-1). To learn more, visit the project website (http://www.fs.fed.us/wwetac/projects/alexander.html).

Keywords: crown fire initiation, crown fire phenomenology, crown fire potential, crown fire rate of spread, crowning, extreme fire behavior, knowledge gaps, research needs.

1. INTRODUCTION

The current edition of the U.S. National Wildfire Coordinating Group (2011) glossary indicates that extreme fire behavior involves "A level of fire behavior characteristics that ordinarily precludes methods of direct control action. One or more of the following is usually involved: high rate of spread, prolific crowning and/or spotting, presence of fire whirls, strong convection column. Predictability is difficult because such fires often exercise some degree of influence on their environment and behave erratically, sometimes dangerously."

In conifer forests at least, the onset of crowning, the type of crown fire and the associated spread rate and fireline intensity (Figure 1) are integral to extreme fire behavior because they dictate the potential for other related phenomena (e.g., medium- and long-range spotting, the type of convection column development, and various types of fire-induced vortices).

In October 2009, a 3-year project supported by the U.S. Joint Fire Science Program (http://www.firescience.gov/) was initiated that aims to synthesize the currently available information on crown fire behavior in conifer forests in relation to the wildland fire environment – i.e., fuels, weather and topography (Alexander 2011a).

This paper provides an overview of the project as well as a progress report. In addition to the authors of this paper, the project team also includes David L. Peterson, USDA Forest Service, Pacific Northwest Research Station, Pacific Wildland Fire Sciences Laboratory.

*Figure 1. Variations in fire behavior within the jack pine (*Pinus banksiana*) – black spruce (*Picea mariana*) fuel complex found in the International Crown Fire Modelling Experiment study area near Fort Providence, Northwest Territories, Canada (Stocks et al. 2004): surface fire, passive or intermittent crown fire, and active or fully-developed crown fire. Photos by M.G. Cruz.*

2. FOCUS, GEOGRAPHICAL SCOPE AND AUDIENCE

Although the focus of the project is on the coniferous forests of the United States and adjacent areas of Canada, the synthesis is intended to be global in nature (Alexander 2011b) and is intended for multiple audiences including the general public to college students, fire and land managers, and university professors and other researchers.

A critical synthesis on crown fire behavior must rest upon as solid a foundation of knowledge as is possible at this time. A sufficient body of scientific, peer-reviewed and technical literature of a practical nature does in fact presently exist to be able undertake a synthesis on crown fire behavior.

In addition to summarizing the existing scientific and technical literature on the subject, project team members are also actively seeking assistance from individuals in the form of field observations of crown fires and related experiences as well as still pictures (Figures 2 and 3) and video footage in both natural forest stands and industrial plantations. Information from all regions of the world would be appreciated and is actively sought, including Mexico, South Africa, Australasia, Europe, Central and South America, and Asia.

*Figure 2. Active crowning associated with the major run of the Bilo Road Fire in New South Wales, Australia, on 10 December 2006 as described by Cruz and Plucinski (2007). The stand height of this 15-year-old radiata pine (*Pinus radiata*) fuel complex is ~18 m. Photo by S. Cathcart, National Parks and Wildlife Service of New South Wales.*

3. SOLICITING YOUR INPUT

We are interested in hearing your opinion on the subject of crown fires and any specific questions and/or research needs and knowledge gaps that you would like to see addressed or discussed as part of the crown fire synthesis project (Alexander *et al.* 2010). The Forest Fire Management Group (2007) of Australia for example has done an excellent job of enunciating their concerns regarding the implications of crown fires in softwood plantations. To share your knowledge and ideas with us, join our My Fire Community Neighborhood (http://www.myfirecommunity.net/Neighborhood.aspx?ID=816).

4. ACCOMPLISHMENTS TO-DATE

Several interim publications have now been produced (Alexander and Cruz 2011a, 2011b, 2012a, 2012b; Cruz and Alexander 2012). Several other journal articles have been accepted for publication, and an expanded version of Alexander and Cruz (2011b) will appear in print later in 2012.

Three additional manuscripts have also been accepted for publication:

Albini, F.A., Alexander, M.E., Cruz, M.G. *A mathematical model for predicting the maximum potential spotting distance from a crown fire.* International Journal of Wildland Fire.

Alexander, M.E., Cruz, M.G. *Modelling the impacts of surface and crown fire behaviour on serotinous cone opening in jack pine and lodgepole pine forests.* International Journal of Wildland Fire.

Jenkins, M.J., Page, W.G., Hebertson, E.G., Alexander, M.E. *Fuels and fire behavior dynamics in bark-beetle attacked forests in western North America and implications for fire management. Forest Ecology and Management.*

A "Volume 2" companion to Alexander and Cruz (2011b) for fire behaviour specialists, fire researchers and fire weather meteorologists is scheduled for publication later in 2012. A manuscript entitled "Assessing the Effect of Foliar moisture on the Spread Rate of Crown Fires" and intended for a scientific journal is also currently under review. A software tool in support of the Cruz *et al.* (2003) canopy fuel prediction models has also been developed (Alexander and Cruz 2010); visit http://www.frames.gov/cfis to download a copy.

5. THE FINAL PRODUCTS

It is presently envisioned that the final products of the synthesis will consist of a book patterned after Cheney and Sullivan (2008) and a special issue of *Fire Management Today*. These are not likely to available in print until mid 2013.

*Figure 3. Flame front associated with a crown fire spreading through a young maritime pine (*Pinus pinaster*) stand in the Pampihosa da Serra region of central Portugal on August 18, 2005. The stand height is ~10 m. Photo by M.G. Cruz.*

6. FOR FURTHER INFORMATION

We have created a project website (http://www.fs.fed.us/wwetac/projects/alexander.html). You will find additional information on the project there, including publications and other products produced as part of project activities.

7. ACKNOWLEDGMENT

This paper is a contribution of Joint Fire Science Program Project JFSP 09-S-03-1. The comments of David L. Peterson on a draft version of this paper are much appreciated.

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Is fire suppression reducing large fires in number and size in Spain? Years 1968-2009

Molina Terren D.M., Cardil Forradellas A.

University of Lleida, Av. Rovira Roure 191 , 25198 Lleida, SPAIN

dmolina@pvcf.udl.es

Abstract

Fires of larger size (100ha+) are the ones that really trouble our suppression resources. Therefore, we have restricted our studied to those fires. After a detailed study of all those wildland fires in the official Spanish Data Base (EGIF) we observed a significant reduction in both the number of fires and the total area swept by fire from 1978 to 2009 (i.e., in regions as Mediterranean Coast). We did not find this trend if we used the first years of the time series (1968-1977). We consider that data from these former years have a different behavior maybe because either the data set was lacking some fires or there were not so many large fires or part of the areas burned in private ownership and was then underreported. Yearly trends were studied with moving five-year average to accommodate the large year to year dissimilarity. We have classified provinces in Spain in three fire pattern regions: North Western region (NW), Mediterranean Coast (MC) and Mediterranean Interior (MI). In MC, in terms of wildland fires larger than 100 ha (100ha+), the number of fires from 1978 to 2009 diminished (R^2=0.83) from 100 to 20 large fires per year. By contrast, in MC, burned area showed a week trend (R^2=0.25) from 95,711 to 6,936 ha of large fires per year although homogeneity test sets that there was a decrease during the period studied with a p-value<0.1. In NW, the number of fires from 1978 to 2009 diminished (R^2=0.55) from 300 to 100 large fires per year. In NW, the area swept by fire went down (R^2=0.30) from 76,776 to 39,118 ha of large fires per year. Homogeneity test shows that there are differences in time in number of fires and not in burned area. In MI, the number of fires from 1978 to 2009 diminished (R^2=0.61) from 139 to 22 large fires per year and homogeneity test set this trend. In MI, the area swept by fire went down (R^2=0.34, a weak trend) from 58,636 to 8,076 ha of large fires per year and homogeneity test show that there are not differences from 1978 to 2009. Therefore, there is a trend to have less LF now than in the 80s; and this is more evident in MC and less clear in MI and NW. The total area burned per year (in 100ha+) has not that clear tendency in areas as MI and NE but in MC the burned area has been reduced along time. Therefore, we cannot depend only on suppression efforts if we want to significantly lessen the yearly area swept by large fires. The trend is similar (but less clear) when using LF as >250ha or >500ha. Our interpretation is that these even larger fires are under more extreme weather patterns and, therefore, our suppression efforts are less efficient in being instrumental to solve the large fire problem.

Keywords: large fires, time series, Spain

1. INTRODUCTION

Extreme forest fires threaten social and ecological values, public and private properties (houses, infrastructures, roads, electrical lines and others) and the life of firefighters and people. In recent year, we have wildland fires more dangerous than thirty years ago with a behavior pattern exceeding firefighting capabilities (Molina et al. 2006). In these fires, our suppression resources have difficulties to suppress them and keep the safety of the firefighters and citizens. There are many examples of firefighter entrapments or citizens in danger on wildland urban interface areas (as those in Ibiza (Spain) in both 2010 and 2011). In addition, these fires account for the majority of our burned area with high intensity, causing social, economic and ecological losses. There are many reasons to explain why fires are more remarkable now. Agricultural abandonment has provided fuel load and fuel continuity that facilitate the fire propagation and severe fireline intensity. In some Spanish provinces as Castellon (Cardil, 2011), urban areas have been sprawling on forest areas, making structures more vulnerable to the fire. Also, small rural villages today are not surrounded by safe agricultural fields. Recently, major changes have been implemented to try to mitigate the large wildland fire problem in Spain; and therefore, we have to evaluate their effectiveness. These major changes include: the creation of both the Emergency Military Unit (in 2005) and the Office of Environment (within the Department of Justice, in 2006).

We have resources that are able to suppress small/medium fires or low/medium intensity fires. However, large fires cause the majority of our tribulations because most of them exceed firefighting capability and, therefore, we have studied them. In the other hand, society is making an effort in suppressing means, investing large amounts of money to reduce fire damage. In this document, we analyze trends in number and size of fires (those larger than 100 ha, 100ha+ thereafter) in three different regions in Spain. We research if there are differences in those trends from past decades to present years where we have more suppression resources.

2. METHODS

We have studied all fires over 100 ha of the official Spanish Data Base (EGIF). We have analyzed fires from 1978 to 2009 to research trends in number and size of these fires. We have not made use of the first years of the Data Base (1968-1977) because we judge that they have a different behavior (in terms of large fire numbers and sizes) because either there are missing fires (i.e., the fires burned in private ownership and were then underreported) or there were not so many large fires yet.

In the study, we have set up three different regions to segregate fires in them like in Bardaji and Molina (1999). These three regions are diverse in continental / oceanic climate, extreme fire weather patterns, population density and fire regimes (i.e., number and sizes). Spanish Environment Ministry also uses this classification in their reports (i.e., Ministerio Medio Ambiente 2006) after Bardaji and Molina (1999) paper. In the Figure 1, we show these regions. These three regions are the following:

- Northwestern Spain (NW): in this area, there are more fires than in other regions in Spain and climatic conditions are different (Bardají and Molina, 1999). In this region, we include La Coruña, Lugo, Ourense, Pontevedra, León, Zamora, Asturias and Cantabria.

- Mediterranean Coast (MC): there is an important sea influence. Wind regime differs to other parts of the country and the weather conditions too. In general, there is high population density. In MC, we have included Girona, Barcelona, Tarragona, Castellón, Valencia, Alicante, Murcia, Almería, Málaga, Cádiz, Huelva.
- Mediterranean Interior (MI): in these provinces, population density is lower than Mediterranean coast and sea influence is minimal. In this region, there are the following provinces: Guadalajara, Cuenca, Toledo, Ciudad Real, Albacete, Huesca, Zaragoza, Teruel, Cáceres, Badajoz, Salamanca, Valladolid, Palencia, Burgos, Soria, Segovia, Ávila, Jaén and Cordoba.

Figure 1. Map of the analyzed Spanish regions. Canary Islands are neither displayed in this map nor included in this study

We have excluded some provinces that could disturb our analysis because of different issues:

- Madrid: It is an interior province; however, its population density is much higher (and suppression resources are much stronger) than other interior provinces.
- Lleida: In this province, suppression resources are much stronger than other interior provinces.
- Navarra, Guipuzcoa, and Alava: They are small size provinces with strong suppression resources and with little fire concurrency.
- Granada and Sevilla: These provinces have a lot of interior area and they also have sea influence areas. We can not use them either Mediterranean coast nor Mediterranean Interior because they do not fit in any of these regions.
- Canary Island and Baleares: They are particular provinces because there are few large wildland fires and there is an important sea influence in all islands.

2.1. Statistical data treatment

We have segregated all fires over 100 ha into three categories (fires larger than 100 ha, 250 ha and 500 ha) and we have analyzed trends in the three regions and the three categories using linear regressions and homogeneity tests. We have researched trends using moving five-year average in linear regressions. In this way, we reduce the annual data variability and we can see better the existing trends.

We use homogeneity tests to set if there are trends in the number of fires and burned area during the period studied (1978-2009), analyzing the homogeneity of the data series. We have used sequences test (Siegmund 1985; Castellví and Elias 2001) analyzing data sequences, using p-value<0.1 to set differences in the data media, setting trends or not in the period studied in the number and burned area of wildland fires and the homogeneity of the series. This follows the World Meteorological Organization (WMO) indications. In these tests, we have not used moving five-year average because the test takes into account sequences with annual original data.

We also research medium size of large wildland fires in three regions to find differences and trends in time. We have divided burned area and number of fires per year and after that we calculated a moving five-year average.

3. RESULTS

We have found some trends in both number of fires and burned area in fires larger than 100, 250 and 500 ha. In Mediterranean Coast (MC), we observed clear trends in all categories. In them, the number of fires has lessen from 100 fires to 20, approximately, in 100ha+ fires, using moving five-year average.

In Figure 2, we show the trend in number of 100ha+ fires in MC. R2 is 0.8323 and sequences test also confirm this trend with a p-value<0,1. In the other categories (250ha+, 500ha+) and in other regions, this trend is less clear as shown in the table 1 (coefficient of determination and homogeneity test in all categories and regions).

In MC, there is a decrease in burned area in all categories. Coefficient of determination is low but it is influenced by the years 1990 to 1995, in which burn area was very high in relation to other years. Homogeneity test sets that there is a trend (decrease) in burned area. In Figure 3, we show the linear regression in MC and 100ha+.

In Northwestern Spain, we only observed a trend in number of fires in 100ha+ fire category (R^2=0.55 and, p<0.10 in homogeneity test). In fires larger than 250 and 500 ha, we observed no trends and in the burned area: neither according to the result of homogeneity test nor the regression coefficient.

In Mediterranean Interior, we only have heterogeneity series in the number of large fires in two categories: 100ha+ and 250ha+. However, for 500ha+ (in number of fires), and in burned area (in all categories, 100ha+ 250ha+ and 500ha+) there are not significant trends.

Average size of wildland fires has not changed with time in MC and NW. However, in MI, we detected that average size of large fires (100ha+) is higher around 2008 than in the late 1980s, using linear regression (Figure 4).

Table 1 Correlation coefficient and homogeneity test in all categories and regions

		Number of fires		**Burned area**	
	Wildland fires	**R^2**	**Homogeneity test**	**R^2**	**Homogeneity test**
Mediterranean Coast	>100	0.83	Trend	0.24	Trend
	>250	0.73	Trend	0.19	Trend
	>500	0.66	Trend	0.14	Trend
Mediterranean Interior	>100	0.43	Trend	0.12	No trend
	>250	0.35	Notrend	0.04	Notrend
	>500	0.17	No trend	0.01	No trend
Northwestern Spain	>100	0.62	No trend	0.45	No trend
	>250	0.5	No trend	0.27	No trend
	>500	0.25	No trend	0.08	No trend

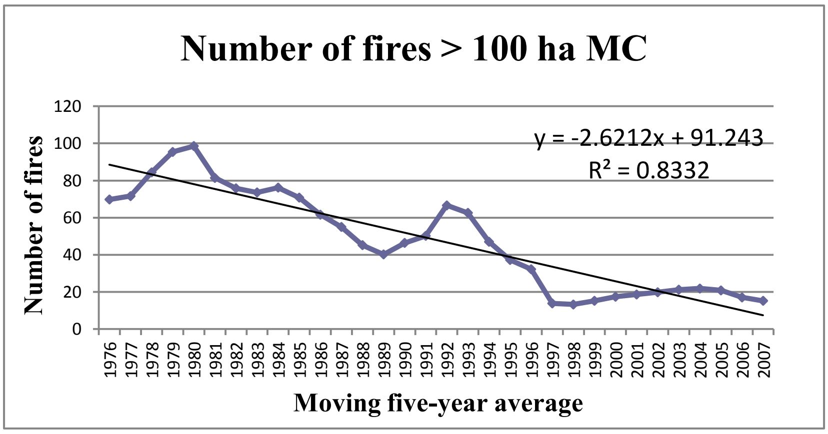

Figure 2. Number of fires larger than 100 ha in Mediterranean Coast

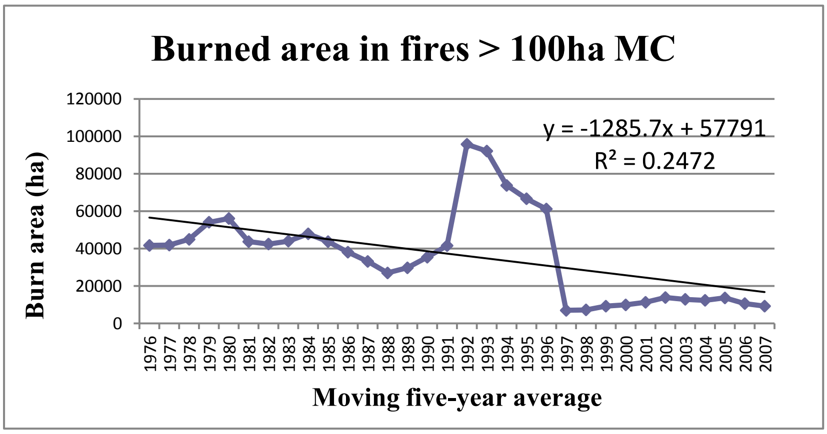

Figure 3. Burned area in fires larger than 100 ha in Mediterranean Coast

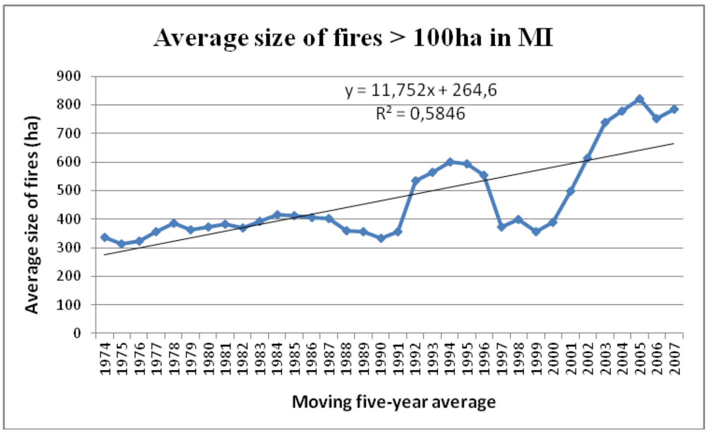

Figure 4. Average size of wildland fires larger than 100 ha in MI

4. DISCUSSION

We discuss of suppression resources and their effectiveness to reduce the impact from large forest fires under extreme fire behavior. Is it better to invest money in suppression or prevention actions?

Recently, major changes have been implemented to try to mitigate the large wildland fire problem in Spain. In October 2005, the Emergency Military Unit was established and forest fire suppression is one of its key action areas. In 2006, a new Office of Environment (within the Department of Justice) was created with the aim, among others, to expedite the prosecution of crimes of forest fires.

In MI and NW, there is not a decrease in burned area in the period studied although there are trends in number of fires (in MI 100ha+ and 250ha+ and NW 100ha+). Therefore, our suppression resources have not reduced the impact of large wildland fires (500ha+ in MI and 100+ha and 250+ ha in NW) in these regions. Zavala et al. (2011) have studied the trends in all fires (small and large fires) in several regions in Spain. They have found trends in number of fires using a set of provinces similar to our MI region. Note that we have used provinces as independent units and Zavala et al. (2011) have employed 10 regions, taking into account administrative borders and biogeographical characteristics. We have excluded from our analysis those provinces that do not fit easily in either "Fire Regime" region as we have defined them. This has forced us to discharge 11 provinces from the set of 50. Zavala et al. (2011) have found an increase in number of fires in the series (R2=0.52). The Spanish Environment Ministry (2006) also has this trend in MI from 1996 to 2005. This is mostly due to the small size fires; however, this does not happen in our study about large fires. Therefore, in large fires (100ha+), we do not see this trend.

Additionally, average size of wildland fires (100ha+) are increasing in recent years and this is possible because of agricultural abandonment has provided fuel load and fuel continuity that facilitate fire propagation, causing fires able to grow bigger. In addition, firefighting resources are less powerful than other areas as MC due to human population density (lower in MI).

In MC, we find clear trends in number of large fires and burned area in all large fire categories. Zavala et al. (2011) also find trend in number of all fires (small and large fires). In this region, we can say that wildland fire suppression resources have being efficient in reducing large fire sizes. In this region, density population is higher; and therefore, suppression resources are higher too.

Climate change issues could be already presented in this study. Synoptic meteorological conditions moving Southern (Saharan Desert dry), warm air masses (SWA, from now on) to Mediterranean Interior region is significantly more frequent circa 2009 than earlier (1973 to 1986) (Cardil and Molina unpublished paper).

5. CONCLUSIONS

- In Mediterranean Interior and Northwestern Spain, suppression resources are not reducing the number of fires and burned area significantly. Correlation coefficient and the homogeneity test do not show clear trends. We only see a slight trend in the number of fires 100ha+.
- However, in Mediterranean Coast, fires are decreasing in number (R^2=0.83 in 100ha+ and heterogeneity series with trend to decrease) and burned area in which correlation coefficient is low (R^2=0.24) but homogeneity test marks that there are differences in time.
- Average size of wildland fires has not changed in Mediterranean Coast and Northwestern Spain. However, we observe in Mediterranean interior that average size of fires is higher around 2008 than in the late 1970s.
- Agricultural abandonment provide fuel load and fuel continuity that facilitate fire propagation. MI is the region where this effect is bigger and this is the reason that explains why average size of wildland fires is larger.

6. ACKNOWLEDGMENTS

We are grateful to the University of Lleida for supporting this paper through a partial grant to Adrian Cardil to enroll in the PhD program.

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Potential effects of prescribed burning and tactical fires on fire risk mitigation

Salis M.[1,2], Diana G.[3], Casula F.[1,3], Farris G.[3], Farris O.[3], Licheri F.[3], Musina G.[3], Orotelli S.[3], Peluffo L.[3], Pirisi A.M.[3], Bacciu V.[2], Fois C.[1], Sirca C.[1,2], Spano D.[1,2]

[1]Department of Science for Nature and Environmental Resources (DIPNET), University of Sassari, Italy; [2]Euro Mediterranean Center for Climate Change (CMCC IAFENT), Sassari, Italy; [3]Corpo Forestale e di Vigilanza Ambientale, STIR Nuoro, Italy

miksalis@uniss.it

Abstract

Prescribed burning and tactical fires in fire-prone ecosystems can represent useful techniques to mitigate wildfire risk and to strengthen fire suppression actions. According to several field experiences and to scientific literature, the efficacy of prescribed burning and tactical fires is particularly significant when the weather conditions result in low or moderate fire risk, while the effect is more limited when wildfires spread in extreme weather conditions. The Sardinia Forest Service (CFVA) has been developing for the last years an innovative integrated approach to fight wildfires that combines classic techniques (direct attack using water) and the use of fire. In particular, in the prevention phase, CFVA is carrying out prescribed fires in order to reduce fuel load, to create fuel breaks, and to enlarge anchor points, while, during a wildfire in the operative phase, small and well trained teams can cooperate with the regular CFVA fire-fighter crews, contributing to extinguish a wildfire by the use of tactical fires. Another important goal of the "smart" and controlled use of fire is to train teams and to test tactics and fire drills in conditions of moderate-low fire behaviour. The Sardinian experiences highlighted the operational capacity of small and skilled teams with limited equipment (drip torch, blowers, and tools for direct attack) in carrying out prescribed burning and tactical fires. The objective of this work is to present the CFVA prescribed burning experience carried out, during June 2011, in three different sites located in central Sardinia, Italy. Fuel characteristics and moisture, weather, and several fire behaviour parameters were monitored and collected in order to characterize the conditions in which the experiments took place. Finally, the potential effects of the controlled use of fire on wildfire behaviour were evaluated using FARSITE.

Keywords: prescribed fires; FARSITE; Mediterranean areas

1. INTRODUCTION

In several European Countries, in the last decades the socio-economic changes have led to an increase of the anthropic pressure in urban and coastal areas and to a progressive abandonment of farming and agro-forestry activities (Castellnou and Miralles 2009). This resulted in a deep modification of landscapes in different fire prone-areas, with a significant fuel build-up, a reduction in fuel discontinuity, together with the reduction of the traditional use of fire to manage landscapes. In addition, several agricultural areas reverted to shrublands and woodlands, due to both natural vegetation recovery and reforestation programs (Castellnou et al 2010). A number of studies showed that, in the last decades, also climate changes were responsible for the rise of potential fire risk, due to the increase of temperatures, heat waves frequency and duration as well as to rainfall reduction (Arca et al 2010). All these changes caused an escalation in megafires incidence (e.g. Greece 2007-2009; Portugal 2003-2005; Italy 2009; etc.) and longer fire seasons. In order to mitigate the potential fire risk, prescribed burning are gaining importance in Europe, although this technique should be restricted to trained and specialized fire crews (Castellnou et al 2010). Following the most common definitions, prescribed burning can be defined as the application of fire under specified conditions to meet specific management environmental objectives and long-term management goals (FAO 2006; Molina 2006). At the present time, the use of fire for fire risk mitigation purposes is relatively common in some European countries (e.g. Spain, Portugal, France), whereas it is more difficult to apply in other countries (e.g. Italy) mainly because of restrictive legal frameworks, complex territorial structures, negative public perceptions (Xanthoupoulos et al 2006). However, Sardinia is not exempt from the general trend described above, and for this reason Sardinia Forest Service (CFVA) and Ente Foreste in the last years have been involved in several experimental activities regarding the application of prescribed burning. The first experiences concerning the application of prescribed fires in Sardinia date back to the ‘80s (Delogu et al. 2010), where the use of fire was related to the firebreaks maintenance and management. In these first applications, the vegetation was mechanically cut before the fire. Later, in the ‘90s, prescribed fire activities were common in some Sardinian forests, in order to manage fuel load in firebreaks (Massaiu 1998). More recently, within the Fire Paradox Project, CFVA has been actively involved in prescribed fire activities and experiences which were carried out in two coastal sites characterized by pine forests (*Pinus pinea* L. and *Pinus canariensis* L.) (Delogu 2009). In the last years, other experimental activities and fire risk mitigation strategies, using prescribed burning, were carried out by CFVA, in collaboration with DIPNET (University of Sassari), within the Proterina-C Project. These activities were concentrated on some areas of southern Sardinia, in Planargia (a sub-region of Western Sardinia) and in the Nuoro area (central Sardinia), aiming to mitigate fire risk, protect areas of interest, and create safer and larger anchor points, as well as to organize training activities for the fire crews, in moderate environmental conditions and controlled fire spread conditions. Recently, several researches have investigated the potential of fire simulators in prescribed burning activities planning and evaluation (Stephens 1998; Finney 2001; Stratton 2004). This paper aims to illustrate the organization, activities and strength points of the use of prescribed fires, presenting the experimental work carried out in the Nuoro area in June 2011. It was also assessed the potential of FARSITE (Finney 2004) and the effects of fuel mitigation strategies through prescribed burning on fire behaviour.

2. MATERIAL AND METHODS

The three prescribed burning sites are located in central Sardinia, Italy (Figure 1 and 2 and Table 1). They are characterised by the presence of a wide orographic valley with elevation ranging from 250 to 550 m a.s.l.. The summer temperatures are usually high (monthly average of maximum temperature in July and August is ≥ 30°C), and the relative humidity is generally low. A warm wind often blows along the axis of the valley (ESE-WNW). The vegetation of the sites is mainly represented by grasslands and herbaceous pastures, with limited presence of wooded pastures and Mediterranean maquis. In each study site, fuel load, height and moisture data, before and after the prescribed fires, were collected in order to characterize the fuels for the simulations with FARSITE (Picture 1).

Figure 1. (Left) Sardinia island. The red square represents the operations area, that is showed in the right

Table 1. Firelines description

Fireline	*Municipality*	*Coordinates (WGS 84)*	*Elevation a.s.l.*	*Fireline Length*	*Fireline Width*	*Fireline Area*
1	Bolotana	(40°18’25”N; 8°58’33”E)	250 m	≈ 3,500 m	25 m	≈ 8.75 ha
2	Orani	(40°18’34”N; 9°12’34”E)	370 m	≈ 2,700 m	25 m	≈ 6.75 ha
3	Nuoro	(40°19’24”N; 9°17’26”E)	540 m	≈ 6,400 m	25 m	≈ 16.00 ha

The prescribed fires operations were carried out between the 13th and the 30th June 2011, in 13 days of work. The operations were concentrated in the afternoon, from 15.30 to 20.30 and were only interrupted in a single day characterised by high wind speed and strong wind gusts. In each site, the CFVA planned and then performed a fireline. The firelines were adjacent to roads, and were generally located in areas considered strategic in order to interrupt fuel continuity, create fuel breaks and/or anchor points. Detailed information on the three sites is presented in the following Table 1. During the days of prescribed burning operations, the weather conditions were generally stable, with wind speed ≤ 4.6 m s^{-1} and an average of 1.67 m s^{-1} (st.dev. 1.01 m s^{-1}); temperatures ranged between 36.4 and 24.1°C (average 30.65°C, st.dev. 3.21°C), and relative humidity between 19.5 and 65.0% (average 37.4%, st.dev. 10.01%).

Regarding the organization of the prescribed burning activities, the fires were carried out by small and nimble operation teams. Each operation team was composed by 5 people and 2 pickups: 3 operators with a first vehicle provided with complete fire-fight equipment, drip torch and blowers; other 2 persons in the second car provided with 0.4 m^3 of water, ready for a direct attack, in case of any need. For these first experiences, in order to guarantee completely safe conditions, a SCAM truck provided with 1.8 m^3 of water was constantly present: the intervention of this truck was not necessary.

The *modus operandi* that CFVA defined for the prescribed burning was defined each day during a general briefing. Initially, a primary thin fireline was created, igniting the fire from an existing anchor point that was therefore enlarged. After this first phase, the thin fireline was completed in width proceeding upwind, otherwise the blowers were used to control and guide the flames. Then, other strips were burned downwind toward the already scorched area (Pictures 2-5).

Using FARSITE (Finney 2004), it was then performed a comparison between observed and simulated prescribed fires activity and it was evaluated the potential effectiveness of the firelines in case of potential fires.

Pictures 1 and 2. fuel load measurements (left) and blowers "driving" the flames downwind (right).

Pictures 3,4,5. Operations area before, during and after the controlled burning. Location: fireline 3, nearby the town of Nuoro.

3. RESULTS AND DISCUSSION

3.1. Fuel characteristics

As previously mentioned, the vegetation of the sites was mostly herbaceous, with an average height of 40 cm. The fuel load ranged between a minimum value of 1.45 Mg ha^{-1} to 2.30 Mg ha^{-1}; average fuel load was 1.65~1.75 Mg ha^{-1}. The reduction in fuel load due to the application of prescribed fires was about 90%. The 1hr dead fuel moisture before the prescribed burning ranged between 20% and 35%. This herbaceous fuel type is characterized by high fire rate of spread (ROS) and low residence time, and fire intensity is relatively low. In these conditions, fires do not damage the seed stock of the terrain nor the pasture regeneration.

3.2. Observed and simulated fire behaviour and spread values

The three firelines had 12.5 km length and were performed in 13 days. The average observed ROS was about 3 m min^{-1}; FARSITE simulations gave an average ROS of about 3.5 m min^{-1}. We measured a ROS peak of 102 m min^{-1} in uphill and upwind (abrupt wind gust) conditions, and minimum ROS values of 0.77 m min^{-1} in downhill and downwind fire spread. The flame length (FL) ranged between 0.40 and 0.60 m and was almost constant, with maximum values of 4 m and minimum of few centimetres. The agreement of FARSITE with the FL values was confirmed in several plots. An important decrease in ROS and FL in late hours in the afternoon and under the trees canopy was observed: this is probably related to the differences in fuel moisture content. It was noticed that terrain exposure sunny oriented (S, SW, W), also played a key role in increasing fire ROS and FL.

3.3. Evaluation of the effects of prescribed burning on potential fire behaviour

In a first phase of calibration, FARSITE outputs confirmed in several cases the data of ROS and FL observed during the operations. After the calibration, the simulator was run taking into account extreme summer weather conditions and different fireline widths, in order to evaluate wildfire severity (final perimeters, ROS and FL) and to test firelines usefulness. These tests were carried out for fireline 2 (Orani). The outputs of the simulator indicated that the fireline capability to stop or slow down a potential wildfire appears to be significant under low-moderate weather conditions, while it decreases in extreme conditions. As expected, the fireline usefulness increases with its width; a 10 m width fireline has a mitigating effect under weather conditions associated to moderate-low risk, while the effect of a 50 m width fireline is evident also wind speed of 25 km hr^{-1}. Figure 3a and 3b show the reduction of burnt areas and how the fireline can inhibit the fire spread. Figure 3c and 3d (simulation with wind speed of 25 km hr^{-1}) clearly show a strong reduction of ROS and FL when the front reaches the fireline. This decrease in fire severity may allow operators to safely face and extinguish the flames, to use the fireline as an anchor point from which ignite a tactical fire, and it also may permit Canadair and helicopters to operate more efficiently on fire fronts less aggressive and intense.

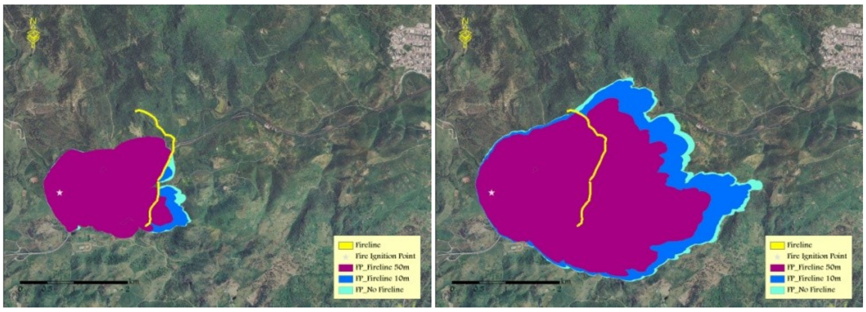

Figure 3a, 3b. FARSITE simulations: effect of firelines of different width (0m, 10m, 50m) on simulated fire perimeters, considering very dry fuel moisture and different wind speeds (15 km hr^{-1} *(left); 25 km* hr^{-1} *(right)). Wider firelines were more useful in slowing down or block the fire spread.*

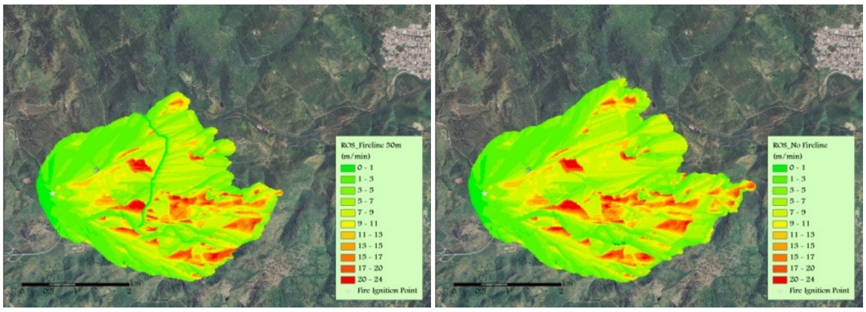

Figure 3c, 3d. FARSITE simulations: comparison of ROS values with 50 m width fireline (left) and no fireline (right), considering very dry fuel moisture and wind speed of 25 km hr^{-1}. The fireline slowed down the fire spread, although its effect in these extreme conditions was not sufficient for stopping the fire.

4. FINAL REMARKS

The prescribed burning experience was useful to create an operative expert group that, day by day, became more efficient and reliable, growing in mutual coordination. Although the team became more and more self-confident, the experience showed that the best way to work safely is to remain constantly aware of the teams limitations and of fire potential to turn into a threat.

Fire crews considered prescribed fires as a new situation in which they can face flames in completely safe conditions. This is very important since during real wildfires, the crews work in emergency with the only aim to extinguish fires as soon as possible. On the contrary, during the described experiences, operators may “drive” flames with blowers, observe fire behaviour (how and how much it can change depending on environmental conditions), being in the meantime able to talk, learn and share experiences. It was highlighted how the possibilities to extinguish fire change with ROS and FL, and how difficult it was to stop fast fire fronts, even if characterized by low intensity.

During the activities, the team safety was guaranteed by the supervisory control of an additional suppression crew. Anyway, it appeared to be sufficiently safe to use a logistic solution of two small teams working closely and always ready to support one another, especially in weather conditions considered as optimal for the prescribed fires, namely when temperatures are ≤ 28°C, wind speed < 8~10 km hr^{-1}, and when fuels are not completely dry. During days of moderate risk conditions, an external suppression crew, with a fire truck supporting the teams, could be a safer solution.

The fire behaviour outputs of FARSITE were analysed together with the fire crews in order to evaluate the effects of firebreaks and prescribed fires on potential fire behaviour. The support of fire simulators in highlighting areas of high potential fire risk and/or weak points for the fire propagation can allow, in the next years, to provide crucial guidelines for addressing type, locations, period of application and the objectives achievable by the use of the best fire risk mitigation option.

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Natural and social factors influencing forest fire occurrence at a local spatial scale

Chas-Amil M.L.[1]; Touza J.[2]; Prestemon J.P.[3]; McClean C.J.[4]

[1]University of Santiago de Compostela, Baixada Burgo das Nacións s/n. 15782 Santiago de Compostela. Spain; [2]University of Vigo, Campus As Lagoas-Marcosende. 36310 Vigo. Spain; [3]USDA Forest Service, Research Triangle Park, NC 27709. USA; [4]University of York, Heslington Road York, YO10 5DD, UK4

marisa.chas@usc.es

Abstract

Development of efficient forest fire policies requires an understanding of the underlying reasons behind forest fire ignitions. Globally, there is a close relationship between forest fires and human activities, i.e., fires understood as human events due to negligence (e.g., agricultural burning escapes), and deliberate actions (e.g., pyromania, revenge, land use change attempts). Wildfire occurrence even for human-ignited fires has also been shown to be dependent on biophysical variables (e.g., fuel conditions). Accordingly, this paper modelled the spatial risk of forest fire occurrence as a function of natural as well as socioeconomic variables. The study area is the region of Galicia (NW Spain). Our data include approximately 86,000 forest fires in nearly 3,800 Galician parishes, the unit of our study, during the ten years period 1999-2008, inclusive. The analysis combines spatial and non spatial econometric approaches to evaluate the consistency of the results and account for spatial autocorrelation in the fire ignitions data.

Keywords: intentional wildfires, fire occurrence, spatial autocorrelation

1. INTRODUCTION

In Spain, wildfires are a recurrent phenomenon, with an annual average of 15,000 forest fires and 173,000 ha burned between 1980 and 2010 (MARM 2010). A significant proportion of these fires, and in particular those intentionally ignited, occurred in the region of Galicia, northwest of Spain (APAS and IDEM 2006). Thus, during the period 1999-2008 an annual average of close to 8,600 forest fires burned about 40,000 ha in Galicia. Most fires are human-caused (99%), approximately 82% are set intentionally and 5% are either ignited accidentally or through negligence (Chas-Amil et al. 2010). However only a limited number of research has specifically evaluated how the human presence in this territory increase the risk of fire ignition (Martinez et al. 2009; Padilla and Vega-García 2011; Prestemon et al. *forthcoming*). This contrasts with the increasing literature on empirical assessments of the influence of socioeconomic aspects on forest fire risks, using variables such as population density, land cover changes associated with agriculture abandonment, distance to road or the density of human settlements (e.g., Brosofske et al. 2007; Maingi and Henry 2007; Moreira et al. 2011; Narayanaraj and Wimberly 2012).

In this study, the spatial pattern in the number of fires throughout Galicia is modelled to determine which topographic, meteorological, and socioeconomic variables best explained a decade-scale pattern of fire activity (1999-2008). However, the analysis of spatial data is complicated by the potential presence of spatial autocorrelation (SAC) (Dormann et al.

2007). SAC occurs when fire data from locations close to each other have more similar values than those farther apart. It may emerge because fire ignitions in a given area are strongly dependent on natural and human factors that are also themselves spatially structured, i.e., values in a given location are strongly influenced by those in their surroundings (Chou 1992). If this SAC still exits in the residuals of an econometric model of spatial data, this may lead to biased coefficients and limit hypothesis testing. We apply non-spatial and spatial models to evaluate the consistency of our results and the effect of spatial autocorrelation on estimated coefficients and inference.

2. MATERIALS AND METHODS

2.1. Study area

Galicia (NW of Spain) comprises a total area of 29,575 km^2, which corresponds to a 6% of the Spanish geographical area. Individual private ownership represents 68% of the forestland, while 30% is under collective private ownership. Forests cover nearly 70% of its territory and approximately 67% of this forestland is wooded. *Pinus pinaster, Eucalyptus globules, Quercus robur,* and *Quercus pyrenaica* are the main tree species.

2.2. Materials

In this work, we studied 1999-2008 wildfire data provided by the General Statistics of Forest Fires compiled by the Spanish Forest Service and the Rural Affairs Department of the Regional Government (Xunta de Galicia). This means a total of 85,784 wildland fires, which burnt 319,651 hectares. Recorded fire ignitions were assembled into a dataset of counts of wildfires for each of the 3,790 Galician parishes. We opted for the parishes as the geographical unit for the analysis because it is the smallest administrative unit that divides the territory. The parishes' mean size is 779 hectares with a standard deviation of 664 hectares.The potential explanatory variables studied in the model specification were based on an extensive literature review and can be divided in three broad types: topographic, meteorological, and socioeconomic. The variable definitions and their sources are summarised in Table 1.

2.3. Methods

We use Moran's Index to evaluate the degree of spatial autocorrelation of the Galician fire data over the studied decade (Moran 1950). Our modelled response variable is wildfire rate defined as the number of fire events per parish divided by the parish area, reported as fires per 100 hectares. Both Negative-binomial regression and OLS estimation were used to model fire ignitions as a function of the socioeconomic and natural covariates. A negative binomial model was chosen because of the overdispersion in the fire data per parish. Following Osgood (2000), we modified the basic Negative Binomial regression so that the analysis focuses on the fire rate per parish rather than counts of fire events. In addition, given the spatial character of fire data, the presence of spatial autocorrelation in the regression is examined using correlogram plots, which measure the similarity of the residuals as a function of geographical distances. A Generalised Least Squares (GLS) estimation, building a correlation structure that captures the fire's spatial patterning, was also applied to evaluate the consistency of estimation parameters and spatial correlation effects. An exponential spatial correlation structure was used, as these fit the variogram of residuals produced when using a simple GLS without a correlation structure (Dormann et al. 2007).

Table 1. Independent variables for modelling forest fire occurrence at the parish level

Variables	Data source	Description	Units
Physiography			
Slope	10 m Digital Elevation Model (1:5,000). SITGA.	Mean, minimum, maximum and standard deviation of the parish slope.	%
Elevation	10 m Digital Elevation Model (1:5,000). SITGA.	Mean and range elevation observed in the parish.	m
Meteorology			
Air temperature	Digital Climatic Atlas of the Iberian Peninsula- spatial resolution 200 m (Ninyerola et al. 2005). Monthly data.	Annual mean, maximum, mininum	ºC
Precipitation	Digital Climatic Atlas of the Iberian Peninsula- spatial resolution 200 m (Ninyerola et al. 2005). Monthly data.	Annual mean	l/m2
Forest use cover			
Forest area:	Third Spanish Forest Inventory cartography (1:50,000). MARM.	Land with tree crown cover, or equivalent stocking level of:	ha
- Wooded land		-higher than 10%	
- Other wooded land		-lower than 10%	
Dominant forest vegetation: Eucalyptus, Conifers, Other broad-leaved species	Third Spanish Forest Inventory cartography (1:50,000). MARM.	Area	ha
Pure monoculture: Eucalyptus, Conifers, Other broad-leaved species	Third Spanish Forest Inventory cartography (1:50,000). MARM.	Pure stands were considered with at least 80% of the area covered by a single species.	ha
Forest plantations	Third Spanish Forest Inventory cartography (1:50,000). MARM.	Area of planted forest consisting primarily of introduced species.	ha
Forest land tenure: Public, Private, Communal	Third Spanish Forest Inventory cartography (1:50,000). MARM.	Area by parish	ha
Protected natural area	Protected natural spaces coverage (1:25,000) Consellería do Medio Rural	Area of protected natural area by parish (dummy variable)	
Human factors			
Population density	Nomenclator (INE)	Mean of parish's population in the period divided by parish area	hab/ha
Road density (paved, path, forest path)	Base Topográfica Nacional (BTN25) (1: 25,000)	m of roads included in the parish divided by parish area	m/m^2
Accessibility index	Base Topográfica Nacional (BTN25) (1: 25,000)	$S_i = \sum_{i \neq j} \exp(-\alpha d_{ij}) A_j$ A is population size in parish j. α takes a value of 0.001 (average travelling distance is 10 km)	

3. RESULTS

The spatial representation of the total number of fires per parish illustrates that wildfires are mainly concentrated on the Atlantic coast and in the South. The global Moran's Index for wildfire occurrence was 0.404, indicating the presence of a statistically significant positive spatial autocorrelation in the parishes' fires (z-score=42.03, p-value: 0.000). OLS, Poisson and GLS estimates show consistent results in terms of the signs of the coefficients (Table 2).

Table 2. Model estimation results.

Explanatory variables	OLS log(rate+0.1)		Negative Binomial		Generalized least squares	
	Coef.	*P*	*Coef.*	*P*	*Coef.*	*P*
intercept	-2.179	0.0000 ***	-5.892	0.0000 ***	-1.3433	0.0228*
ln(Pop_density)	0.3186	0.0000 ***	0.3490	0.0000 ***	0.2450	0.0000 ***
% forestland	1.042	0.0000 ***	1.013	0.0000 ***	0.6326	0.0000 ***
ln(% plantation)	-0.1034	0.0074 **	-0.1246	0.0000 ***	-0.0625	0.1137
% wooded forest	-0.7535	0.0000 ***	-0.8943	0.0000 ***	-0.5053	0.0000 ***
DV protected land	-0.2015	0.0000 ***	-0.1736e	0.0000 ***	-0.099	0.0279*
% Communal forest	0.2643	0.0005 ***	0.2007	0.0036 **	0.2045	0.0209*
% Eucalyptus	--0.594	0.0000 ***	-0.6605	0.0000 ***	-0.194	0.2076
% Conifers	-0.435	0.0001 ***	-0.4348	0.0000 ***	-0.1814	0.1809
% Broadleaves Pure	0.7280	0.0000 ***	1.013	0.0000 ***	0.311	0.0729
Mean temp summer	0.1249	0.0000 ***	0.1511	0.0000 ***	0.1135	0.002**
Mean precip summer	-0.0118	0.0000 ***	-0.01267	0.0000 ***	-0.0126	0.0004***
Slope mean	-0.0077	0.0016**	-0.0064	0.0045 **	-0.0069	0.026*
Paved_density	149.5	0.0000 ***	153.7	0.0000 ***	100.82	0.0000 ***
Path_density	147.3	0.0000 ***	126.9	0.0000 ***	93.42	0.0000 ***
Forest_path density	25.20	0.1507	51.71	0.0013**	14.96	0.423
Access	6.1e-07	0.0000 ***	4.2e-07	0.0000 ***	0.00000	0.0000 ***
Ln(area_parish)	0.0844	0.0034**				
R^2	0.3		-2LL	28994		
			Residual deviance	4237 (1.037e-07)		

The variables explored have a significant effect on forest fire events in both the OLS and negative binomial models, except for forest path density. In addition, the regression coefficients for population density, percentage of forestland, and communal private forestlands were always positive and significant for all models. This means that, as expected, the higher the population pressure and the greater the share of forestland with respect other land uses in the parish, the greater the probability of fire occurrence. A negative relation is shown, however, with the percent of forest plantations and the percentage of forest area that is wooded. This result indicates that sparsely wooded landscapes are at lower risk of fire, while less densely wood landscapes are at greater risk, ceteris paribus. The high percentage of eucalyptus and conifers on forestry plantations may explain the negative effect of these two tree species on fire risk. Density of rural paved roads and paths as well as a higher accessibility index increase the probability of fire ignitions. We have also found that OLS and the negative binomial models do not completely explain the fire distribution, as they do not take into account the spatial structure of the dependent variable. Figure 1 shows that the negative binomial model's residuals display spatial autocorrelation up to 30 km.

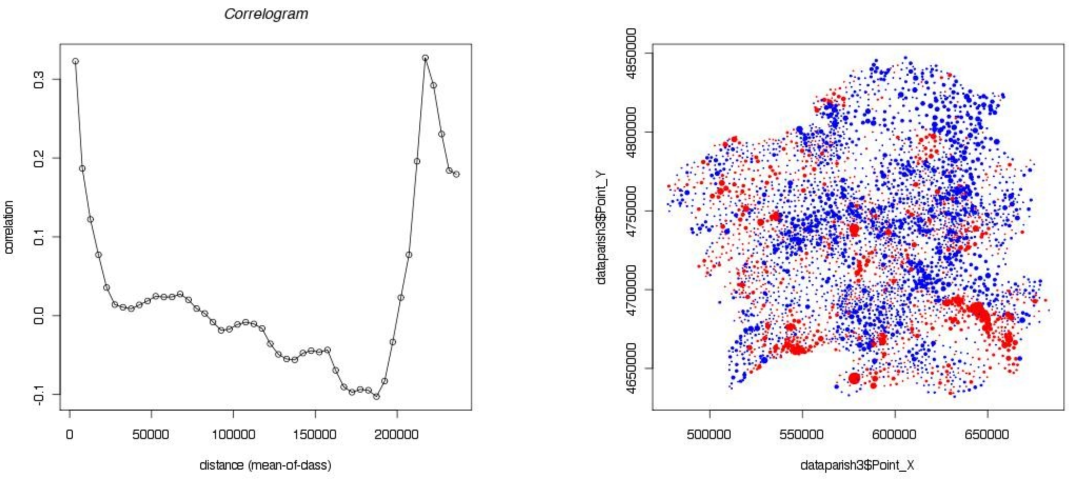

Figure 1. Correlogram plot and spatial representation of residuals from the estimated negative binomial model. Negative residuals (overpredictions) are represented as blue, positive residuals (underpredictions) as red.

4. CONCLUSIONS

Our models have identified variables that have significant relationships and signs to explain where forest fires are ignited in Galicia. Higher population pressure, communal ownership, and higher road and path accessibility to the forest increase the probability of fire, while increasing the productivity of forestlands through forest plantations decreases this probability. This econometric analysis, however, has so far failed to shed full light on the strong spatial pattern in the fire occurrence pattern, with significant clusters of fire events in the Atlantic coast and in the South of the region. The question remaining is how the number of fires reported at one location encourages/discourages occurrences at other nearby locations. Given the high proportion of deliberate fires in this region, this may be attributable to serial or copycat fire setting, with a relatively few individuals responsible for multiple fires over long time spans. It may also be related to the omission from our models of key covariates, still to be identified, whose spatial distributions closely align with the residual spatial patterns observed in our models.

5. ACKNOWNLEDGMENTS

This research was funded in part by Consellería de Economía e Industria-Xunta de Galicia (Project 09SEC011201PR). The Spanish Forest Service and Consellería do Medio Rural (Xunta de Galicia) provide the forest fire database.

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Evaluation of the Integrated Fire Index (IFI) in Sardinia

Spano D.[1,2], Salis M.[1,2], Arca B.[3], Duce P.[3], Bacciu V.[1,2], Sirca C.[1,2]

[1]DipNET- University of Sassari, via E. de Nicola, 9 – 07100 Sassari, Italy; [2]CMCC – Euro-Mediterranean Centre for Climate Change, IAFENT Division, via E. de Nicola, 9 – 07100 Sassari, Italy; [3]CNR IBIMET – Institute of Biometeorology, traversa La Crucca 3, regione Baldinca, 07100 Sassari, Italy

spano@uniss.it, sirca@uniss.it

Abstract

This study presents a new fire danger model suitable for Mediterranean-type vegetation. The model Integrated Fire Index (IFI) requires three types of inputs: weather data, fuel, and topography. The model was calibrated in Sardinia, the second largest Mediterranean island with a high fire occurrence, mostly during the summer-fall period. The model was tested using both observed weather data and forecasts from a limited area model (BoLam). A comparison with other well diffuse fire danger models was carried out after the calibration. The analysis generated satisfactory results, indicating a high potential of the model to predict a fire occurrence. Thus, preliminary observations unveiled that this new index could be a useful tool for assisting fire managers with the control and mitigation of the harmful effects of wildfire in Sardinia.

Keywords: fire danger, model, Mediterranean vegetation

1. INTRODUCTION

Usually, estimation of fire danger is obtained by the identification of potentially contributing variables and integrating them into a mathematical expression, i.e. an index. Numerous fire danger evaluation models have been developed, and most of them are based on empirical approaches, mainly because there is no general theory to explain the complexity of factors and interactions involved in fire danger.

Fire danger models are also developed based on data from specific geographic areas. When used in areas other than those where calibration was conducted, the performance of fire danger models may be inconsistent. In addition, statistical model evaluation did not receive sufficient attention and no comprehensive model evaluation protocol was applied to fire danger models yet (Mandallaz and Ye 1997; Andrews et al. 2003).

Fire danger models integrated in complex systems are commonly used in most of the countries, where fire forest occurrences are an important natural threat to forests and wooded areas (e.g. Canada and the U.S.A.). The relative lack of the model use in the Euro-Mediterranean area may be related to limited fire/fuel databases in the region, high climate and fuel variability that are less well quantified, and vegetation different from regions where the models were developed.

This report presents an integrated fire rating model, called Integrated Fire Index (IFI). IFI was developed using forest fire data from Sardinia, an Italian region where forest fire events often represent the highest percentage of fires throughout Italy. Considering that no fire danger models were calibrated for Sardinian conditions, our group investigated existing models and developed IFI specifically for the application in Sardinia and in the nearby

Mediterranean region. IFI was developed with reference to meteorological, ecophysiological, topological and vegetational characteristics of Sardinia. In addition, this paper reports the preliminary results on IFI performances compared with others fire danger indices.

2. MATERIALS AND METHODS

IFI model has three groups of input data: weather or climate, fuel, and topography. Data are processed with 4 codes: 1) Drought Code (DC) linked to water status of plants; 2) Meteo Code (MC) related to turbulence and weather conditions; 3) Fuel Code (FC) based on fuel characteristics and moisture; and 4) Topological Code (TC) which considers slope and aspect of the study area. The sum of these codes gives the fire danger value (dimensionless, ranging from 2.5 to 17), usually expressed in the maps as fire danger class ranging from 1 (very low) to 5 (extreme) (Figure 1).

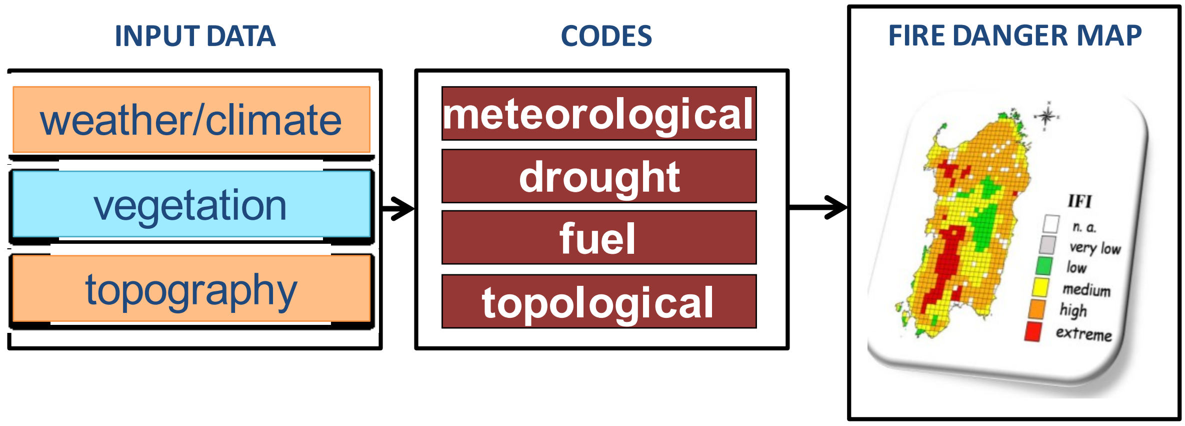

Figure 1. General structure of IFI

The first version of the model was modified in the project PROTERINA-C (Spano et al. 2003). IFI was calibrated using the daily weather data from 50 weather stations of ARPAS network and the fire database from CFVA, Sardinian Forest Corp, for the period of 2000-2006. To statistically evaluate the ability of the IFI model to predict the burned area and the number of fires occurring at that area, IFI was compared with some other fire danger indexes. The daily value of the selected indexes, namely FWI Fire Weather Index (Van Wagner and Pickett 1985), MK5 McArthur Forest and MK4 Grassland Fire danger Meters (Noble et al. 1980), FFWI Fosberg Fire Weather Index (Fosberg 1978; Goodrich 2002; Sharples et al. 2009), and F index (Sharples et al. 2009), was calculated for each climatic area of Sardinia (Figure 2).

The mean daily index values for each climatic area (period of 2000-2007) were normalized on a 0-100 scale and then separated into equal-sized fire danger classes numbered from 1 to 10. Further, a comparison was conducted using the linear regression between the fire danger level and the following fire parameters:

- percentage of days with fires over all days of that class;
- daily burned area over 50 km^2;
- daily fire number over 50 km^2;

- mean burned area per fire.

Next, the model was adapted to integrate weather input data from daily forecast at 5 km resolution for Sardinia (BOLAM Limited Area Model, produced by ARPAS, Sardinian Environmental Agency), available since 2007. This version of the model was implemented in software to generate daily fire danger forecast that is currently used by the CFVA – Regional Forestry Corp of Sardinia for operative purposes during a high fire season.

Figure 2. Weather station network and climatic areas of Sardinia

3. RESULTS

IFI outputs computed from observed weather data from the years 2000-2007 were compared with fire occurrence. The comparison revealed that the IFI was clearly related to both burned surface class and the number of fire events per day. As reported in Figure 3, which shows the relationship among the IFI value, the number of fires, and the burned area at regional scale, IFI values elevated along with increasing values of burned surface class and the number of events per day, and tended to level off at higher values for burned area and number of fires.

Figure 4 plots the percentage of days with fires versus the IFI and FWI danger classes (1-10). The same analysis was conducted for all others fire danger indexes. Figure 4 lefts and right are similar but differ somewhat with regard to the percentage of days with fire tends to rise at lower values of FWI and levels off at a lower danger class than the IFI. A similar analysis was done for each of the fire danger indices and fire parameters, and the least squares regression of the observed fire parameters versus the various models was completed to assess their performance. The key results of this analysis are reported in the Table 1. In all parameters except for the fire events/50 km^2, the IFI performed best at explaining the variability of the observed data relative to the predicted model.

To evaluate the potential of the model to predict fire events using weather forecast for the period 2007-2009, the fire occurrence (number of events and burned area) was compared with the IFI output calculated from the BOLAM weather forecast. Figure 5 shows the trend of these variables. The shape of the IFI and the fire number curves is similar, indicating a 1-day forecast capacity of the IFI-BOLAM tool to notify about a potential fire danger. This fact is confirmed with Figure 6, where the relationship between the forecasted IFI and the number of fires is presented.

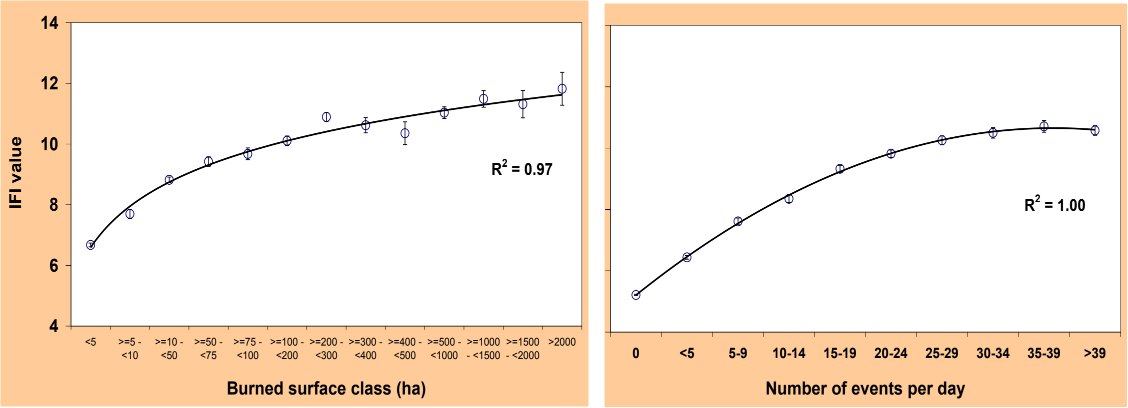

Figure 3. Relationship between IFI value, burnt area and number of fires for the period 2000-2006.

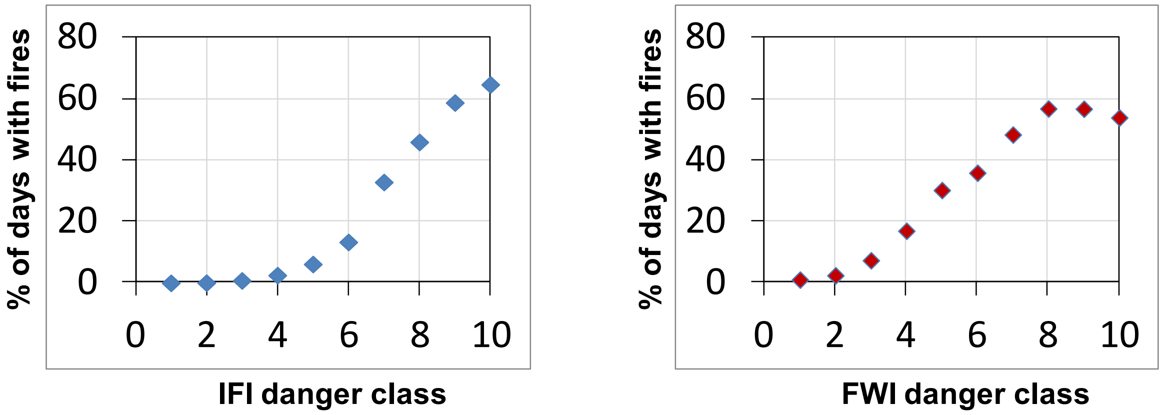

Figure 4. IFI (left side) and FWI (right side) danger class plotted versus the % of days with fires.

Table 1. Coefficient of determination R^2 between the fire danger class and fire parameters

	Days with fires		**Burned area/ fire**		**Burned area/ 50 km^2**		**Fire events / 50 km^2**	
	R^2	***p***	**R^2**	***p***	**R^2**	***p***	**R^2**	***p***
IFI	0.94	**	0.78	**	0.65	**	0.92	**
FWI	0.89	**	0.53	*	0.55	*	0.95	**
MK V	0.63	**	0.28	ns	0.30	ns	0.73	**
MK IV	0.19	ns	0.19	ns	0.24	ns	0.21	ns
FFWI	0.77	**	0.24	ns	0.32	ns	0.76	**
F	0.89	**	0.18	ns	0.20	ns	0.72	**

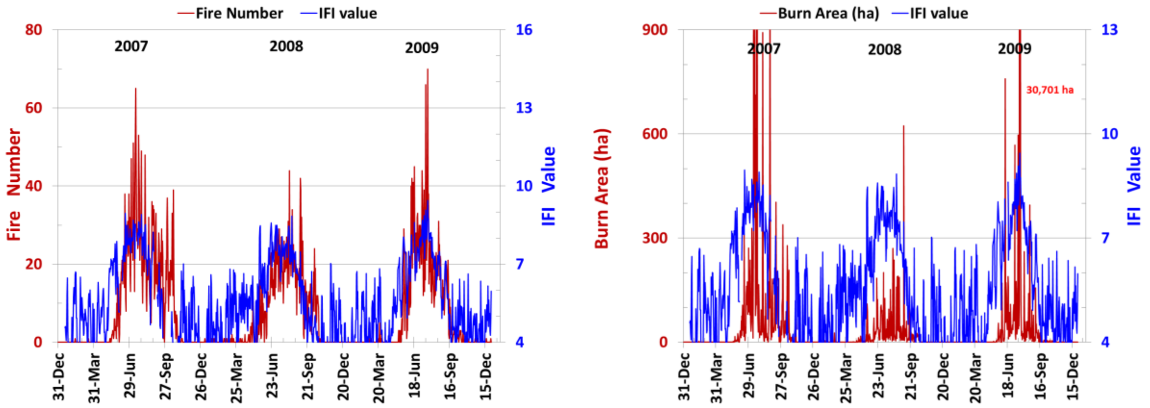

Figure 5. Forecasted IFI values, number of fires and burnt area during the 2007-2009 period

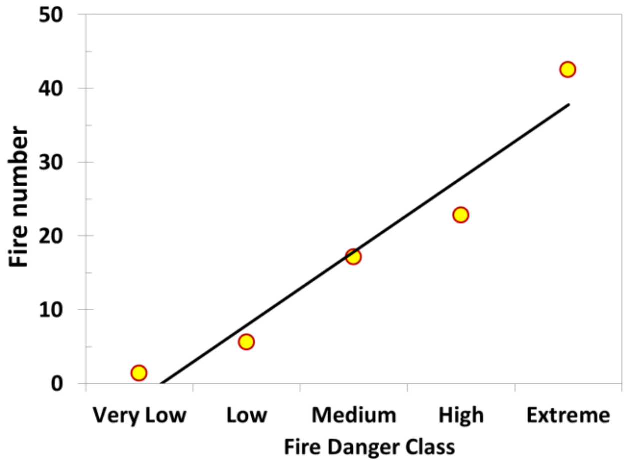

Figure 6. Relationship between IFI forecasted values and number of fires (2007-2009)

4. CONCLUSIONS

Although several of the commonly-used fire danger indices are available, the results of this study show that model performances tend to vary when indices are applied outside the ranges of vegetational and environmental conditions of the regions, where they were developed and calibrated. IFI produced more accurate results than other indices in Sardinia, which is characterized by a mosaic of landscapes with a high occurrence of summer fire events. In addition, IFI showed good predictive capability, when calculated using meteorological forecasts. These preliminary observations suggest that IFI may become a useful tool for assisting fire managers with the control and mitigation of the harmful effects of wildfire in Sardinia.

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An operational diagnostic chain, implemented within the Proterina-C project, to include weather measures in RISICO model

Dessy C.[1], Fiorucci P.[2], D'Andrea M.[2], Trasforini E.[2], Di Carlo L.[1], Fois G.[1], Canu S.[1], Casula M.[1], Cavalli G.[1], Congiu G.[1], Idini M.[1], Petretto F.[1], Pinna Nossai R.[1], Rancati S.[1], Sirca C. [3], Pellizzaro G.[4], Arca B.[4]

[1]ARPAS - Environmental Protection Agency of Sardinia, HydroMeteoClimatic Department, Sassari, Italy; [2]CIMA Research Foundation – International Centre in Environmental Monitoring, Savona, Italy; [3]Department of Science for Nature and Environmental Resources (DipNeT), University of Sassari, Italy; [4]National Research Council of Italy, Institute of Biometeorology (CNR-IBIMET), Sassari, Italy

cdessy@arpa.sardegna.it, paolo.fiorucci@cimafoundation.org, cosirca@uniss.it, g.pellizzaro@ibimet.cnr.it

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Abstract

Within the Operational Project "PROTERINA-C" (a forecast and prevention system for climate change impacts on risk variability for wildlands and urban areas), co-funded by the European Regional Development Fund (ERDF) under the Italy-France Maritime Program, methods and strategies, already in use in the regions of Sardinia, Liguria and Corsica, for the predictions of wildlands fires have been developed and adapted; RISICO System, by CIMA Foundation which plays the role of technical and scientific support for the region of Liguria, used by the Italian National Civil Protection Department, is one of them. In such a prediction model of risk of wildlands fires, it was arranged the integration, on a regional scale, of products related to the main meteorological, diagnostics and prognostics forcing, measured by ground stations, weather radar and advanced limited area weather prediction models. ARPAS and his partners, in the “Phase 5” of the project, have designed and developed an operational chain to insert data from ground meteorological monitoring network operating in Sardinia, in RISICO model to improve prediction of fire. In fact, the forecast errors can be reduced by conditioning the initial state of dynamic models of fuel moisture on the information obtained from sensors on land, at each time interval at which the fields of meteorological variables of interest are available, these fields can be obtained by a process of interpolation of the measures to the ground possibly complemented by large-scale measures obtained from remote sensors. In the present work are argued the characteristics of the system, in particular the configuration of the network of meteorological stations and the operational diagnostic chain to include the weather measures in the model of wildfire risk, and some preliminary results are discussed.

Keywords: weather, fire danger rating, measures, sensors, models

1. INTRODUCTION

In the framework of the project PROTERINA-C (http://www.proterina-c.eu) the risk assessment system RISICO (Fiorucci et al. 2008) has been implemented by CIMA Research Foundation at very high resolution in Sardinia; the regional implementation, in addition to weather forecast, currently uses weather data from at least 28 Sardinian ground stations, operated by the local Environmental Protection Agency (ARPAS), to provide the rate of spread and the linear intensity of a potential fire generated by accidental or deliberate ignition.

Data are collected in a database for storage and processing using an integrated hardware/software platform available to the partnership on defined policies; this support tool, run by ARPAS, presents itself as a remote point of data access allowing file-level sharing of all information necessary for risk models. Every day hourly raster maps of temperature, relative humidity, wind and rainfall are then created by interpolating values between weather stations using suited interpolation techniques. The weather grids, with the same time and space granularities of the Limited Area Models, are used to initialize the runs of the fuel moisture model within RISICO.

A preliminary analysis of wildlands fires that affected the island in the summer 2011 shows encouraging results of the regional implementation of RISICO system and the noticeable improvement resulting from the integration of the measured weather data than the exclusive introduction of forecasts provided by numerical weather prediction model. Some results on the most severe events occurred in Sardinia in the last years (2007 and 2009) are reported for a comprehensive analysis.

2. RISICO MODEL

RISICO has been providing Italian Civil Protection Department (DPC) with daily wildlands fire risk forecast maps relevant to the whole national territory since 2003. The main objective of the dynamic Risk Assessment System is to identify, within the considered territory, a finite number of areas affected by the highest risk values. The implemented semi-physical models are able to simulate in space and time the variability of the fuel moisture content, i.e. the main variable related with the ignition of a fire.

The design of the module followed reasoning lines similar to those of the Fire Weather Index (Van Wagner and Pickett 1985; Van Wagner 1987) of the Canadian Forest Fire danger Rating System (CFFDRS). In fact, the risk assessment system module is made by two separate models: the first is a model that provides the dynamics relevant to the fine fuel moisture content, and the second is a potential fire spread model able to evaluate the potential behaviour of the wildfire front in terms of rate of spread (m s^{-1}) and linear intensity (kW m^{-1}).

In RISICO it is assumed that the moisture contents of a unit of fuel should be modelled through a functional relationship between the main meteorological variables. The model stems on the assumption that the moisture content $u(t)$ of a particle of dead fuel, within a system with constant temperature and humidity, depends on time t so that it increases or decreases until, eventually, a value denoted as Equilibrium Moisture Contents (EMC) is reached; the model is expressed by the differential equation:

$$\frac{du}{dt} = -\frac{u - EMC}{\tau} \tag{1}$$

where *EMC* is a function of the temperature and relative humidity nearby the fuel (Catchpole et al. 2001) and τ is a time constant which represents the fuel response time, i.e. the time used by fuel to absorb or release about 63% of the variation between the initial moisture and his asymptotic value.

The solution on discrete time can be expressed as function of meteorological variables and of various parameters suitably calibrated to the regional environment conditions. Meteorological data are the main dynamic information used by the system; the considered fields are the 3-hour cumulated rainfall, the air temperature, the relative humidity and the wind speed and direction.

The system simulates (Figure 1) the dynamics of (fine) dead and live moisture contents with a resolution of 3-hour time step and 100 metres grid cell. Basing on these values and on other parameters (topography and fuel load) the system calculates the potential rate of spread and the linear intensity of the cells, whose aggregation in time and space represents the expected risk.

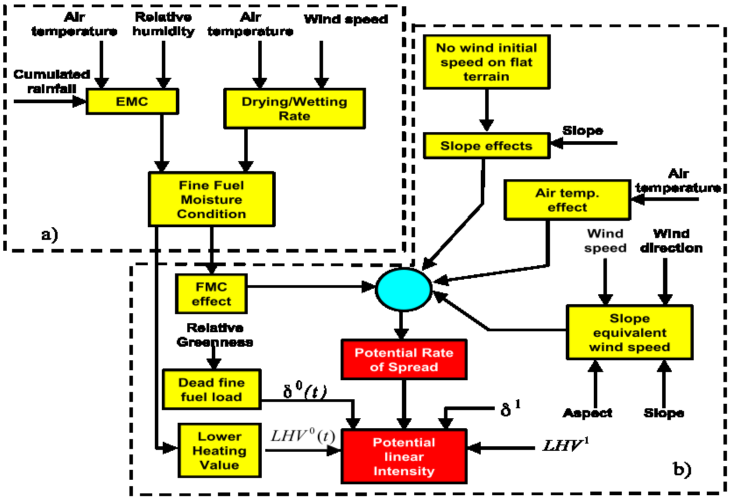

Figure 1. Logical architecture of RISICO system.

All obtained information are intrinsically conditioned by the uncertainty of weather forecasts that can propagate to each run of the daily pattern, thus generating errors in the state of humidity of the fuel that gradually propagate for different time intervals, up to alter the estimate of the areas subject to fire risk. Prediction errors can however be reduced by conditioning the initial state of the dynamic models of humidity of the fuel to information obtained from sensors on the ground, at each time interval at which they become available fields of the meteorological variables of interest obtained from a process of interpolation of ground measurements. Whenever the operational chain has these fields, the RISICO system performs a new run at the time instants in which fields are available, continuously updating the information estimate, and thus making it more reliable.

3. METEOROLOGICAL NETWORK

The stations usable for the purpose of the project belong to the network managed by ARPAS, are located throughout the region (Figure 2), homogeneous by devices and sensors, follow the directions of WMO and are capable of automatic remote transmission.

The individual stations, designed as a data logger (SIAP SM3830) that acquires measures

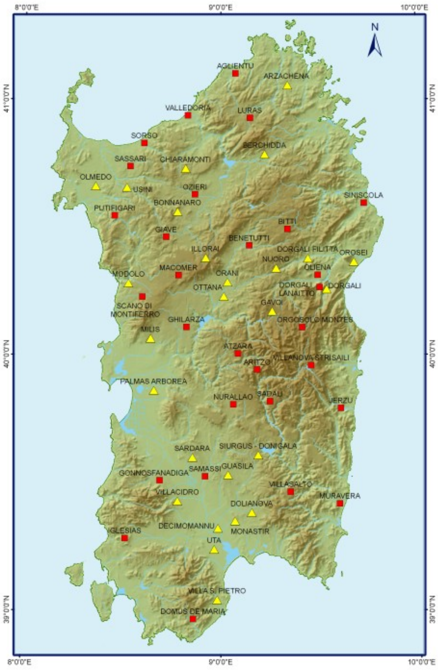

Figure 2. ARPAS weather ground stations; squares and triangles denote, respectively, stations with and without anemometer.

from sensors wired directly to it, are connected by GSM mobile telephone network to front-end at the HydroMeteoClimatic Department, and from this to the back-end for insertion into a client-server database defined in ORACLE. The call of the weather stations is automatic and sequential on time, twice a day, but the interrogation may be carried out in manual mode at any time. The sensors used are of the "intelligent" kind as they have a microcontroller that oversees the acquisition and pre-processing of measured data; each sensor communicates with the data logger via an asynchronous serial line using ASCII messages. The acquired data are stored locally in a circular RAM buffer waiting for the call on the GSM network from the front-end, and stored on removable EPROM memory modules (FMM), which are periodically collected to verify the measures already put in the database and the *"coverage"* of any missing data.

Through the management console, the ARPAS operator is able to program the automatic acquisition of data from the stations, eventually to perform any calls extemporaneous and also send a new remote configuration of operation to the data logger of the stations. The validated information, measured in the set of available stations, are collected at regular intervals from the ARPAS database through automatic procedures, implemented on both SUN and Linux Server, and then typed in files in ASCII format; all procedures were developed and implemented in a Unix environment and mainly in open-source GNU-Linux in order to facilitate the dissemination and reuse.

Data on different variables of interest are taken from the online database through some SQL procedures so that new lists containing the measures of physical quantities for all stations are built in matrix format: the temperature at two meters and the relative humidity at two meters are sampled by instruments every ten minutes and it is determined the hourly median, the wind direction at ten meters and the wind speed at ten meters are sampled and acquired at intervals of ten minutes, the rainfall is measured as accumulated every ten minutes. The data are automatically provided to CIMA to be available for RISICO.

4. PRELIMINARY RESULTS

To the end of evaluating the performances of the regional implementation of RISICO, i.e. his predictive capacity in terms of rate of spread and linear intensity of the wildfire front, and particularly the impact resulting from the integration of the ground measured weather data, we considered the events occurred in the municipalities of Arbus, Bonorva and Nuoro respectively on the 26th August 2011, 23rd July 2009 and 23rd July 2007. The three considered cases, spanning from one of the largest fire occurred during summer 2011 and the highest fire risk scenarios in the last years. Although they are few to have statistical significance, are anyway particularly relevant because of the involved forest areas and the total burned area.

As can be seen from the graphs in Figure 3, the system shows encouraging results with noticeable improvement resulting from the integration of the weather observations than the exclusive introduction of forecasts provided by NWP model. In all the considered case studies, using observation allow to better identify the extreme danger conditions close to the time of ignition. Certainly the results suggest the usefulness of carrying out a broader analysis by considering more cases and a longer period.

5. ACKNOWLEDGMENT

This work has been supported by *"PROTERINA-C"* Project (*A forecast and prevention system for climate change impacts on risk variability for wildlands and urban areas, http://www.proterina-c.eu*) co-funded by the European Regional Development Fund (ERDF) under the Italy-France 2007-2013 Maritime Program.

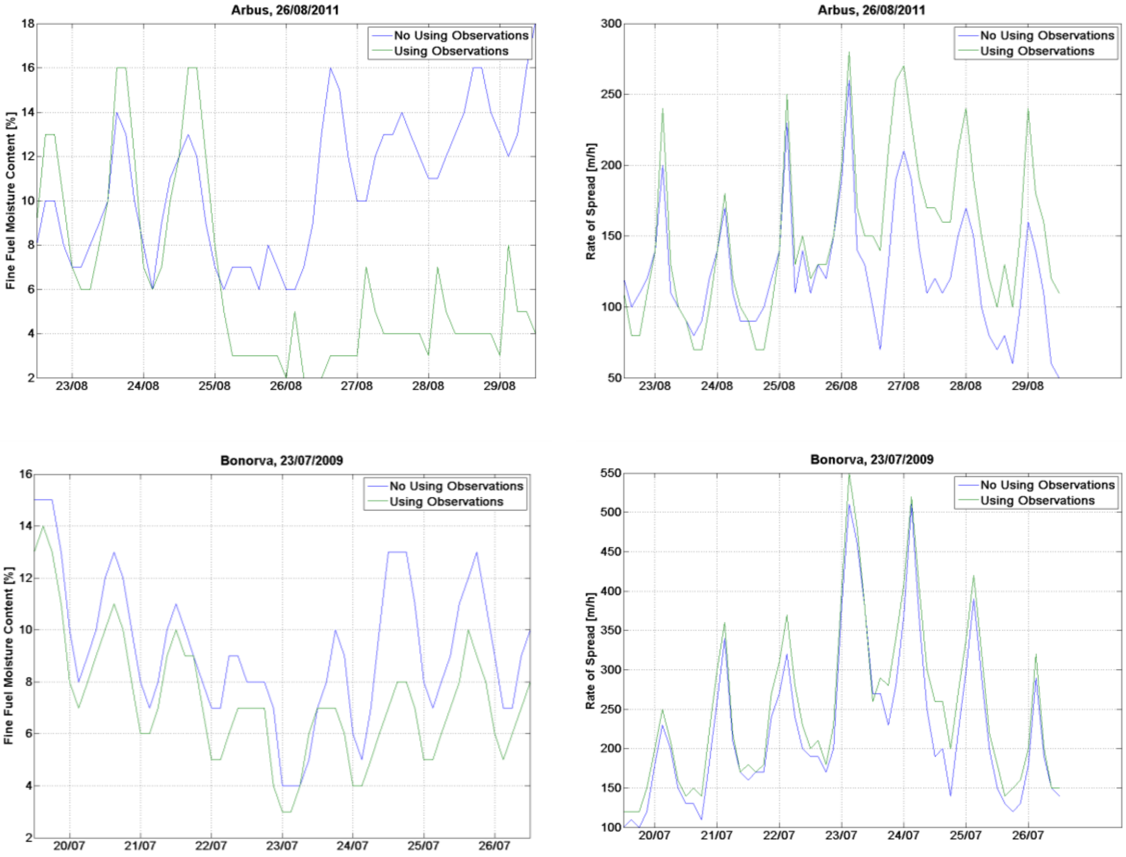

Figure 3. Trend of fine fuel moisture content and rate of spread in the three considered case studies: Arbus (26 August 2011), Bonorva (23 July 2009) and Nuoro (23 July 2007).

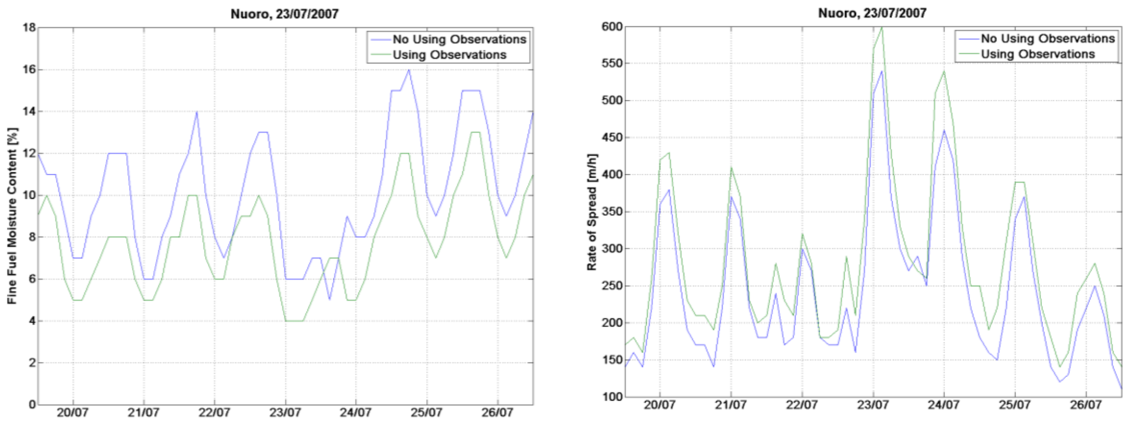

Figure 3. Continued

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Using real time remote sensing data in the RISICO system: the case study of Sardinia region

Cavalli G.[1], D'Andrea M.[2], Fiorucci P.[2], Mannu G.[1], Pinna Nossai R.[1], Capece P.[1], Bianco G.[1], Canu S.[1]

[1]ARPAS - Environmental Protection Agency of Sardinia, HydroMeteoClimatic Department, Sassari, Italy; [2]CIMA Research Foundation - International Centre on Environmental Monitoring, Savona, Italy

gcavalli@arpa.sardegna.it, paolo.fiorucci@cimafoundation.org

Abstract

This study shows how remote sensing data can improve fire danger estimation introducing dynamic information on dead fuel fraction observed by satellite. A dynamic estimation of fire danger was performed using an approach based on the integration of satellite information within a comprehensive fire danger rating system. The performances obtained introducing satellite information in the RISICO system, implemented at very high resolution (100 m) in Sardinia, has been analyzed on the basis of the spring and summer season 2011 considering all the fires occurred during the fire season. A preliminary analysis of the spring season and of the incoming summer season show that the use of satellite data could reduce efficiently the overestimated danger areas, thus improving the fire forecasting rate obtained without using satellite-based maps. Such findings can be directly extended to other similar Mediterranean ecosystems.

Keywords: remote sensing, fire danger rating, Mediterranean ecosystem.

1. INTRODUCTION

Fire danger forecast is one of the main issues to implement fire prevention activities. Using meteorological information, both observed and predicted, it is possible to provide, trough several suitable models, an estimation of the dead fine fuel moisture content and then an estimation of the potential fire rate of spread and linear intensity. However, the dead fuel fraction is not related only with meteorological variables but is subject to species-specific phenological processes. The dynamic of these processes are very slow if compared with the hourly dynamics of fine fuel moisture. Defining models for phenological process simulation needs a long series of data to understand the influence of meteorology on this process. In this study, the use of remote sensing data with the aim to observe dead fuel fraction has been investigated. The capability to observe dead fuel fraction allows to identify when the fire season starts because of the amount of dead fuel reducing overestimation in the low danger season. The performances obtained introducing satellite information in the RISICO system, implemented at very high resolution (100 m) in Sardinia, has been analyzed on the basis of the spring and summer season 2011 considering all the fires occurred during the fire season. Sardinia is highly representative of Mediterranean ecosystems and it is one of the most interesting test cases for wildfire occurrences within the Mediterranean basin. A preliminary analysis of the spring season and of the incoming summer season shows that the use of satellite data could reduce efficiently the overestimated danger areas, thus improving the fire forecasting rate obtained without using satellite-based maps. The feasibility of the use of greenness indexes in order to estimate fire susceptibility has been tested. The satellite Relative Greeness (RG) maps used for this study were obtained from a temporal series of NDVI (Normalized Difference Vegetation Index) produced from MODIS sensor (Moderate Resolution Imaging Spectroradiometer), mounted on board of EOS (Earth Observing System) satellites, Aqua and Terra. Such NDVI and RG data are available at 250 meters resolution. The investigations were performed using the satellite time series data made up of maximum value composite (MVC) of NDVI performed over a 10-day period (decadal). Historical maximum and minimum NDVI maps for the study area were produced on a pixel basis by selecting the highest and lowest values observed from the MVC–NDVI maps recorded over the considered 10-yr period, from 2001 to 2010. These NDVI values were then composed into maximum and minimum maps and used with current 10-day composition NDVI maps to perform the relative greenness calculations. Note that pixels affected by snow, clouds, and residual atmospheric contamination were detected and excluded.

2. DATA AND METHODS

Time series of NDVI (Normalized Difference Vegetation Index) have been used in this study. The NDVI is obtained by two different channels of MODIS with a spatial resolution of 250 m:

$$\mathrm{NDVI} = (\mathrm{NIR} — \mathrm{VIS})/(\mathrm{NIR} + \mathrm{VIS}) \qquad (1)$$

where VIS is Channel 1, visible band (wavelength 620-670 nm), and NIR is Channel 2, Near Infrared Band (wavelength 841-876 nm).

The NDVI is elaborated to obtain 10 days - maximum value composite (MVC). Given a map of max and min value elaborated using a time series of 10 years (2001-2010), provided by E-Geos S.p.A., the Relative Greeness Index has been obtained, as follows:

$$\mathrm{RG} = (\mathrm{ND}_0 - \mathrm{ND}_{\mathrm{min}})/(\mathrm{ND}_{\mathrm{max}} - \mathrm{ND}_{\mathrm{min}}) \qquad (2)$$

where ND_0 is the present value of NDVI, $\mathrm{ND}_{\mathrm{max}}$ and $\mathrm{ND}_{\mathrm{min}}$ are the max and min value of the 10 years time-series NDVI respectively. All the values disturbed by snow, clouds, or other interferences are neglected. RG data are used in the RISICO system to reduce the dead fine fuel load and then to reduce the potential fireline intensity as represented in the picture below.

Only the values between 0 and 1 are considered. Values <1 or >1 represent areas where the NDVI is below the minimum value observed in the last 10 years or above the maximum respectively. The RG map obtained in April (Figure 2, on the left) is characterized by many anomalies (grey pixel). One month later such anomalies disappear (Figure 2, on the right).

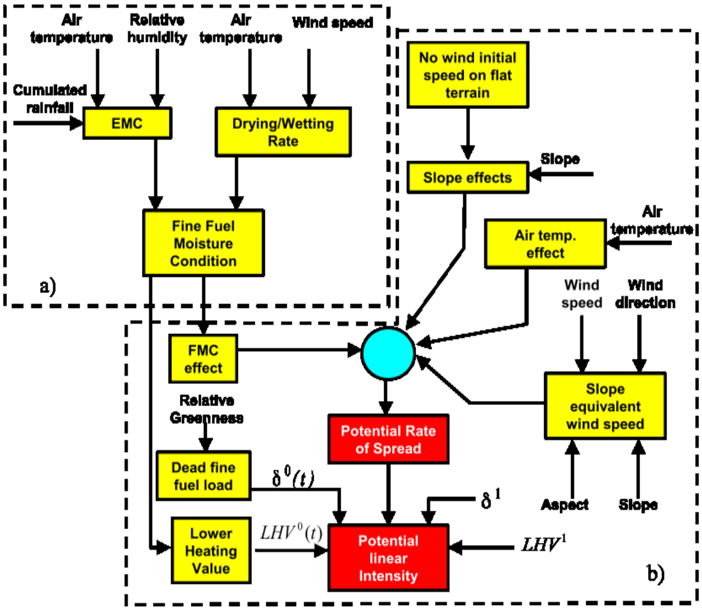

Figure 1. RISICO functional scheme

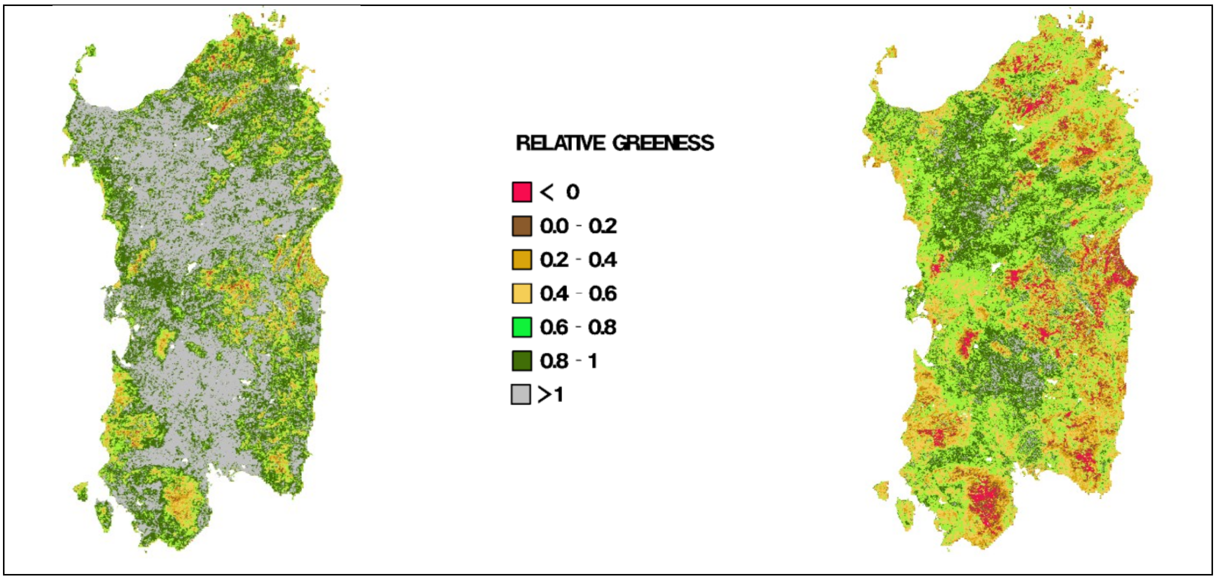

Figure 2. Comparison between April and May 2011 RG map.

The causes are mainly two:

a) the series of 10 years (lifetime of the mission Modis) is too short and not suitable to identify the extreme values of NDVI, especially given that the autumn-winter 2010-2011 was one of the wettest of the last 50 years, and this may have generated a strong vegetative growth in spring to justify many values greater than the maximum of the last 10 years;

b) a comparison was made between processing stations for receiving data generated by the different places and institutions, which could bring forth some procedural differences: it would be appropriate to revisit the analysis with calculations produced by the same receiving station.

Using RG in RISICO (Fiorucci et al. 2008) it is expected to reduce the over estimation of fire risk in that areas where the live fraction of vegetation is higher (Fiorucci et al. 2007). In fact RISICO assumes that at the ground there is always a certain amount of dead fine fuels. The analysis, at this time, is still partial and not complete. Only the early summer season has been considered from April to July 2011. An example of the application of RG is reported in Figure 3. In these maps the comparisons of the potential linear intensity provided by RISICO using (on the right) or not (on the left) the RG are reported for the day 19/06/2011 along with the RG map used as input (in the center). In this case, it is well evident the contribution of RG to the reduction of fire risk.

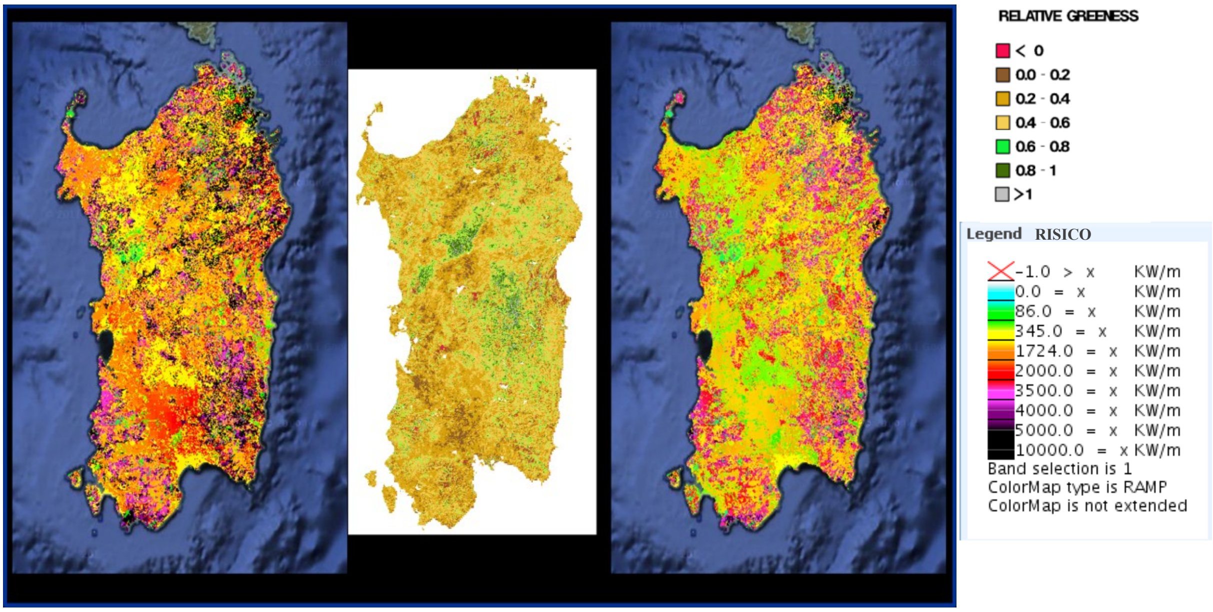

Figure 3. Potential linear intensity provided by RISICO without RG (on the left), RG (center), Potential linear intensity provided by RISICO using RG (on the right) for the 19/06/2011.

3. RESULTS AND VALIDATION

The validation of the approach presented in this poster has been carried out considering two different aspects. The former was that considering the general reduction at regional level of the areas classified by high and extreme risk. In Table 1 the total area is partitioned in 5 classes on the basis of the potential linear intensity I [kW/m] provided by RISICO. Potential linear intensity is dependent on the potential rate of spread and the fuel load. For this reason, the live/dead fraction provided by RG is able to modify significantly the considered variable. The same effect can be observed on the basis of the histogram of the potential linear intensity estimated for all the pixels in which the region is discretized.

From Figure 4 it is well clear as the effect of reduction is more evident in the late spring than in the early summer because of the phenology of the herbaceous vegetation.

In the latter, a specific analysis of the most severe fire occurred during the analysed period in Sardinia has been considered. In particular, the fires occurred during the 13 and 14 July were the most severe. More than 2500 ha were burned in the fire of Oschiri in the north of Sardinia. In the picture below, the municipalities where some fires occurred in this period are reported, over the map of the potential fireline intensity provided by RISICO using or not the RG values. Within the municipalities affected by fires the effect of RG is negligible. The areas characterized by extreme values (i.e, I>3000 [kW/m]) are not modified by the RG. In fact, in this case RG is close to 0.

Table 1.The total area is partitioned in five different classes on the basis on the potential linear intensity I [kW m^{-1}]. For each considered day, the percentage of total area classified in each risk class is reported using (green line) and not (yellow line) RG values. It is well evident the effect of reducing the high and extreme risk area shifting the classification in the lower risk classes.

	Very Low I<86	**Low 86<I<350**	**Medium 350<I<1500**	**High 1500<I<3000**	**Extreme I>3000**
01/04/2011	27%	26%	44%	4%	0%
	9%	35%	45%	11%	0%
17/06/2011	9%	30%	44%	16%	1%
	3%	26%	42%	24%	5%
19/06/2011	4%	23%	43%	22%	9%
	2%	6%	48%	21%	22%
11/07/2011	4%	25%	44%	24%	4%
	3%	14%	50%	21%	13%
22/07/2011	4%	28%	43%	22%	2%
	3%	25%	42%	23%	6%
01/08/2011	6%	31%	47%	16%	0%
	3%	27%	44%	23%	2%

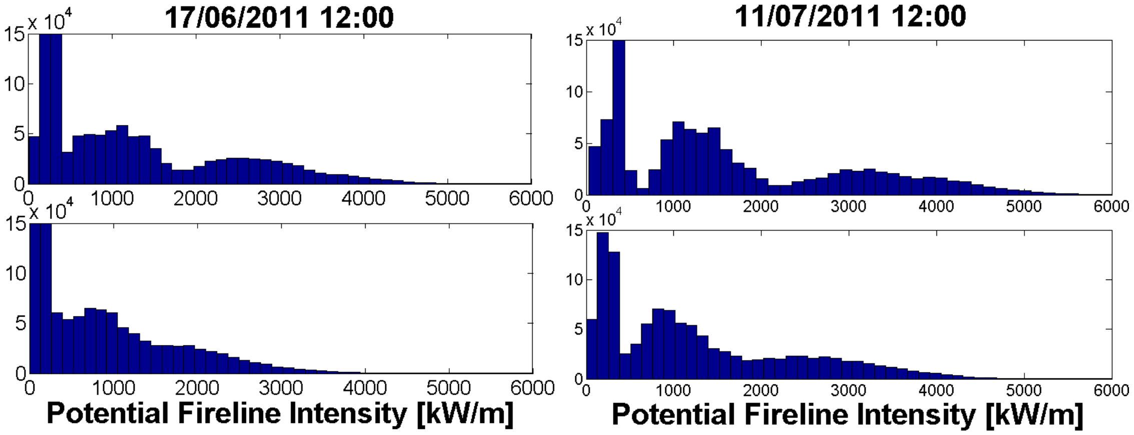

Figure 4. Effect of RG in the evaluation of the potential linear intensity expressed by the histogram of the pixels values provided by RISICO at 12:00 for the 17 June (left) and 11 July (right) respectively.

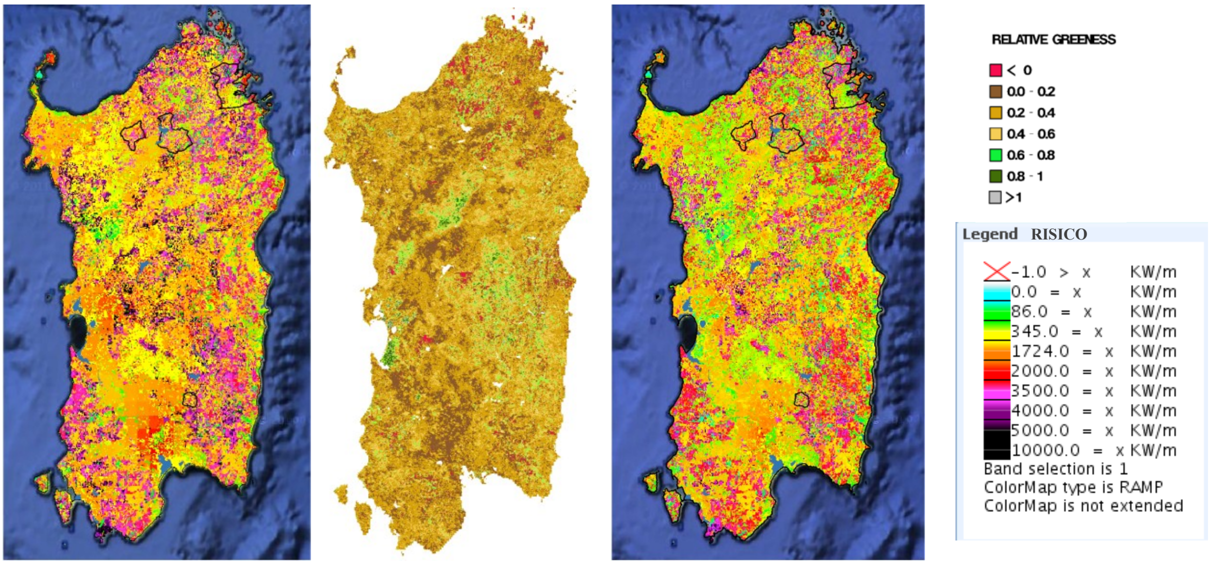

Figure 5. Potential linear intensity provided by RISICO without RG (on the left), RG (center), Potential linear intensity provided by RISICO using RG (on the right) for the 11/07/2011. In black are reported the administrative boundary of the municipalities affected by fires.

4. CONCLUSIONS

Despite the limited observation period (late spring and early summer 2011), presently analyzed using only partial data, and the time series of maximum and minimum values of NDVI needs to be improved, it is well evident the reduction of high fire risk areas at regional level provided by using RG index. In addition, it is evident that the risk reduction is higher in the spring season and it is lower in the summer season, when the dead fraction of vegetation is higher. Then it is possible to assume that RG index improves the sensitivity of RISICO, reducing the overestimation when and where no fires occurred, leaving unchanged the fire risk in the areas damaged by large fires.

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Evaluating fire risk associated with repetitive armed conflicts

Mitri G.[1], Nader M.[1], Van der Molen I.[2], Lovett J.[2]

[1]Institute of the Environment, University of Balamand, Lebanon; University of Balamand - P.O.Box: 100, Tripoli - North Lebanon, Lebanon; [2]Technology and Sustainable Development (TSD) Group, Center for Clean Technology and Environmental Policy (CSTM), University of Twente, The Netherlands

george.mitri@balamand.edu.lb, p.vandermolen@utwente.nl

Abstract

Direct and indirect effects of armed conflicts are often visible on the landscape and are manifested as changes in the environment. Such changes make vegetated areas more susceptible to degradation, which can lead to an increased risk of fires. The aim of this work was to assess fire risk associated with repetitive armed conflicts on the coastal zone in North Lebanon. A number of armed conflict events (dating between 1982 and 2008) which are deemed as hazards to the communities and the environment on the coastal area of North-Lebanon were considered in this study. The methodology of work involved the use of five multi-temporal Landsat (MSS and TM) imageries acquired between 1975 and 2010. The Object-Based Image Analysis (OBIA) approach was employed in this work. The satellite images were segmented and then classified incorporating contextual and semantic information. This involved the use of image object attributes and the relationship between networked image objects of the different Landsat images. The fire risk classes were associated to the degree of negative changes (e.g. forest fires) and positive changes (e.g. vegetation recovery) in the green cover using information from images taken before and after each conflict event. A fire risk map was produced comprising five classes, namely, “No risk”, “Low risk”, “Moderate risk”, “High risk” and “Water”. Data from field surveys showed that the fire risk pattern reflected many of the direct and indirect effects of the repetitive armed conflicts on vegetated areas. There has been a major displacement of populations in areas affected by armed conflicts which contributed to increasing the vulnerability of the surrounding green cover. In addition, agriculture areas suffered from the interruption in the labor supply and the inaccessibility of some farming fields. This increased the risk of fire, especially within areas which sustained the largest amount of landcover/landuse change. Further investigation of the results showed that most high risk areas were mainly located in vegetated areas along the North Lebanon coastline, especially those neighboring agricultural areas and big urban conglomerations and the surrounding villages. Low risk classes were located 1) in areas that are relatively distant from villages and infrastructure, and 2) near villages with low population density.

Keywords: Fire risk, armed conflicts, coastal zone, Landsat, Object-Based Image Analysis

1. INTRODUCTION

The recent history of Lebanon has known repetitive armed conflicts which had significant impacts in terms of mortality and injuries, displacement, insecurity, economic disruption, and damage to the physical environment. More precisely, repetitive armed conflicts may be directly responsible for severe bio-physical modification (UNDP 2006) by causing damage to the environment (e.g. impact on natural resources from quarrying, loss of flora and fauna, and degradation of ecosystems due to fires, among others). The environment may also be indirectly affected by conflict as the result of changes in the way of life of inhabitants and their use of natural resources (Mubareka and Ehrlich 2010).

Forests and other Wooded Land are most often severely affected by fires, which are directly or indirectly (i.e. inaccessibility to land and accumulation of biomass) resulting from armed conflicts. Forest fires create deep changes in the structure and functioning of natural ecosystems (Mitri and Gitas 2008). The Lebanese Ministry of Agriculture (MoA) has estimated a total area of 1,800 ha of forest and other wooded land to have been affected directly or indirectly by fire in the South and Mount Lebanon Governorates during and after the July 2006 war. This value represents about 5 percent of total recorded forest and wooded land in the affected area prior to the war event (UNDP 2006). Direct bombing was found to be the main direct cause for fire initiation in southern Lebanese municipalities, which were directly affected by armed conflicts during the July war in 2006 (AFDC/UNDP/SAAR 2007). Also, induced burnings of forest cover were conducted for military strategic purposes. Further investigations showed that fires burning during an armed conflict period were not easily controlled and suppressed. Indirect causes of fires included accumulation of thick biomass due to inaccessibility to forested areas and lack of maintenance of vegetation cover leading to high severity fires, and consequently, to soil erosion and land degradation (Mitri and El Hajj 2008).

Monitoring and assessing the impact of post-fire effects (forest regeneration and vegetation recovery) in the long term is important to understand fire risk, to establish post-fire resource management, and to design re-vegetation programs (Keely 2000). Producing accurate maps of fire risk associated with armed conflicts remains more of a challenge due to the complexity of factors contributing to fire risk. Direct and indirect effects of armed conflicts are often visible on the landscape and are manifested as changes in the environment. Such changes are supposed to increase the susceptibility of vegetation cover to fire. This can eventually lead to an increased risk of fires (Mitri and El Hajj 2008). Accordingly, monitoring changes in vegetation cover at the landscape level can help in interpreting fire risk.

Since satellite sensors are able to cover wide areas at a high frequency and are also able to provide information about non-visible spectral regions, they represent a very valuable tool for monitoring vegetation cover (Chuvieco 2009). Remote Sensing has proved to be efficient, accurate, objective and operational tool for forest fire management (Mitri and Gitas 2004). More specifically, multi-temporal remote sensing is very suitable for the detection of temporal (fire frequency) and/or spatial patterns (heterogeneity) of fire impact (Mitri and Gitas 2008). The Object-Based Image Analysis (OBIA) represents a valuable tool for analysis multi-temporal satellite images (Mitri and Gitas 2008). The concept here is that the information necessary to interpret an image is not represented in a single pixel, but in image objects. Moreover, object-based classification, which is based on fuzzy logic, allows the integration of a broad spectrum of different object features such as spectral, shape and texture and contextual values, for image analysis.

The aim of this work was to assess forest fire risk associated with repetitive armed conflicts on the coastal zone in North Lebanon. A number of recent armed conflict events which are deemed as hazards to the communities and the environment on the coastal area of North-Lebanon were considered in this study. More precisely, the work focused on three particular conflicts which affected North-Lebanon: the 1982 Israeli invasion, the 2006 Israel-Lebanon war, and the 2007 Nahr El-Bared clashes.

2. STUDY AREA AND DATASET DESCRIPTION

The study area is Lebanon’s Northern coastline which extends over 80 km and constitutes around 37% of the total Lebanese coast (Figure 1). The coastal zone of North Lebanon can be grouped into 6 categories of major land use types (IMAC 2009; ECODIT-IAURIF 1997): 1) agricultural lands 23,838 hectares; 2) natural areas or undisturbed areas 22,881 hectares; 3) urbanized area 8,870 hectares; 4) rural area 1,846 hectares; and 5) wetland areas amounting to 372 hectares. Forested areas (comprising mainly *Quercus calliprinos*) are mainly found on the southern coastline of the North Mohafaza.

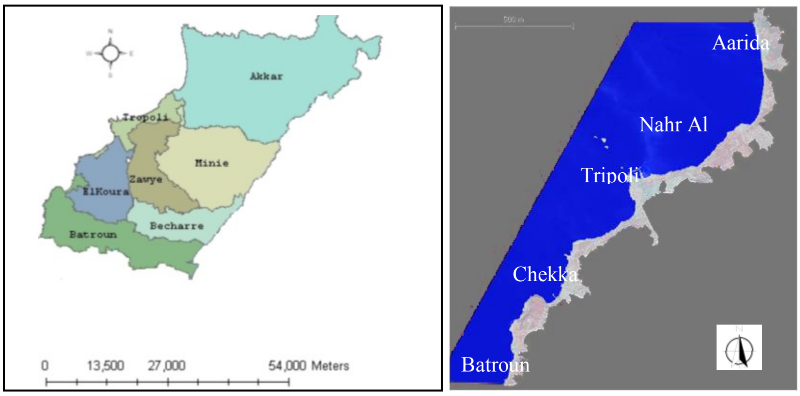

Figure 1. Administrative units (casas) of the Mohafaza of North Lebanon – source: GIS centre University of Balamand (left), and extent of the study area in light grey (right)

North Lebanon has been directly and indirectly affected by repetitive armed conflicts among which the 1982 Israeli invasion and associated conflicts, the 2006 Israel-Lebanon war, and the 2007 Nahr El-Bared clashes. More specifically, North Lebanon was severely affected by the 2007 Nahr El-Bared armed conflict which resulted in direct impacts such as injuries and environmental damages. Other indirect impacts were witnessed by the surrounding areas (ELARD 2008), namely 1) increase of population in surrounding areas which constituted a main destination for immigrants, 2) interruption of labor supply, and 3) inaccessibility to resources of agricultural production, among others.

Landsat Multispectral Scanner (MSS) and Landsat Thematic Mapper (TM) images were acquired for this study. The satellite images included: Landsat MSS (9-9-1975), Landsat MSS (8-10-1984), Landsat TM (5-10-2006), Landsat TM (6-9-2007), and Landsat TM (3-12-2010). In addition, a field survey was conducted in the summer of 2011 for data collection. The survey consisted of one visit to each of the cadastral units along the coastline of the study area (a total of 26 visits). A field protocol was developed for data collection. Accordingly, information about changes in landcover/landuse, their location, their main causes, and time of change were collected. In most of the cases, the questions were addressed to local authorities covering each the involved cadastral units.

3. METHODOLOGY

The methodology of work involved the use of five multi-temporal Landsat (MSS and TM) satellite images acquired between 1975 and 2010. The use of OBIA involved two steps, namely, segmentation and classification of the satellite images. The classification of forest fire risk incorporated contextual and semantic information. This involved the use of image object attributes and the relationship between networked image objects of the different Landsat images. The methodology is detailed below.

3.1. Image segmentation

Segmentation parameters were determined empirically in order to produce highly homogeneous objects in specific resolutions and for specific purposes. A series of segmentations was generated by adjusting the parameters of scale, band weights, color, and shape. The scale parameter here is an abstract term that determines the maximum allowed heterogeneity for the resulting image objects. Next, a six-level graded scale of segmentation was created. Size of image objects varied from small size objects at lowest level to large size objects at highest level. Super-objects at higher levels in the hierarchical network would provide information about the classification of sub-objects at lower levels. This hierarchical network is topologically definite, i.e. the border of a super-object is consistent with the borders of its sub-objects. The area represented by a specific image object is defined by the sum of its sub-objects' areas.

3.2. Classification

Classification was based on fuzzy logic and consisted of a combination of several conditions that had to be fulfilled for an object to be assigned to a class. The fuzzy sets were defined by membership functions that identify those values of a feature that are regarded as typical, less typical, or not typical of a class, i.e. they have a high, low, or zero membership, respectively, of the fuzzy set. The highest level of image segmentation was used for the classification of the initial vegetation cover in 1975 by employing the spectral values of the Landsat MSS (9-9-1975). Then, the lower level comprised 1) mapping vegetation cover of 1984 with the use of Landsat MSS (8-10-1984), and 2) identification of changes in vegetation cover between 1975 and 1984. In subsequent steps, classification of vegetation cover of 2006, 2007 and 2010 were conducted at the lower levels using Landsat TM (5-10-2006), Landsat TM (6-9-2007), and Landsat TM (3-12-2010), respectively. Also, changes in vegetation cover between consecutive years were mapped.

Then, fire risk map was produced at the lowest level (small size objects). The classification scheme comprised five classes, namely, "No risk", "Low risk", "Moderate risk", "High risk" and "Water". Field visits to 21 cadastral unit showed that at least 70% of cadastral units within the study area had their vegetation cover directly or indirectly affected by at least one armed conflict event between 1975 and 2010. Accordingly, the fire risk classes were associated to the negative type of changes, namely burned areas, and positive type changes, namely vegetation recovery, throughout the entire period of repetitive armed conflicts. Information about changes in the vegetation cover was extracted from the previously described classifications at the higher levels. Consequently, the class "high risk" of fire consisted of vegetated objects that have been 1) burned at least once since 1975 and have recovered their vegetation cover, and/or 2) affected by at least one type of change in vegetation cover. The class "low risk" of fire consisted of objects where 1) vegetation has not burned at any time since 1975 and 2) there is not any direct contact with objects classified as "high risk". The class 'no risk" consisted of objects 1) converted from seawater to land, 2) transformed to non-vegetated land by 2010, or 3) classified as non-vegetated land since 1975. Finally, the class "moderate risk" of fire consisted of objects which did not satisfy any of the above conditions.

4. CLASSIFICATION RESULTS AND DISCUSSION

The assessment of the classification results (Figure 2) showed that most sites of high risk were mainly located in vegetated areas along the North Lebanon coastline, especially those in proximity to agricultural areas and urban conglomerations directly affected by armed conflicts such as the municipalities of Tripoli and the surrounding villages. Low risk classes were located in areas that are relatively distant from conflict centers. Also, it was observed that fire risk pattern reflected many of the direct and indirect effects of the repetitive armed conflicts on vegetated areas. In 1982–1983 societies in Tripoli and the surrounding areas were gravely disrupted by the civil war and there has been major displacement of populations in the region which possibly contributed to increasing the vulnerability of the green cover neighboring dense urban conglomerations. In 2006-2007 agriculture areas suffered from the interruption in the labor supply and the inaccessibility of some farming fields because of two other armed conflicts, namely the July war and the war in the Palestinian camp of Naher El Bared. This increased the risk of fire within cadastral units which sustained the largest amount of landcover/landuse change.

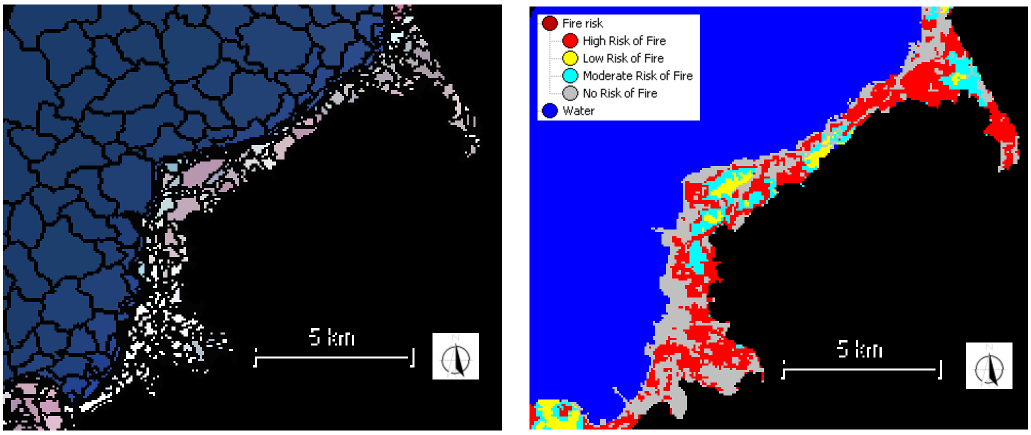

Figure 2. Segmented image subset (left) and corresponding fire risk map (right)

5. CONCLUSIONS

This work focused on identifying fire risk associated with repetitive armed conflicts using multi-temporal satellite images. Object-Based Image Analysis proved to be a successful approach in mapping changes in vegetation cover, and therefore fire risk, with the use of multi-temporal Landsat images. The results allowed the identification of fire risk which reflected many of the direct and indirect effects of repetitive armed conflicts on vegetated areas. Although the mapped fire risk classes are not only attributable to armed conflicts alone, but also to other factors such accidental or intentional human activities, this work can be considered as informative for conducting more advanced studies (e.g. risk of land degradation) to assess the impact of armed conflicts on the environment.

6. ACKNOWLEDGEMENTS

The authors wish to express their appreciation to the Netherlands Organization for Scientific Research and the WOTRO Science for Global Development for providing financial assistance to pursue the current work.

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FIRES AND WILDLAND URBAN INTERFACES

Residential Fire Destruction during Wildfires: a home ignition problem

Cohen J.D.

US Forest Service, Fire Sciences Laboratory, 5775 W Highway 10, Missoula, Montana, USA 59808

jcohen@fs.fed.us

Abstract

Wildfires are inevitable and thus wildfires burning during extreme conditions are inevitable. In the United States, 2-5 percent of wildfires overwhelms firefighters and escapes control to become large. These wildfires occur during extreme burning conditions. Wildland-urban interface (WUI) fires resulting in hundreds of destroyed homes occur during these large, intensely burning wildfires. This suggests WUI fire disasters are also inevitable. However, research reveals opportunities for preventing WUI home destruction by focusing on home ignition rather than wildfire control. Results from modeling, experiments and actual disaster examinations indicate a home's exterior materials, design and maintenance in relation to its immediate surroundings principally determine home ignition potential. I call this area of the house and its immediate surroundings the *home ignition zone* (HIZ). Reducing home ignition potential within a community's HIZs provides the opportunity to prevent WUI fire disasters without necessarily controlling wildfires. And controlling wildfires is not an option for some wildfires during extreme burning conditions.

Keywords: wildland-urban interface (WUI), home ignition zone (HIZ), home ignition, wildfire

1. WILDLAND-URBAN INTERFACE FIRE DISASTERS

Home destruction during wildfires has come to be known as the wildland-urban interface (WUI) fire problem (or a similar variation). The problem of wildfire threatening residential development has become an emergency response issue common to fire agencies worldwide. In the following discussion, I use the United States experience to describe how WUI disasters occur and how homes ignite during wildfires with implications for how we might prevent WUI fire disasters.

Preventing WUI fire destruction is typically approached with wildfire control rather than wildfire compatibility. That is, we tend to tactically react to wildfire threatening a community rather than strategically reduce community vulnerability to wildfire. It is commonly assumed there is an unbreakable link between wildfires and WUI residential fire disasters unless wildfires are controlled before spreading to communities. This assumption certainly supports the current fire control approach with its recent increasing firefighting resources. However, our fixation on wildfire control fails to consider the apparent inevitability of wildfire occurrence and that WUI fire disasters depend on homes igniting during wildfires. Certainly extreme wildfires initiate ignitions within residential areas, but if homes do not ignite and burn during wildfires, then the WUI fire problem largely does not exist.

Widespread WUI home destruction during wildfires does not occur when normal wildfire control and structure protection capabilities limit the fire spread. Wildland fire suppression operations successfully control 97-99% of all wildfires with the initial response (Stephens and Ruth 2005), and firefighters typically limit a fire to a single structure or prevent the fire from spreading beyond that structure. However, big flames and extensive showers of burning embers (firebrands) resulting from high intensity fires over broad areas (i.e., extreme wildfire conditions) is not a typical situation. When residential development is exposed to extreme wildfire conditions, numerous houses can ignite and burn simultaneously, overwhelming firefighters and reducing fire protection effectiveness. WUI fire disasters principally occur during these extreme wildfire conditions that account for the one to three percent of wildfires that escape control (Menakis et al. 2003). Table 1 lists U.S. WUI fire disasters between 1990 and 2011. Every one of these disasters occurred because extreme wildfire conditions overwhelmed firefighters attempting wildfire control and firefighters attempting structure protection.

Year	*Incident*	*Location*	*Homes destroyed (approx.)*
1990	Painted Cave	Santa Barbara, CA	479
1991	Spokane "Firestorm"	Spokane, WA	108
	Tunnel/Oakland	Oakland, CA	2900
1993	Laguna Hills Old Topanga	Laguna and Malibu, CA	634
1996	Millers Reach	Big Lake, AK	344
1998	Florida Fires	Flagler and Volusia counties, FL	300
2000	Cerro Grande	Los Alamos, NM	235
2002	Hayman	Lake George, CO	132
	Rodeo-Chediski	Heber-Overgaard, AZ	426
2003	Aspen	Summerhaven, AZ	340
	Old, Cedar, etc.	Southern CA	3640
2006	Texas-Oklahoma Fires	Texas and Oklahoma	723
2007	Angora	Lake Tahoe, CA	245
	Witch, Slide, Grass Valley, etc.	Southern CA	2180
2010	Fourmile Canyon	Boulder County, CO	168
2011	Texas Fires	Central and East Texas	3017

Table 1. U.S. wildland-urban interface fire disasters for 1990 to 2011. Extreme fire behavior occurred during all these disasters.

The WUI fire disaster context can be generally described as a sequence of contingencies (Figure 1). The disaster sequence starts when a wildfire or multiple wildfires burn during severe fire conditions. The extreme combination of vegetation, weather, and topographic conditions produces fast-spreading, intensely burning fires that overwhelm wildfire suppression efforts. If extreme wildfire spreads close enough to residential development with its flames and firebrands, hundreds of ignitable homes can be simultaneously exposed. Although protection may be effective for some homes, an extreme wildfire's high intensities and rapid spread combine to produce broad residential fire exposures that potentially ignite many houses and jeopardize firefighter safety. This typically limits fire protection to a small fraction (< 0.1) of all exposed structures. With homeowners likely evacuated and firefighters unable to protect every house, small, easy-to-extinguish sustained ignitions can result in total home destruction (Figure 2). The total destruction seen in Figure 2 is not indicative of high intensity fire exposure but rather the unimpeded burning to virtually complete consumption of flammable home materials.

Notice in Figure 1 that the sequence leading to a WUI fire disaster depends on homes burning (Residential Fires). If homes are sufficiently ignition resistant such that many homes do not simultaneously burn, then fire protection remains effective. Thus, for a residential development having high ignition resistance, the disaster sequence is broken; the residential fire disaster depends on the ignitability of the homes not wildfire control. If homes do not ignite, homes do not burn; if homes do not burn, a WUI fire disaster does not occur. This defines the WUI fire problem in terms of home ignition potential but is sufficient ignition resistance a practical approach for preventing WUI fire disasters? To answer that we must examine how home ignitions can occur related to extreme fire behavior conditions.

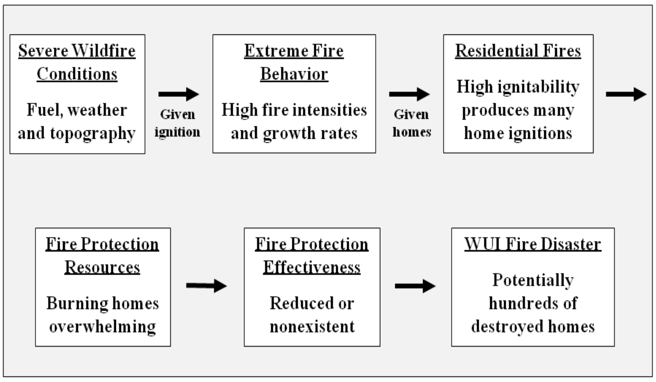

Figure 1. The WUI fire disaster is characterized by a sequence of conditions. If homes do not ignite the disaster sequence is broken; WUI fire disasters do not occur.

2. HOME IGNITION: A LOCAL PROCESS

Ignition and fire spread, whether on structures or in wildland vegetation is a combustion process. Fire spreads as a continuing ignition process whether directly associated with flames or spot ignitions from firebrands with subsequent fire spread. Fire does not spread like a mass rolling over objects in its path such as an avalanche or a flash flood. Fire spreads because the requirements for combustion have been met – a sufficiency of fuel, heat and oxygen. Post-wildfire burn patterns reveal the requirements for combustion are met or not over relatively short distances even for intense active crown fires. One can commonly observe unburned patches of forest vegetation within 30 meters of areas burned as intense crown fire.

Figure 2. Unconsumed vegetation surrounding destroyed homes indicates ignitions from lower intensity surfaces fires and/or firebrands directly igniting homes. These homes were among hundreds of homes simultaneously exposed to ignition and unable to be protected. The wood construction burned to total consumption.

The requirements for combustion apply equally to homes during extreme WUI fires. In the context of WUI fire, the home becomes the fuel that ignites. All the burning objects surrounding a home (the fuel) contribute the heat. During extreme WUI fires the requirements for combustion can be met, resulting in home (fuel) ignitions in two principal ways: 1) direct heating of flames—radiation and convection (flame contact), and 2) firebrands collecting on flammable house surfaces (burning ember spot ignitions) (Cohen and Wilson 1995; Cohen 2000a). Oxygen is always sufficient for WUI home ignitions. Importantly, wildfire cannot spread to homes unless homes meet the requirements for combustion. This suggests that WUI fire disasters can be prevented by keeping homes from meeting combustion/ignition requirements.

Research indicates that WUI fire destruction occurs principally due to conditions local to destroyed homes. Computational modeling and laboratory and field experiments describing the heat transfer required for ignition have shown that the large flames of intensely burning shrubs and tree canopies (crown fires) must be within 30 meters to ignite a home's wood exterior (Cohen 1995; Cohen and Wilson 1995; Cohen and Butler 1998; Cohen 2000a; Cohen 2004). Actual case examinations find that extreme wildfire behavior does not occur within most residential areas (Cohen 2000b; Cohen and Stratton 2003; Cohen and Stratton 2008). Unconsumed vegetation surrounding most destroyed homes and generally throughout burned residential areas (Figure 3) indicate home ignitions occur from lower intensity surface fires spreading to contact a home and from firebrands collecting on and contacting the flammable surfaces of a house.

Figure 3. Typical WUI destruction. Home ignitions occur from fires spreading within the residential area and directly from firebrands. Homes commonly ignite and burn after the wildfire spreads past. (left to right: Los Alamos, NM 2000; Heber, AZ 2002; Lake Arrowhead, CA 2007)

Computations, experiments, and WUI fire disaster examinations show that a home's ignition potential during extreme wildfire is principally determined by the characteristics of a home's exterior materials, design, and associated flammable debris related to surrounding burning objects within 30 meters and firebrands (lofted burning embers).

I call this area—a home and its immediate surroundings—*the home ignition zone* (HIZ). Thus, given an extreme wildfire, the HIZ principally determines the potential for home ignition and reveals an effective approach for preventing WUI fire disasters without necessity of wildfire control.

3. IMPLICATIONS FOR PREVENTING WUI FIRE DISASTERS

The inevitability of wildfires is axiomatic, including the extreme wildfires that account for the one to three percent of fires that escape control in the U.S. (Stephens and Ruth 2005). Importantly, WUI fire disasters occur during this one to three percent of uncontrollable wildfires. This might suggest the inevitability of WUI fire disasters; however, research shows it is the condition of the HIZ that principally determines the potential for WUI fire disasters during extreme WUI fire conditions. This indicates an alternative for preventing disastrous home destruction without the necessity of controlling wildfires. Addressing conditions within the HIZ can significantly reduce the home ignition potential. Thus, given ignition-resistant homes, extreme wildfires can spread near residential areas without incurring WUI fire disasters. However, WUI ignition resistance has not been the primary approach used by most fire agencies in the U.S. or elsewhere to prevent disastrous WUI fire destruction. Although the HIZ approach for preventing WUI fire disasters has been adopted by the U.S. Firewise program (*www.firewise.org*), a focus on wildfire suppression and pre-suppression fuel treatments outside the home ignition zone remains the principal approach. The traditional wildfire exclusion and control approach with elevated levels of fire suppression capability has failed to prevent repeated WUI fire disasters. The continued focus on fire suppression largely to the exclusion of alternatives that address home ignition potential suggests a persistent inappropriate framing of the WUI fire problem in terms of wildfire exclusion and control.

Preventing WUI fire disasters requires that the problem be framed in terms of home ignition potential. Because this principally involves the HIZ, and the HIZ primarily falls within private ownership, the responsibility for preventing home ignitions largely falls within the authority of the property owner. If we are to prevent extensive home destruction within the WUI, property owners must become engaged, matching their authority over the HIZ with the responsibility to create ignition resistant homes. Fire agencies must recognize their wildfire control limitations and the effective alternative of reducing home ignition potential within the HIZ. Fire agencies can facilitate the prevention of WUI fire disasters by educating and advising homeowners on the necessity of and actions for reducing the ignition vulnerability of their homes.

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Improving educational aspects as a way to prevent fire risk in fire prone communities. Cases of study in Spain

Quesada C., Quesada D.

University of Córdoba, Spain

claraquesada@gmail.com, danquefer@yahoo.es

Abstract

Communities and fire is not a new combination nowadays. Use of fire by humans has been considered and used in *daily tasks* over the centuries in economic, cultural, religious and other aspects of life especially in rural areas. This situation has been known as *fire culture* and it has not been a conflictive relation between people and natural spaces. But the rapid and disordered development of structures into fire prone areas has produced residents and owners less implicated in fire aspects, like for example an urban conception of rural zones. They actually are seeing these aspects as not related to fires and other risks, and they do not realize properly where they live and how they live. At the same time, rural communities have decreased their population due to migration processes into towns and to aging. Finally, the majority of this rural and wildland urban interface (WUI) zones present unusual characteristics in responding to fire agencies. Many state, regional and local agencies have tried many options to prevent and control this problem, but they have realized that this not enough to hold this situation, whose frequency is increasing every year. Foresters, State Agencies, Fire Departments and civic leaders have reached the conclusion that residents should not be considered as part of the problem but part of the solution. Through educational activities, it is possible to conduct them to further their knowledge on how to reduce fire risk, adopting special but cheap and easy measures. Nonetheless, the homeowners involvement is a difficult issue that requires special understanding and approaches. Human behaviour is an aspect impossible to be simulated and so unpredictable in emergency cases such as those in wildland urban interface that could dangerously increase the value of risk in fire prone zones. The situation in Spain presents many fire prone areas as well as other Mediterranean zones. In that sense, in the last years some regions have been following programs to show the population the proactive steps in reducing home vulnerability to wildfire; i.e., what every resident of rural-wildland urban interface areas at risk should know to protect their properties, their lives from wildfire and realizing that their activities contribute to a firefighting safer job as well. This paper explores some examples of the actual situation in Andalusia, Balearic Islands, Galician Region and many others, analysing the main findings and what could be future recommendations.

Keywords: educational aspects, fire emergency, educational aspects, emergency evacuation, emergency preparedness, fire safety education

1. INTRODUCTION

Communities and fire is not a new combination nowadays. Fire has been considered and used in *daily tasks* over the centuries in economic, cultural, religious and many other aspects of life, especially in rural areas. The so-called *fire culture* has not been a conflictive relation between people and natural spaces.

The rapid and disordered development of structures into fire prone areas (Figure 1) has produced residents and owners less implicated in fire aspects, like for example an urban conception of rural zones. At the same time, rural communities have decreased their population due to migration processes into towns and to aging.

Although most of the forest fires have an anthropogenic origin, few research lines have been opened in order to deep into the knowledge of socio-economic and cultural factors leading to the origin of these fires. Wildland/rural/urban interface fire is a devastating and growing problem in communities all around the world.

Figure 1. Disordered development of structures into fire prone areas in Andalusian Region, Spain (left). The real situation of forest fuels accumulation into a fire prone community (right). Source: *Quesada C, 2008 and 2011.*

2. OVERVIEW IN SPAIN

In 1985, Central Government of Spain transferred State powers and responsibilities to regional Governments. Forest and environmental issues changed to territorial authorities but Central Government retains certain existing competences as international cooperation and regional collaboration.

The desertion of rural areas produced an abandonment of land, which is later overruned by spontaneous vegetation that remains highly combustible for many years. The population shortage also represents now a decrease in labor in the field of forest management in general, and particularly, in protection against fires.

A new problem which becomes more evident with each coming summer is the risk of fire in the urban/forest interface ought the creation an increasing concern as communities grow into forest, coast, and mountain areas with primary and secondary homes with large city influences. Owners and residents actually are seeing these areas not related to fires and other risks, and they do not realize properly where they live and how they live. The majority of this rural and wildland urban interface zones present unusual characteristics to responding fire agencies (Figure 2).

In many cases, the concentration of property requiring protection in urban areas, along with the development of firefighting services in these areas, has produced the transference of fire suppression responsibilities to those services, disassociating them from forest activities. Accidents resulting in the destruction of homes and the loss of human lives have become more frequent. Firefighting services find themselves forced to concentrate their efforts on the protection of housing, leaving forest areas unprotected. Wildland fire protection issues in the interface are extraordinarily complicated (Figure 2a). Finally, preventive legislature for this problem does not exist in majority of cases or is clearly insufficient so that this problem might reach catastrophic gravity.

Figure 2. Example of an uncontrolled building zone with not safety zones or escape routes in Ibiza Island in Balearic Island (left). Bad use of fire in a sort of back fire by rural population (right). Source: *Quesada 2007 (left) and Quesada 2005 (right).*

Figure 3. Bad maintenance of property structure's borders and accumulation of many types of fuels. Source: *Quesada 2011.*

Many state, regional and local agencies have tried many options to prevent and control this problem, but they have realized that this not enough to hold this situation, whose frequency is increasing every year.

How to accomplish better preparedness by WUI residents has been studied from a number of approaches (Absher and Kyle 2008). The occurrence of a natural disaster increases the public's perceived risk of such an event (Mueller et al. 2008). Through educational activities, it is possible to conduct them to further their knowledge on how to reduce fire risk, adopting special but cheap and easy measures. New problems at the urban/forest interface may urge society to demand more attention into prevention projects, with effective actions rather than rhetorical declarations.

Foresters, State Agencies, Fire Departments and civic leaders have reached the conclusion that residents should not be anymore part of the problem but part of the solution. But involving homeowners is a difficult issue that requires special understanding and approaches. Human behaviour is an aspect impossible to be simulated and so unpredictable in emergency cases such as those in wildland urban interface that it could dangerously increase the value of risk in fire prone zones. The real challenge is to plan in the absence of a motivating catastrophe (Bailey 2008), i.e, planning in advance.

The Spanish situation presents many fire prone areas as well as other Mediterranean zones. In particular, we can define two zones, the north-northern (Atlantic) and the south-southeast (Mediterranean). In the Atlantic areas (Galicia, Cantabria, Asturias, Castilla-León), the main causes of the fires resulted from the use of fire to eliminate forest vegetation and its subsequent replacement by agricultural crops (grass burning and crops burning). On the other hand, the causes in Mediterranean regions are related to disordered development and population pressure (Andalusia, Comunitat Valenciana, Catalonia, Balearic Islands).

In the last decades, Central and Regional Administrations have been following programs to show population to learn reducing fire risk (Vélez 2002), with the main objective of disseminate information and raise awareness on environmental issues, such as forest fire prevention, providing support for communication actions and campaigns.

In northern regions, more rural than others, the Ministry of Environment has worked together with rural communities to develop a model of community based fire management training in controlled burning (Vélez 2007) with the help of specialized teams (EPRIF) that are organized in the areas where the number of fires is higher. In southern regions, the recently FP6 co-funded Interreg European project Pyrosudoe has implemented the case of study based on fire culture and fire risk in wildland urban interface zones through regional and local entities collaboration. The Pyrosudoe pilot project sites were Andalusian Region, in provinces of Córdoba (local level), Málaga and Granada, all territories into Balearic Islands and province of Aragón Region, province of Teruel (Figure 4). The case of Córdoba municipality with 125,356 hectares, 21% of them (26,741hectares) into forest land territories is very interesting in particular for the high numbers of illegal constructions occupying territory and the wide area they are covering (Figure 5).

The special case of Andalusian Region sites highlights the problems and the constant threats to fire prone areas from disordered development of structures, urban and building chaos on wildland urban interface zones and the establishment of illegal settlements on historical fire prone areas. One of the main assumptions focused on information dissemination to population living in fire prone communities of the eight provinces, i.e., what every resident of rural-wildland urban interface areas at risk should know to protect their properties, their lives from wildfire realizing at the same time that their activities contribute to a firefighting safer job as well.

3. CONCLUSIONS

Fire suppression alone is not reducing the number and size of fires so that information and environmental and educational aspects must be improved for it. In Spain, accordingly with the state of the art, the “pre fire” actions should be more taken into account than the “post fire” status ones.

There is a need to publicly acknowledge the role of fire in preventive silviculture as a way to incorporate it in future forest policies better adapted to the present socio-economic situation in the Mediterranean Basin.

Foresters, State Agencies, Fire Departments and civic leaders have reached the conclusion that residents should not be anymore part of the problem but part of the solution. So now is definitively time to owners and residents recognize themselves as part of the solution.

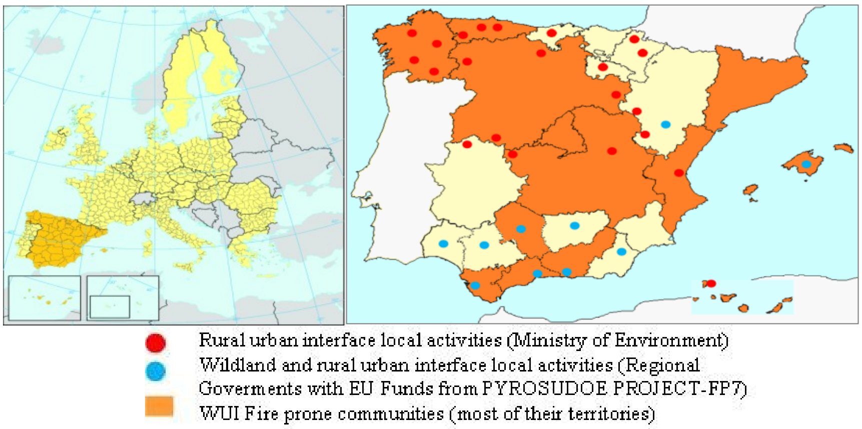

Figure 4. Examples of information programs to population in fire prone areas in Spain. Source: Quesada D., 2011 and 2012.

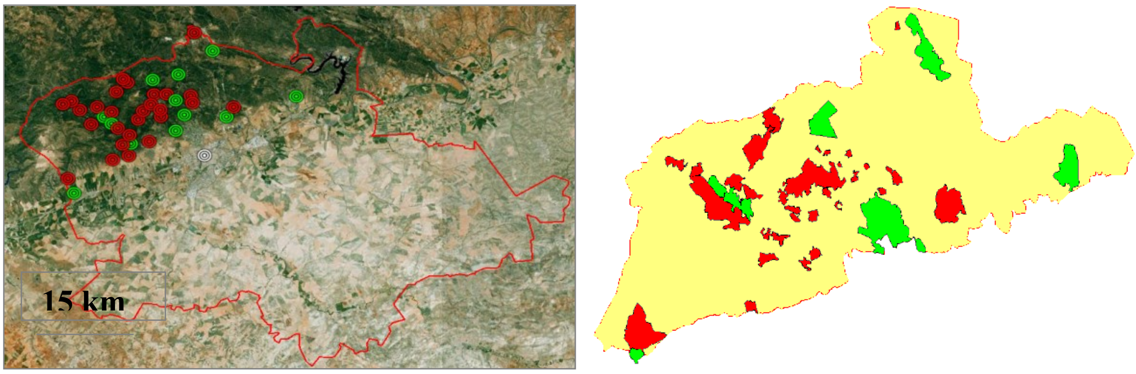

Figure 5. Example of settlements on fire prone areas in Córdoba province, legal or considered equivalent (green) and illegal (red). Detail of extension of settlement structures in forest territories on the northern part of the municipality. Source: *Quesada, D., 2010.*

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Enhancing forest fires preparedness in Portugal: the relevance of integrating risk communication with community engagement and development

Paton D.[1]**, Tedim F.**[2]

[1]*School of Psychology, University of Tasmania, Launceston, Tasmania, Australia;* [2]*Faculty of Arts, University of Porto, Via Panorâmica s/nº, 4150-564- Porto, Portugal*

Douglas.Paton@utas.edu.au

Abstract

The growing incidence, size, intensity and duration of forest fires and escalating economic constraints has made reliance on fire suppression activities as the main fire management strategies in Portugal less tenable. Recognition of this led fire and municipal civil protection agencies to include community preparedness in comprehensive risk management planning. Because this is a new element of risk management in Portugal, agencies need information on cost effective approaches to facilitate community preparedness. Using data from a study of forest fire preparedness in Portugal, this chapter discusses the development and testing of a model of forest fire preparedness. Data from 197 residents from several communities in northern Portugal were used to test the model. Analysis confirmed that people's beliefs about the effectiveness of preparing (outcome effectiveness) interacted with social processes and competencies (community participation, collective efficacy) to explain differences in levels of forest fire preparedness. Because the social processes and competencies identified derived from people's life and community experiences, the findings highlight the importance of integrating risk communication with community engagement and development strategies if the goal of increasing preparedness is to be effectively pursued. Activities fire and municipal agencies can use to facilitate preparedness are discussed, as is the potential for using the model in Europe and Australia.

Keywords: Forest fire preparedness, risk communication, community engagement

1. INTRODUCTION

Forest fire incidence is very high in Portugal where, in 2010, were recorded half the fires and burnt area of all southern European countries (JRC 2011). Fire represents significant ecological, social and economic threats to many communities in Portugal. The traditional approach to managing forest fires focuses on suppression with a minor emphasis in mitigation (e.g., controlled burning). However, reliance on these strategies is becoming less tenable as a result of the growing number, intensity and duration of fires exceeding available fire fighting resources and economic pressures reducing fire fighting resources. This has led to recognition of a need for communities and fire agencies to work collectively to manage shared risk. If people prepare and develop strategies to defend their properties, fire agency resources can focus more on suppression activities and suppression is easier if fire fighters do have to defend homes. This can be done by increasing community involvement in planning and facilitating community preparedness in ways that increase people's capacity to prevent and respond to fire events.

People can prepare by, for example, creating a defensible space around their property, using fire-resistant materials for renovation or building, safeguarding their house (e.g., ensuring roof tiles fit tightly to prevent embers entering through the roof, screening vents and eves with metal fly wire to prevent ember entry, and fitting shutters or metal screens to windows). Preparing reduces the risk of injury and death, facilitates people's capacity to cope with disruption, and helps them adapt to and recover from fire impacts. Well prepared people and homes also increase the likelihood of people being available to assist recovery efforts in their community, facilitate the maintenance of the social networks that assist social recover, and helps sustain the economic vitality of areas adversely affected by fire. Encouraging preparedness thus plays a significant role in risk management. The question is how to accomplish this task. The challenge of doing so is complicated by the fact that the move to including a community or social dimension introduces a significant point of departure in forest fire risk management planning in Portugal (Paton and Tedim 2012).

To facilitate preparedness, agencies need to know how to develop the community resource. This chapter discusses research into identifying community predictors of preparedness. In so doing it provides agencies with guidelines for developing community preparedness within a risk management strategy designed to facilitate greater community involvement in local forest fire risk management. It discusses the development and testing of a model that identifies the predictors of forest fire preparedness in communities.

2. PREDICTING COMMUNITY PREPAREDNESS

The model is founded on recognition that peoples' perception of risk and how they might mitigate it is socially constructed (Paton and Bishop 1996; Earle 2004). This suggests that the ability of community members to interpret forest fire and prepare to manage their risk will be a function of the degree to which they possess the processes and competencies that help them to interpret their circumstances and take action to deal with novel issues facing the community. Processes and competencies that are relevant here are the degree of connectedness within a community that underpins the sense of social responsibility for managing risk, being actively engaged with others in ways that facilitates developing risk beliefs and discussing how to manage risk, and having experience of taking action to deal with issues that represent collective problems for a community. The model identified community participation and collective efficacy as variables that would capture these processes and competencies (Eng and Parker 1994; Zaccaro et al. 1995). These processes and competencies develop as a result of experiences community members accumulate over time. Once developed, they provide the foundation for how people, for example, determine what consequences they could face, work out what would be an effective response, and then consider what information and resources they require to enact their risk management strategies.

The theory introduced a need to examine whether people believe or *expect* that preparedness will lead to the *outcome* of increasing safety or preventing or reducing loss and damage (Paton 2008). The 'outcome expectancy' construct describes this interpretive process. Negative outcome expectancy reflects a belief that forest fire consequences are too catastrophic for personal action to make any difference to peoples' safety. If people hold this belief, they are less likely to prepare. In contrast, if people hold positive outcome expectancy beliefs, they believe that a measure will increase personal safety and protect the home. If people hold positive outcome expectancy beliefs, preparation will be mediated by the social processes (collective efficacy, community participation) used to articulate community members needs and expectations. This chapter discusses the findings of a study applying this theory to forest fire preparedness in Portugal.

3. TESTING THE MODEL

Data were collected from communities in northern Portugal that experience a high frequency of forest fires. The Municipalities in which the questionnaires were distributed were: Arcos de Valdevez, Baião, Cinfães, Melgaço, Mirandela, Montalegre, Ponte da Barca, Terras de Bouro, and Vieira do Minho. Data from 197 respondents were collected. The items included in the questionnaire are listed in Table 1. Because it allows the assessment of multiple and inter-related relationships between variables simultaneously, structural equation modelling (SEM) was used for the analysis. Screening and assessment of data confirmed that the data were suitable for SEM analysis. The means and standard deviations are listed in Table 1.

Table 1. Variables used and descriptive statistics

Measure	Source	No. of Items	Mean	Range	Standard Deviation	Cronbach's α
Positive Outcome Expectancies	Paton et al. (2005)	3	10.41	3-15	2.92	0.71
Negative Outcome Expectancies	Paton et al. (2005)	3	8.81	3-15	2.46	0.64
Collective Efficacy	Zaccarro et al. (1995)	4	14.37	7-20	2.03	0.71
Community Participation	Eng and Parker (1994)	4	10.36	4-16	3.08	0.83
Intentions to Prepare	Paton et al. (2005)	3	6.69	3-12	1.74	0.74
Preparedness	AFAC	16	5.94	1-16	3.25	0.82

Confirmatory factor analysis indicated that the measurement variables significantly represented their respective latent variables. This provided the basis for testing the structural model (Figure 1). The hypothesised structural model was evaluated using the maximum likelihood method of estimation. Each latent variable was allowed to covary in order to represent unanalysed associations, and each indicator loaded on only one latent variable (Kline 2005) to test whether the proposed model was a good fit to the data.

Multiple fit indices were inspected. The likelihood-ratio chi-square (χ^2) statistic is the primary measure of fit. Non-significant differences indicate a good fit of the model to the data. Because of the sensitivity of the chi squared statistic to sample size, Hu and Bentler (1999) recommend using the chi-square/df ratio (CMIN/DF). CMIN/DF ratios close to one suggest a very good model fit, while values < 2 indicate a good fit (Hu and Bentler 1999). The Root Mean Square Error of Approximation (RMSEA) assesses the amount of error present in the fit and is considered to produce accurate assumptions about model quality

(Kline 2005). Values that are < 0.05 suggest a good fit to the data, while values between 0.05-0.08 reflect an adequate fit. The Goodness-of-Fit Index (GFI), Normed Fit Index (NFI), Tucker-Lewis Index (TLI), Incremental Fit Index (IFI), and Comparative Fit Index (CLI) all approximate the degree to which the theoretical model is superior to the null or independence model. They range from 0 (no fit to the data; a fit that does not improve on the null model) to 1 (perfect fit to the data) and values greater than 0.90 are considered to reflect an adequate fit to the data.

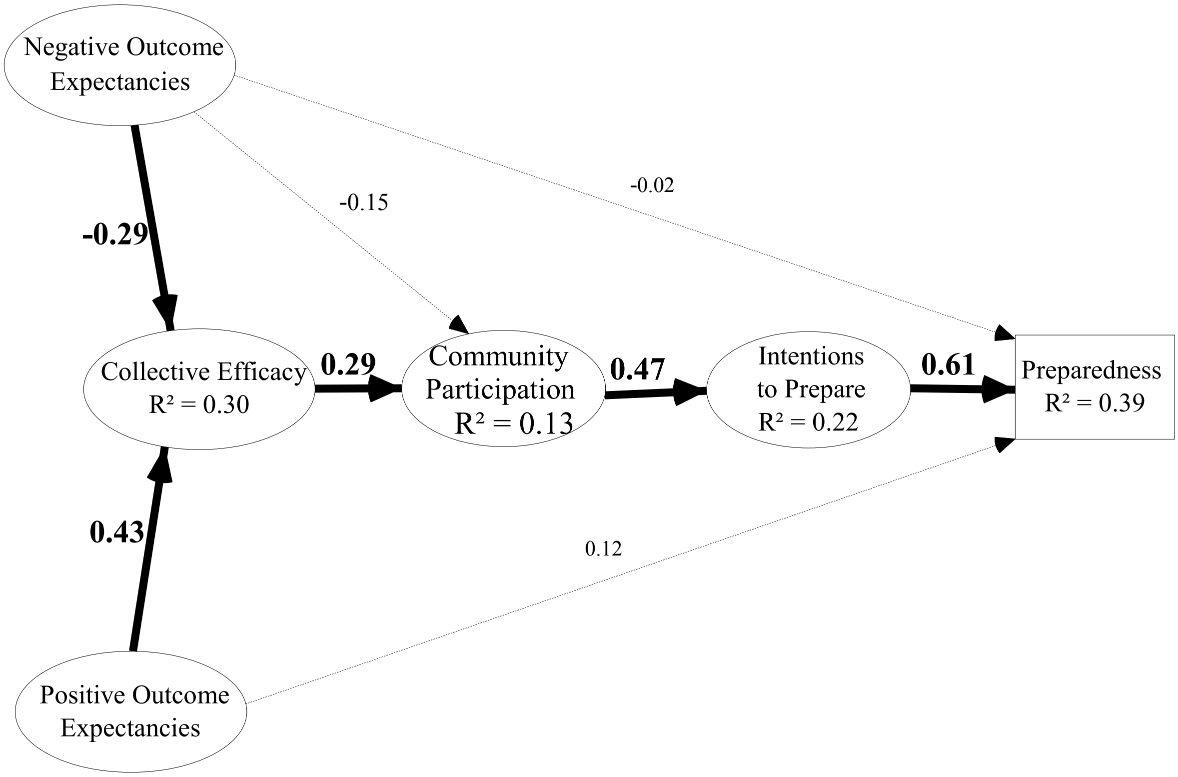

Figure 1. A summary of SEM analysis

The analysis demonstrated that the model was a good fit to the data, (χ^2 (123, $N = 197$) = 143.80, $p = 0.10$, CMIN/DF = 1.17, RMSEA = 0.03, 90% 0.00→0.05, NFI = 0.87, TLI = 0.97, IFI = 0.98, CFI = 0.98, PCLOSE = 0.97). Significant relationships are in bold. Overall, levels of forest fire preparedness were low. The average number of house protection measures adopted was 6 (of 16). The model accounted for 39% of the variance in levels of forest fire preparation. This confers upon these findings a good/moderate effect size (Sheeran 2002), supporting the use of the model as a guide for developing risk communication strategies to facilitate forest fire preparedness.

4. DISCUSSION

The analysis confirmed that personal beliefs regarding the efficacy of preparedness interacted with social characteristics (community participation) and competencies (collective efficacy) to help explain differences in levels of forest fire preparedness in

Portuguese communities. As predicted, negative outcome expectancy reduced the likelihood of people preparing (Figure 1).

The analysis demonstrates how preparedness results not just from providing information and resources but also from ensuring that people can make sense of and use information and resources to meet their needs. It follows that, from a risk management perspective, an effective public education strategy must work with and engage with the community. In this context, it is important to note that the social context factors that predicted the adoption of forest fire protective measures were pre-existing community characteristics (e.g., participation) and competencies (e.g., collective efficacy) that derived from people's engagement in daily community activities over time.

This suggests that the effectiveness of risk management strategies can be increased by integrating them with mainstream community development strategies (Paton 2008; Pearce 2003). Thus community engagement strategies must assess and if necessary develop and encourage use of social networks (e.g., active participation) within which people can develop appropriate risk beliefs; the competencies (e.g., collective efficacy, planning) that help people identify ways to respond and that help people identify how to put strategies into action.

This work identified a need for community outreach strategies to increase preparedness. This need was indicated by finding that, on average, only 6 or 16 preparedness measures were undertaken. In particular, current preparedness activities are problematic as people were least likely to adopt the structural (e.g., defensible space, house protection) and planning (e.g., household fire response plan) activities that will make the greatest impact on helping fire agencies focus on suppression activities. If people do not adopt structural protection (e.g., defensible space), they and their properties remain more at risk and will require fire agencies to divert more suppression resources to protecting homes. If people adopt structural measures, agencies and communities can actively complement one another in an integrated risk management strategy.

Strategies to promote preparedness should focus on influencing outcome expectancy beliefs and the use of social processes to facilitate preparedness (Paton and Wright 2008). Negative outcome expectancy arises because people assume that forest fires are too catastrophic for personal actions to be effective. Such beliefs could be countered by presenting images that compare properties close to each other where one is damaged by fire and the other not to illustrate how actions can affect damage. This approach can be supplemented by clearly differentiating the fact that while people cannot control forest fire they can control its consequences (e.g., a defensible space reduces threat from embers and protects property) and emphasising the need to focus on consequences.

Preparedness can be facilitates by getting people to personalize impacts (e.g., asking them to consider what a fire might mean for them and their community) and by arranging discussions with people from communities that have prepared and who can talk about its effectiveness. Information should focus on explaining how fire affects properties and how specific actions prevent loss (e.g., see example above). Information is most effective when it deals with specific topics (e.g., discuss embers, their causes, and how to protect from them) rather than covering everything at one time and when people discuss how to use this information. This can be facilitated through organising social meeting that include property assessments and showing what an effectively prepared property looks like. Workshops, consultative liaison committees, public forums can be used to promote discussions and identify new ideas and issues from within the community. This work may have applicability beyond Portugal. Consistency between this study and a research in Australia suggests that the model of forest fire preparedness developed here has cross-culturally applicability and can be used throughout Europe and Australia.

5. CONCLUSION

This chapter identified a need to accommodate personal beliefs and social processes in strategies to facilitate forest fire preparedness. The analysis suggested that this can be cost effectively by integrating risk management with community development initiatives. This fosters social capital and will result in enduring benefits for communities and not just in the context of their experiencing forest fires. This increases the cost effectiveness of this aspect of risk management, an important and pragmatic consideration at a time when financial constraints need to be accommodated in risk management planning.

The authors would like to acknowledge and thank the Portuguese Science Foundation (FCT-Fundação para a Ciência e a Tecnologia) for supporting the research under the project PTDC/GEO/65344/2006.

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Modeling changes in WUI to better preview changes in forest fire risk

Maillé E., Espinasse B.

Irstea, Mediterranean Ecosystems and Risks Research Unit, Aix-en-Provence, France;
Information Sciences and Systems Laboratory (LSIS), Paul Cézanne Aix-Marseille University, France;

eric.maille@irstea.fr, *bernard.espinasse@lsis.org*

Abstract

Forest fire risk is overall determined by the spatial relationship between some fuel geographical objects and highly vulnerable geographical objects, often co-located within Wildland Urban Interfaces (WUI), where the risk is maximized. Therefore, change in WUI lead to change in local forest fire risk level. Previewing changes in WUI is a key factor of medium term forest fire risk management. Modeling WUI spatial changes is difficult, due to the fact that objects have very different dynamics described by very different scientific disciplines: dynamic of vegetal fuel objects is described by ecological models. On the other hand, dynamic of human goods (houses, infrastructures) is modeled by geographers. Fire itself is also an important factor of change of WUI, and has to be modeled. We present an example of WUI change dynamic model, aimed at assessing possible future changes in risk level at the WUI, at a local scale, called MicropolisFIRE. It integrates one ecological model representing fuel dynamic, one discontinuous urbanization model, and one fire model. It is an agent-based decision support system (DSS), where agents represent either human being (the socio-system) or geographical objects endowed with a dynamic behavior.

Keywords: wildland urban interface, land cover change modeling, forest fire risk

1. INTRODUCTION

Because of the global change, number and surface of forest fires have tended to increase for the last decades, in most regions with a Mediterranean climate (Rego and al., 2010), in Europe, North America (California), South America (Chile, Argentina), Australia, but also in some regions up to now not affected by forest fires, like in Russia in 2010 (fire of 1935 km² and about 30 casualties).

Regarding forest fire risk, WUI have a high level of risk (Duce and Spano 2011). They are also highly changing areas. Both house density and vegetation mass might quickly change relatively to other more stable kinds of space (continuous urban zones, forest lands or pure agricultural lands). At a local scale, for medium term forest fire risk management and planning, it is crucial to be able to assess future spatial changes in WUI. Spatio-dynamic models dedicated to simulation of land cover change (Veldkamp 1996) might be used, but due to the semantic complexity of WUI, they present several limitations. The specification of specialized models might be required, in order to properly represent WUI dynamics. Then, new fire risks models have to be specified in order to assess changes in risk levels within WUI.

In this chapter, we present a modeling demarche aimed at representing WUI dynamics and changes in risk levels. We first precise the nature of WUI spatial dynamics, and their theoretical effect on changes in risk level. Then we describe a simulator of risk change in WUI, called MicropolisFIRE, based on specific land cover changes and risk models.

2. WUI DYNAMICS AND CONSEQUENCES ON CHANGES IN RISK LEVEL

WUI represent spatial and temporal transition areas between wild lands and urban lands. Spatially, they surround continuous urban lands, and separate them from wild lands. Temporally, they are not equilibrated spatial systems, evolving from wild lands toward continuous urban lands.

2.1 WUI dynamics

WUI appear as a consequence of two very different spatial processes: (i) the human driven discontinuous urbanization process and (ii) the forest land ecological progress, usually on abandoned agricultural lands (Figure 1). First process is described by models specified by (urban) geographers, while the second one by ecological models. Land abandonment itself might be represented as a spatial human driven process described by models specified by economists or agronomists.

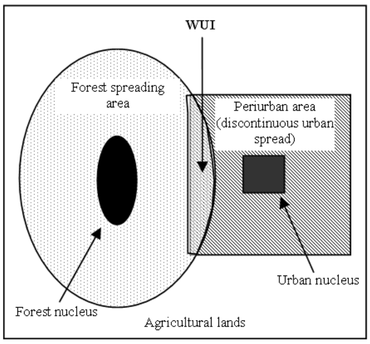

Figure 1. Formation of WUI resulting from the interaction between forest advance and discontinuous urban spread

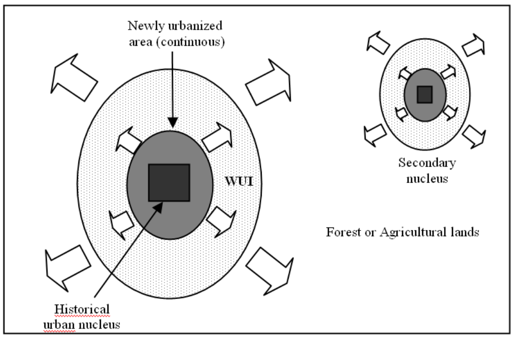

Figure 2. Centrifugal progress of WUI around the historical urban nucleus

Formation and dynamic of WUI are so the results of the interaction between very different spatial processes, i.e. ecological and human driven processes.

After having been formed, WUI continue to evolve, in particular, regarding their spatial characteristics: location, surface, shape, etc. WUI usually change into urban area on the side of the urban nucleus, and “progress” around this nucleus towards the out side, in a kind of “areolar centrifugal” movement (Figure 2). Given this purely theoretical spatial dynamic, surface and shape of the WUI might considerably vary in relation to the local context (topography, urban policies, etc.).

WUI also change in semantic attributes values, like fuel vegetal biomass and buildings density. Change in fuel vegetal biomass is a process mainly determined by ecosystems dynamics, studied and modeled by ecology. Models describe the evolution from an initial state of an herbaceous formation up to a climax forest. Changes in houses density are a human process, described by different scientific disciplines like geography or urbanism. The process begins with a null density of buildings (houses), then grows up progressively to reach a continuously built up urban state (Curie 2010).

2.2 Theoretical changes in risk level within WUI

Forest fire risk evolution within WUI results from the interaction between the two previously described spatial process: the growth of fuel biomass, and the increase of buildings (houses) density. In a first theoretical approach, forest fire risk increases with the fuel biomass growth (mainly due to the rise of propagation hazard) (Syphard 2002). As soon as the discontinuous urbanization process starts, risk starts to increase drastically due to the installation of buildings within this fuel biomass (rise of the ignition hazard and vulnerability level). Then buildings take the place of fuel biomass, which begins to decrease. The risk also decreases to reach again a null level in continuous urban areas far from the forest limit (Figure 3).

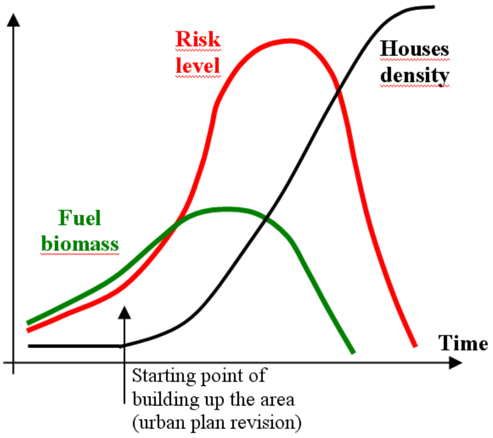

Figure 3. Theoretical evolution in time of fuel biomass, houses density and risk level within WUI

In relation to local conditions, this theoretical scheme might radically differ from the real processes occurring on a given situation. In order to be able to control forest fire risk in land management planning activities, it is necessary to assess the effect of a given planning decision on future forest fire risk level. To do so, simulations computer tools might help. We propose an example of risk change simulator at WUI called MicropolisFIRE.

3. AN EXAMPLE OF SIMULATOR: THE MicropolisFIRE

MicropolisFIRE[1] is a simulator dedicated to land planning decision support for forest fire risk management at local (micro) scale. It is a multi-agents based model (Ferber 1999) developed on a spatial multi-agents based system (MABS NetLogo). MicropolisFIRE is designed to represent WUI spatial changes at a local scale, and give an assessment of the evolution of risk levels at each point of the simulated territory. Three main modules were developed: a module to represent changes in fuel ecosystems (ecological model), a module for representation of spatial changes in scattered built up areas (geographical model), and a fire model to simulate fire occurrence and possible contours, including ignition and fire fighting models, for risk assessment by fire multi-simulations.

3.1. Change in fuel vegetal mass: representing the dynamics of ecosystems

This module is composed of two main atomic models: an agricultural land abandonment model (human decision) and an ecological model for vegetal fuel mass increase representation. Agricultural land abandonment model is an agent-based model, where a

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[1] MicropolisFIRE is an extension of MICROPOLIS (Maillé 2011), that focuses on structural spatial changes within WUI (developped in native JAVA, with the Tilab JADE API), with no fire model.

farmer decide to abandon an agricultural field, in relation to its spatial attributes (area, shape, access, distance from the farm), and its own situation (age, production, etc.).

As soon as an agricultural patch is abandoned, the vegetation growth ecological model starts to represent its fuel mass evolution. In MicropolisFIRE growth of vegetation is supposed to be homogeneous on a given former agricultural patch, or on a whole burnt area. Only ecological series are represented, in relation to the ecological station. A fuel index is associated to each stage of the series, from herbaceous formations, just after the abandonment of an agricultural land, up to the climax forest.

3.2. Change in ignition probability and vulnerability: representing the dynamics of built up areas

Both ignition probability and global vulnerability depend on buildings density and the relationship between vegetal fuel objects and buildings. In MicropolisFIRE increase of building density within WUI is represented by a simple temporal function, easily calibrated, for each territory, using past diachronic mapping. Changes in the spatial relationship between fuel geographical objects and vulnerable geographical objects have to be represented by a specific module. A dedicated mutlti-agents based sub-model is used to represent the social process at the origin of change in spatial structures of the discontinuous urban zones. Parcel splitting and commercial exchanges activity between historical landowners (farmers, forest owners) and buyers whose objective is to build a house are represented (Figure 4).

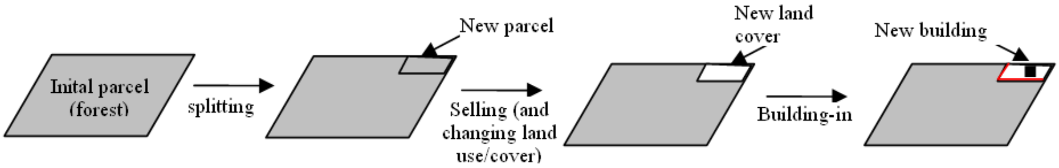

Figure 4. Spatial restructuration process within WUI due to change in land tenure

3.3. Fire simulation

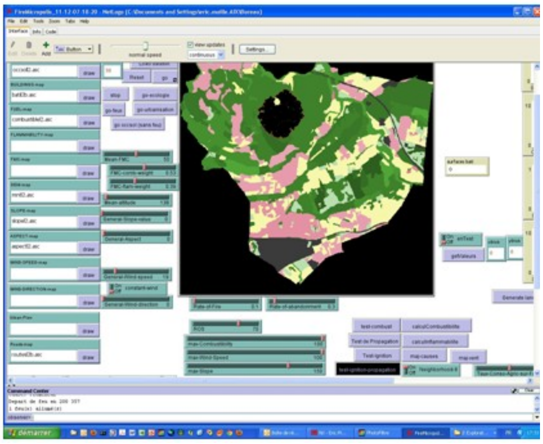

Figure 5. The MacropolisFIRE user interface during a simulation with fire

MicroFIRE is a fire simulator module of MicropolisFIRE, dedicated to both land cover change due to forest fire (opening of wild lands) and risk assessment (fire multi-simulation). It is composed of an ignition model and a propagation model.

-The ignition model is based on fire *causes* analysis and statistics. It is also an agent based model in order to represent some particular human behaviour (pyromaniac, simple walkers, etc.).

-The propagation model itself is a usual raster like grid of cellular automata (Batty 2001; Torrens 2001). Propagation depends on usual geographical variable (slope, local wind, combustibility of vegetation) (Dupuy 2006). Propagation is limited by a fire fighting agents-based model.

At each time step of the land cover change simulation (one step of time represents one “fire season”, i.e. one year) several fires may occur, depending on land cover state, and stochastic weather conditions. Forest fire risk evolution is assessed at each point of the territory by the obtained fire regime map that represents the number of fires and the fire frequency during the simulated period. An example of simulation of land cover, fire regime and risk change on a local territory of the French Mediterranean area is proposed in Figure 6. It permits to identify some critical areas (for example the western part of the commune, cercled), where risk increasment is more notable. For land planning decision makers, these areas have to be carefully taken into account.

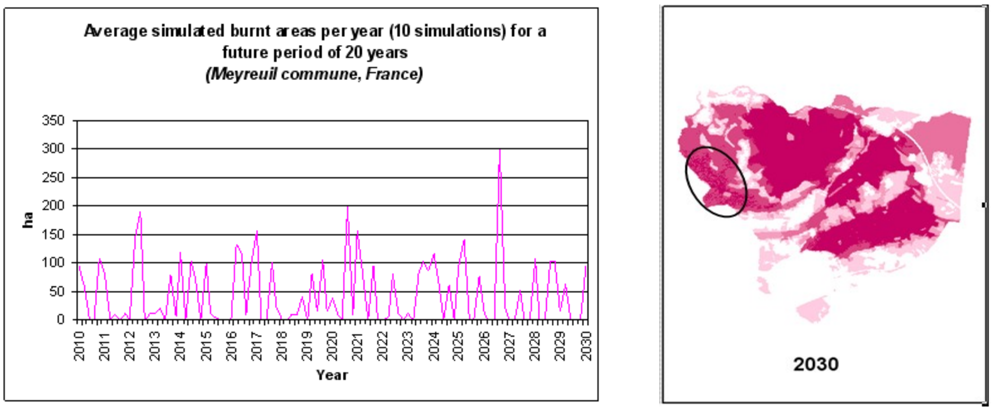

Figure 6. Simulated evolution of burnt area per year and the map of the simulated risk level in 2030 (Meyreuil commune, France)

4. CONCLUSION

Changes in risk levels within WUI are determined by land cover changes and climate changes. Land cover changes are highly complex spatial processes resulting from the interaction between social systems and ecosystems. In order to anticipate the future evolution of risk, dynamic modeling is a key tool for land planning decision making. Individual based models (grid of cellular automata, agents based models, etc.) are often the best adapted (Grimm 1999).

We propose a multi-agents based model called MicropolisFIRE, which integrates human processes, ecological processes and fire processes, in order to represent forest fire risk possible future evolution within WUI. Although it can provide a realistic view of a future possible state of the territory, such a model cannot be used as a predictive tool. The simulator should be used to test different options and scenarios of planning decisions in order to select the best plan to limit future risk.

Many improvements remain to be brought to the model. Complex human decision making, like agricultural land abandonment decision or parcel splitting by farmers to sell to buyers, have to be refined. The fire propagation model is also very simple: specialized propagation dynamic models like FARSITE (Finney 1998) or FIRETEC (Linn et al. 2002) have to be tested. Validation of the model is now being processed on a sample of territories of Southern France and other Mediterranean territories, in the framework of the FUME European research project.

Finally, climate change is a second important factor to be taken into account in order to better preview change in forest fire risk. Climate change can be previewed using standards climate models. However, many difficulties have to be solved before being able to apply these models to risk at the WUI, in particular scale issues (climate models are usually not local scale models) and wind regime prediction capabilities of these models. These questions are now being processing by many research teams, like for example in the FUME European research project.

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An analysis on wildland urban interface in Portugal

Ribeiro L.M., Viegas D.X.

Forest Fire Research Centre (CEIF/ADAI), Rua Pedro Hispano n12, 3030 - 289 Coimbra, Portugal

luis.mario@adai.pt

Abstract

The problem of forest fires in the Wildland-Urban Interface (WUI) is a growing issue not only in Portugal but worldwide where fires tend to coexist with increasing frequency and danger with human presence in dwellings or settlements. Some of the worst wildfire disasters involving human losses are precisely associated with the approach of fire to settlements, as was the case of Greece in 2007 or Australia in 2009. A simple definition of WUI is the physical space where vegetation and structures coexist in a fire prone environment. In Portugal this is applicable to a large extension of the territory. Although there is some work done is European countries, there is still a gap in the research and understanding of the WUI problem concerning its characterization and real extent. This work aims to present a diagnostic analysis and characterization of the problem performed for Portugal. The main objective was the production of a WUI risk map at a regional level identifying high priority areas in terms of structural and human exposure to wildfire. Given the scale of the work as well as the financial means and input data available for this study the methodology used is mainly based on the use of free data sources. A catalogue for the identification of WUI situations and the respective associated risk was the basis for its assessment. This catalogue, that was adapted from published bibliography, aims to be representative of Portugal, and it allows a fast and precise way to identify WUI situations comparing real cases to an intuitive photographic key. This photographic key associates a risk class to each WUI typology. The catalogue of WUI situations is divided into 3 groups, according to the main land use where buildings are established: A) forests, B) shrub lands and C) agro-forestry. In total 21 different situations compose the 3 groups of the catalogue. Each one of these situations has a correspondent risk value associated, from 1 (low) to 4 (very high). The work consisted of an individual analysis of each of the considered regions (Portuguese districts). In every district a value of presence for each situation of the catalogue was attributed. Values of presence range from 0 (non-significant) to 3 (very frequent). The results were then merged with other relevant information (land use, fire history…) in order to produce individual analysis for each district. The proposed methodology can be adapted to other regions of Europe with similar types of house construction. Extension of the typology to other types of structures is the vicinity of the forest or rural areas is being developed.

Keywords: wildland-urban interface; risk assessment; free data sources

1. INTRODUCTION

The term Wildland Urban Interface (WUI) was first used in 1974 by Butler from the Stanford Research Institute. Butler stated that in its simplest terms the interface fire is any point in which the fuel feeding a forest fire changes from natural fuel (forest) to manmade fuel (urban) and in order for that to happen forest fire must be near enough so that burning embers or flames can be in contact with parts of the structure. Since then several definitions have appeared in the literature (e.g. Davis 1990; Cohen and Butler 1996; Cohen 2000; Nowicki 2001; Sanchez-Guisandez et al. 2002; Cohen 2003), usually identified with specific objectives of individuals or organizations (BRP 2000). The Blue Ribbon Panel (BRP 2000), in an attempt to simplify this issue, defined WUI as the space where vegetation and structures coexist in a fire prone environment. In the United States, Canada and Australia the WUI problem has been an object of reflexion for several years. National research or operational programs are established, like for instance FIREWISE, FIRESMART or PARTNERS IN PROTECTION. Although there is some work done is European countries (e.g. Camia et al. 2002; Caballero et al. 2007), there is still a lack in the WUI research and understanding concerning its characterization and real extent (Camia et al. 2002). In the last decades forest fires have come increasingly closer to settlements mainly due to the development of houses or infrastructure near or inside forested areas where they propagate. As a consequence, the scientific community started to develop new efforts in this topic, as shown in different works like Brown, 1994; Close and Wakimoto, 1995; Alexandrian, 1996; Kalabokidis and Omi, 1998; Jasper, 1999; Cohen, 2000, 2003; Camia et al. 2002 or Caballero et al, 2007, among others. In more recent years, in Mediterranean countries, the WUI problem has been identified as a priority, partially as a result of the events of 2003 and 2005 in Portugal, 2003 in France, 2006 in Spain or 2007 in Greece.

2. OBJECTIVES AND METHODOLOGY

With this work we aimed at producing a diagnostic analysis on fire risk at the interface in Portugal using only freely available data. A preliminary analysis was performed based on fire history, land use and population and building density, thus making a qualitative description for each district of the main aspects related to fire in the WUI. Afterwards, the WUI analysis was based on a catalogue of typologies that identifies the most common situations that can be found in these areas. The original catalogue, developed by Caballero et al. (2007) for Spain, was adapted to Portugal. It is divided into 3 groups of typologies, according to the fuel strata that dominate the WUI area: (A) forest, (B) shrubs and (C) agro forestry. In total 20 models were defined. There was a need to define 3 more than in the original catalogue as we identified in Portugal some typical situations that did not occur in Spain. At the same time we found that 5 models from the original catalogue had small expression or none at all in Portugal. Nevertheless we decided to leave them in the Portuguese catalogue as some cases can be found if the analysis is made at a finer scale. The full catalogue is composed of pictures to aid in the identification, as well as a text description of the environment, the potential fire behaviour and the basic prevention measures associated. With the typology catalogue as a starting point the analysis was undertaken using Google Earth. Each one of these situations has a correspondent risk value (R) associated, from 1 (low) to 4 (very high). The work consisted of an individual analysis of each of the considered regions (Portuguese districts). In every district a value of presence (VP) for each situation of the catalogue was attributed. Values of presence range from 0 (non-significant) to 3 (very frequent). The results were then merged with the other referred information (land use, fire history…) in order to produce individual analysis for each district. The WUI risk map (WUI_{risk}) is a result of the simple combination of each individual situation's risk and the corresponding value of presence: $WUI_{risk} = \sum (R \times VP)$.

As the catalogue is divided into three groups (according to land use) the WUI risk can also be shown in its three components. The sum of these components represents the global WUI risk at district level.

2.1. Land use, fires and meteorology

Portugal suffers from a common problem amongst the Mediterranean countries which is the rural areas desertification. Several factors contribute to this but the main issue is that this desertification is among the main factors responsible for the increasing of the wildland fire risk especially near the practically abandoned small villages or settlements. Nowadays the inverse also happens near the big urban centres, where people increasingly tend to move away from their working places in the city centres, choosing to live in the peripheral areas. With this aspect arises a new issue that is the expansion of housing into the forested areas, most of the times without clear rules or guidelines. Housing density shows similar patterns to population.

For this work the Corine Land Cover map was used in order to identify the main occupation according to the catalogue groups: forest, shrubs or agro-forestry. The North/Centre Regions are dominated by forest (mainly conifers) and large areas of shrubs. There is also a large stripe of eucalyptus plantations that runs parallel to the Atlantic coast from North to Centre/South. In South, eucalyptus presence is noticeable but in the Alentejo region the main land use is agro-forestry with the presence of cereals and *Quercus suber* and *ilex*. In the Southernmost areas of Portugal (Algarve) shrubs dominate. One very important point that is not easily extractible from Corine is the agricultural fields and the herbaceous surrounding the settlements. Due to the above mentioned desertification these agricultural fields are becoming more and more abandoned, bringing the forest space dangerously close to the urban space. From a first analysis, although superficial, the problem of highly urbanized areas of the North/Central Coast (districts of Porto, Braga, Aveiro, Viana do Castelo) that have a very strong forestry component is highlighted. In these districts there are several cases of interface. On the other hand there are districts with a strong component of mountainous areas and land use dominated by forest and scrubland, as are Coimbra, Viseu, Guarda or Castelo Branco. In these cases there is, as already mentioned, a population concentration in large urban centers, and rural depopulation. In both cases similar situations happen of mixture of homes with vegetation, though for opposite reasons. In major urban centers the population pressure forces the expansion, often unruly, of housing. The urban sprawl leads to the disappearance of a defined border between houses/structures and forest. For the same reason there are also increasingly common cases of isolated dwellings within the forest patches. Contrarily in the rural settlements, especially in the interior, it is the vegetation that is advancing into the urban areas, again as a result of the aforementioned abandonment. In terms of burned areas there is a clear concentration in the center of the country, precisely in the region mainly occupied by pine forests. Practically all the northern region with forest or shrubland occupation has already been burned at least once in the period analyzed. The South (Alentejo) has smaller burned areas and Algarve had most of its forest areas destroyed by fire (mainly the mountainous areas). Some of the districts that make up the Pinhal Interior region (Coimbra, Castelo Branco and part of Guarda) are the ones that have been suffering the most with the abandonment and the rural aging of the population. The discontinuities that could be observed a few years ago, as a result of human occupation, are not so evident, which favors the development of large fires when the right conditions are met. In the northern districts (Viseu, Porto, Vila Real, Braga, Viana do Castelo and part of Guarda) we can observe a high incidence of minor burnt areas but with accentuated recurrence. The Algarve is cyclically affected by large fires (1991, 1995, 2003, 2004), especially in mountainous areas to the west. Areas that were burned 4 or more times are practically all situated North of Tejo (Tagus) River, mainly in Viseu, Guarda, Vila Real, Porto, Braga e Viana do Castelo. Meteorologically Portugal is a typical Mediterranean country, with hot dry summers and rainy winters. Within this classification a distinction must be made between the Atlantic influence in the West, noticeable by a more humid climate than the rest of the country, and the interior which becomes drier as we move to the East. The summer period corresponds to the so called “Fire Season”. In fact, according to the records, and in the period 1980 to 2000, 93% of the area burned in Portugal occurred in the months of July to September. Furthermore, most of the area burned each year (around 80%) occurs in days meteorologically classified as of extreme danger, which correspond more or less to 10% of summer days (Fernandes 2007).

3. RESULTS

The result of the analysis was reflected in a map of Portugal showing the respective risk level per District (Figure 1). An individual analysis was also performed for each one of them, which will not be described here as it is an extensive one. As explained before, the final map results from the combination of the risk in each one of the three groups in the catalogue. Each one can also be mapped individually. This methodology does not establish specific risk classes for WUI. In theory the maximum value would come from the very frequent (value 3) presence of all catalogue situations in an area, which is very unlikely to happen. The most common result is to have “some cases” (value of presence 1) of several situations and have 2 or 3 situations that are more frequent (either with value 2 or 3). The highest result obtained in the global analysis should be used as a reference for the others. The maximum value of risk found was 25 and it occurred in the district of Coimbra. High values were also found for Braga (23), Viseu and Aveiro (22), Porto (21) and Viana do Castelo, Leiria, Santarém e Castelo Branco (20). With values that can be considered medium appeared Faro and Vila Real (15), Bragança (9) and Guarda (8). With low values of risk in the WUI there is Beja (6) and Évora, Lisboa, Portalegre and Setúbal (5). WUI risk in areas with forest dominance has the highest influence in the final result. All the districts with a high values of risk have a high risk value in group A (forest dominated WUI) of the catalogue.

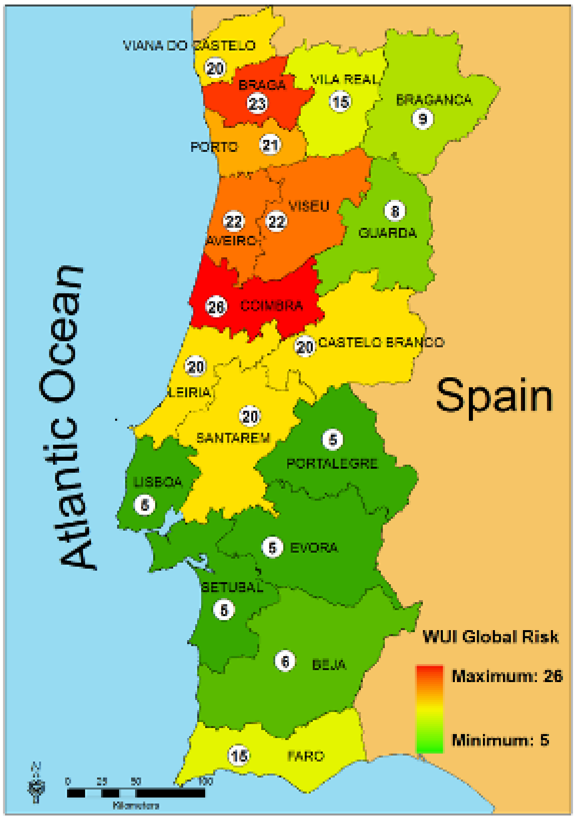

Figure 1. Global WUI risk in Portugal at district level

4. CONCLUSION

As referred before this was a diagnostic study intended to demonstrate the need to deepen the analysis and our knowledge on the Wildland Urban Interface in Portugal. Some considerations have been made in the original study regarding the use of its results and from which we can highlight some:

- Some of the images from Google Earth used for the analysis were not very up to date, so we cannot be sure about the reality of land use in some cases.
- The fact that some of the typologies do not appear in the final results does not mean they are not present in some locations. Simply their presence is not significant enough at the scale that this work was done.
- It is not easy to distinguish the degree of abandonment of agricultural fields. The safety of the population decreases inversely with this degree of abandonment. The proliferation of herbaceous and shrubs in the once cultivated fields blurs the boundary between the forest area and the human occupied space.
- Across the country there are, in almost all urban centers and regardless of their size, individual buildings or small groups of buildings outside their boundaries and which are mixed with vegetation, in different degrees. In large urban centers such situations occur with the proliferation of new neighborhoods or housing developments on the periphery. These are perhaps the situations to earn a first approach in managing the problem of fires in the interface.
- The same typologies can have a very different risk according to their topographic location, especially the small villages or settlements in forest dominated areas whose risk is much higher if they are on top of a slope in relation to those found in the valley or hillside
- The fact that a given region has a very high fire risk does not mean it has also an implicit interface high risk. There are areas where settlements are well isolated from the forest area (or shrub area).

A final note should be given to some special cases, mainly in forested areas, which deserve a special care like small chapels or isolated churches, camping sites, recreational areas, gas stations, touristic spots, sports facilities, etc. In general any location that concentrates people, either in a long period (e.g. camping sites) or in a small one (e.g. chapels), should have a specific protection plan, not only because of the danger to people and property but also because of the potential to be ignition spots. To these special situations we called "***Wildland-Human Interface***" as we are dealing with spaces where there might be large groups of people more or less seasonally or periodically in places that alone may not elicit much attention. In these cases the top priority in protection plans should be directed to the safeguarding of the human lives that are there and who have not, in principle, responsibility for management of those areas.

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European software tools for mapping Wildland Urban Interfaces in the Mediterranean context

Bouillon C.[1], Fernández Ramiro M.M.[2], Sirca C.[3,4], Fierro García B.[2], Long-Fournel M[1]., Casula F.[3]

[1]Cemagref, UR EMAX, 3275 route de Cezanne, CS 40061, 13182 Aix-en-Provence cedex 5; [2]Tragsatec, C/Julián Camarillo 6B, 1B, 28035, Madrid, Spain; [3]DipNET- Dipartimento di Scienze della Natura e del Territorio, University of Sassari, Via E. De Nicola, 9 – 07100 – Sassari, Italy; [4]Euro-Mediterranean Center for Climate Changes, IAFENT Division, Sassari, Italy

christophe.bouillon@cemagref.fr, mfra@tragsa.es, cosirca@uniss.it

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Abstract

This paper aims to present a software tool allowing to map Wildland-urban interfaces (WUI) on local and global scales. Two methods have been produced for mapping WUI on local scale (one or several district level) and one method for the broad scale (European level). These works are part of the European FUME project (7th Framework Program). The two methods for local mapping were developed by Cemagref/Irstea, and Tragsatec, and were tested by DipNET (University of Sassari) in three study areas which are located in South-Eastern France, in Eastern Spain, and Sardinia (Italy). The UNISS team uses the WUImap software for mapping WUI on local and European levels. The aim is to evaluate changes in time of main WUI descriptors. The software is designed to work with ESRI Arc GIS 9.3, ArcInfo license.

Keywords: WUI, RUI, geography, GIS, forest fire

1. INTRODUCTION

The main purposes of this work are:

1) to set the WUI mapping methods on different scales (local and global scales) according to available data and local contexts;

2) to present a developed easy-to-use WUImap toolbox giving an automatic mapping of WUI using GIS;

3) to provide guidelines for using the tool, including customization of inputs.

Cemagref/Irstea and Tragsatec have developed different approaches for characterizing WUI at local and global scales.

On local scale, both these approaches seem to be efficient and complementary. Their usefulness and applicability depend on the available data on local or regional scale. A toolbox able to manage the two methodologies gives the opportunity to choose between them. The approach has to be selected according to the availability of data for the examined area, and to the context of the country.

For the global scale, corresponding to the European scale, only one method has been implemented and proposed by the two partners Cemagref/Irstea and Tragsatec. The principal input data for the global tool is the Corine Land Cover. Another database is also used to improve the information about dwellings, urban structures, infrastructures: the Soil Sealing Europe produced by the Join Research Center, the European Commission in-house science service.

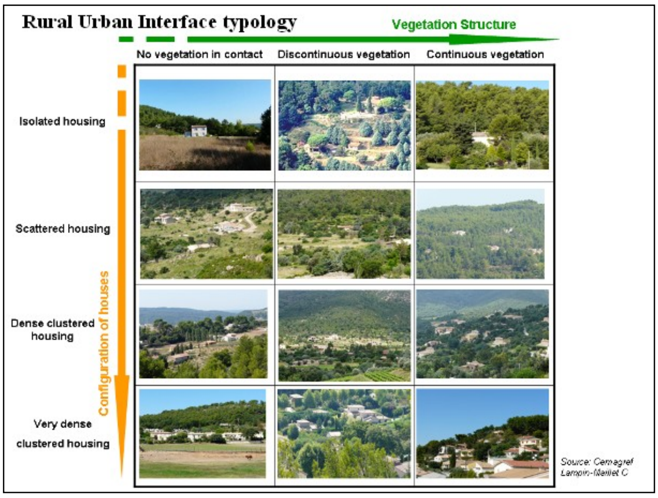
2. METHODS FOR WUI MAPPING

2.1. Mapping at local scale: Cemagref/Irstea's method

The characterization of Wildland-Urban Interfaces is necessary to improve actions for forest fire prevention. In France, forest fire prevention is generally based on a legislative framework. Key points include the brush clearing obligations for homeowners around their houses but also for communities and public establishments around buildings and near the roads. As more than 90% of well-known causes of forest fire ignition are due to human activities (especially carelessness), prevention actions must be enhanced by and for inhabitants involved in fire risk (in many cases people living in the WUI).

Cemagref/Irstea has implemented a method to map WUI on local and regional scale (Lampin-Maillet et al. 2010). This method is an improvement of a previously developed tool and guide to map WUIs, a result of the FIREPARADOX European project (6th Framework Program).

The method considers WUIs, all the areas delineated by a radius of 100 m around residential houses which are inhabited permanently, and that are, at the same time, located at a distance ≤ 200 m from forests or shrublands. At first, the tool calculates a housing configuration with 4 classes of buildings density: isolated housing, scattered building, dense clustered housing and very dense clustered building. Then, having access to satellite or aerial image a vegetation aggregation index (AI) can be calculated by the use of FRAGSTATS3.3© software (McGarigal and Marks 1994). It represents the horizontal continuity of vegetation in 3 classes: no aggregation, medium aggregation and high aggregation. The combination of the housing layer with vegetation aggregation index results in the typology with 12 classes (Figure 1).



Source: Cemagref Lampin-Maillet C

Figure 1. Cemagref/Irstea WUI typology

2.2. Mapping at local scale: Tragsatec's method

According to Regional Forest Law, only settlements located within a distance of 400 m from the forested areas are to be considered WUIs. In fact, this value determines the forest influence zone. This parameter can be modified in the tool according to the laws of each country. Moreover, the forest fire management actions are under the responsibility of the Autonomous Regions; therefore there is not a national general rule on the prevention of forest fires in the WUI areas. One of the responsibility of the Forest fire management is the execution of an analysis about how the settlement and structural characteristics of forest ecosystems interact, creating different types of WUI. Each Interface must be provided with a tailored strategy. So in order to achieve the objective to protect the population against forest fires, it is first necessary to know how the population inhabits the land. The location and the type of the settlements are indispensable land descriptors in order to give a fast, coordinate and efficient answer in case of emergency.

TRAGSATEC has worked out in the characterization of WUIs. The Spanish method is structured in three stages: a settlement map creation, a buffering according to the settlements and land uses types, and a WUI type map creation.

In the first step, the various types of settlements are characterized and located in the Settlement map. Then, using this first output, different types of WUI are identified and located through a buffering. The creation of the final WUI map takes in account, first, the type of settlement (the buffer radius depends on it) and then, the vegetation-settlement connection around houses (the context in which the settlement is situated).

Two layers are required as inputs to generate the settlement maps: a Land Use layer to evaluate the urban zones and buildings (in the case of Spain it has been used the SIGPAC map with a 1:5,000 scale of photo interpretation), and a Vegetation Cover layer to evaluate the context in which settlement are located (in the case of Spain it has been used the National Forest Map of Spain -MFE50- whose scale is 1:15,000).

Table 1. TRAGSATEC WUI types

Classes	Types
1	WUI dispersed buildings in forested area
2	WUI isolated buildings in forested area
3	WUI settlement in forested area
4	WUI urban settlement
5	WUI dispersed buildings in agricultural area
6	WUI isolated buildings in agricultural area
7	WUI settlement in agricultural area

The size of the buffer created around the established settlements depends on the difficulty in protecting the houses against fire: Urban Settlement = 400m; Settlement in Forested Areas = 300m; Settlement in Agricultural Areas = 200m; Dispersed Buildings in Forested Areas = 300m; Dispersed Buildings in Agricultural Areas = 100m; Isolated Buildings in Forested Areas = 200m; Isolated Buildings in Agricultural Areas = 100m.

The different types of WUI are defined according to the type of settlement and vegetation-settlement connection around houses (Table 1). A final buffer for each type of settlement defines the Wildland-urban interface surface.

2.3. Mapping at global scale

The method has been developed to produce a map at the global European scale. The best available data on the European level to create a continental map is the Corine land cover. It has been decided to improve the precision of urban plots by combining it with the European soil sealing. The module, implemented by Cemagref/Irstea, calculates a WUI map on the European scale (100m pixel) combining improved housing in 3 classes: isolated, scattered, dense clustered with vegetation in 3 classes: mineral, agriculture or sparse vegetation, forested area.

3. RESULTS

The modules corresponding to the French part and the Spanish part of the tool were tested in Sardinia (Italy) by DipNET. The data came from 3 test sites.

3.1. Local scale

3.1.1. The Cemagref/Irstea method: Figure 2 presents a detail of the WUI Type map in Alghero municipality (NW Sardinia) made by DipNET. It shows all the 12 classes generated and the general housing configuration of the area.

The French method is based on a 100 m buffer, corresponding to the maximum value that the French law sets for the brush clearing zone around the houses.

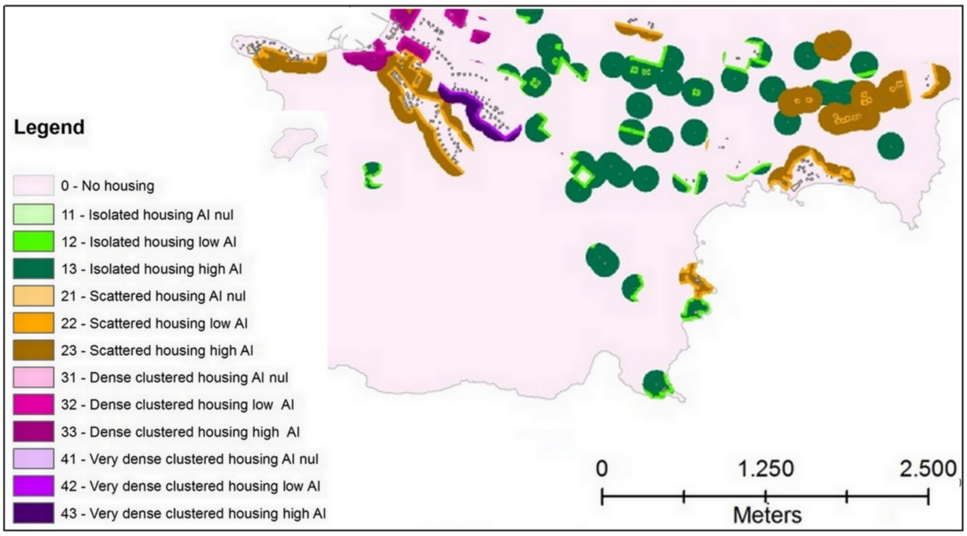


Figure 2. Map of WUI in the Western part of Alghero area (Cemagref/Irstea method)

The tool is also able to calculate maps on large areas. DipNET has developed the housing configuration map (first output of the tool) of north east Sardinia (~3200 km^2). The calculation tests are continuing on the NW of Sardinia and are not over yet. A validation test is completed for the whole method in several municipalities in the Marseille-Aix region.

3.1.2. The Tragsatec's method: Figure 3 shows all the 7 WUI Types emerging from the housing density and the settlement surrounding environment according to the Spanish method.

3.2. Global scale

The Figure 4 shows the 9 global WUI types calculated by the global tool using the Corine Land Cover and the Soil Sealing European database.

4. CONCLUSIONS

The outputs produced by the tool were compared and a significant consistency between the obtained maps was observed. The direct knowledge and some surveys in the territory to visually compare the outputs with the real situation enable us to verify a clear agreement between the software result and the WUI distribution on the territory.

The two approaches, global and local, are both useful to know, describe and map the territory on different scales and level of definition. The map that the global tool produces can be used to have a general view of the territorial characteristics on regional scale and to focus the areas where the use of the local tool would complete the analysis.

In a general interpretation of the local tool application, the CEMAGREF/IRSTEA and TRAGSATEC methodologies could be considered as complementary. The first method developed by Cemagref/Irstea analyses the residential buildings and the presence/continuity of vegetation. The Tragsatec methodology also works on dwellings but it considers the environment in which they are located, forested, urban or agricultural. More information can be collected and a more complete description of single WUI contexts can be obtained by running the local tool with both methods. The use of the tool could be very advantageous for fire risk analysis on WUI scale and for local quantification of fuels charge and continuity. The information and the direct knowledge of the general context are both very important for the local fire risk assessment.

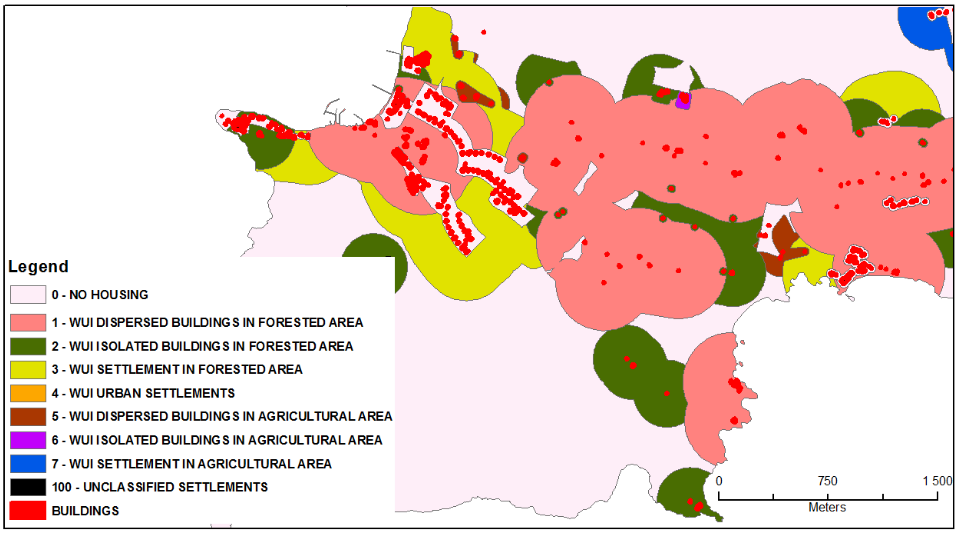


Figure 3. Map of WUI in the Western area of Alghero (Tragsatec method).

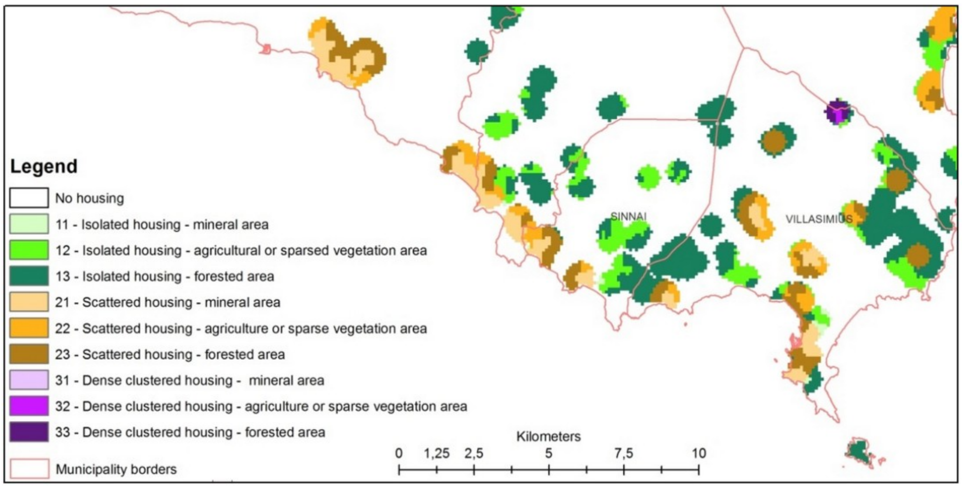


Figure 4. Map of WUI at global scale. South-East Sardinia island.

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Wildland-urban interface dynamics during the last 50 years in North East Sardinia

Pellizzaro G., Arca B., Pintus G.V., Ferrara R., Duce P.

National Research Council of Italy, Institute of Biometeorology
(CNR-IBIMET), Sassari, Italy

g.pellizzaro@ibimet.cnr.it

Abstract

In Sardinia, forest fires showed an increase in both occurrence and number of extreme fire seasons during the last three decades. In addition, an increasing number of fires threatening the wildland-urban interface (WUI) can be observed. This study, briefly presented here, is focused on a coastal area located in North East Sardinia. In the study area, due to large tourism development occurred in the last thirty years, most of the vacation resorts were built within and surrounded by Mediterranean vegetation. It is well known Mediterranean shrubland is really prone to wildfire events. In addition, costal wildland-urban interface areas show an elevated fire risk especially in summer when the presence of tourists is highest and weather conditions are extreme. This study explores WUI dynamics and landscape change in a tourist area located in North-East Sardinia from 1954 to 2008. Characterization and mapping of WUI zones were performed using temporal steps of about 10 years. For each temporal step, WUI areas were identified, classified and mapped for the purpose of analyzing and evaluating the temporal evolution of their presence and properties. Results from this study can contribute to develop planning policies for implementing strategies aimed at preventing and reducing fire risk in coastal WUI areas.

Keywords: Wildland-urban interface, Urbanization, Landscape change, GIS analysis, Fire risk

1. INTRODUCTION

Housing development is one of the most important causes of landscape change in many countries of the world. The last decades showed a gradual movement of urban population to the country sides and an outward spreading of cities forward rural and natural areas. This demographic change has resulted in an increase of rural-urban fringes intermixed with forest and rural lands. In addition, especially in tourist and coastal areas of European Mediterranean countries, a large number of new little villages and resorts have been built within and surrounded by natural vegetation due to attractive recreational amenities and the beauties of the landscape. Areas where houses and structures meet or intermix with natural vegetation and undeveloped wildland are defined as wildland-urban interface, WUI (Vince et al. 2005; Stewart et al. 2007). Different problems related to expansion of WUI have received increasing attention by scientific community because of ecological and sociological implications for natural resources management and land use decision (Avalapati et al. 2005; Field and Jensen 2005; Zhang et al. 2008). One of the main concerns in WUI management is reducing fire risk. Several authors emphasized that ignition sources and probability of fire occurrence are related to both human presence and spatial arrangement of houses in natural vegetation (Syphard et al. 2007; Lampin-Maillet et al.

2009; Badia et al. 2011). Mediterranean Basin countries are historically subjected to forest fires, which often threaten wildland-urban interface areas. Moreover, as Mediterranean vegetation is really prone to wildfire events, these areas are characterized by high potential fire risk. With particular reference to coastal areas of Sardinia, the risk of damage for villages, tourist resorts, other human activities and people is really high, in particular during summer season when human presence increases and extreme weather conditions can occur. Consequently, developing planning policies is essential for implementing strategies to prevent and reduce wildfire risk in WUI areas (Hammer et al. 2004; Hammer et al. 2009). In United States, Canada, and Australia problems related to fire in WUI have been object of research for several years and many papers are available in literature. Information and data has been recently collected relative to the rate of expansion of US wildland-urban interface in the last decades (e.g. Cova et al. 2004; Radeloff et al. 2005; Theobald 2005; Hammer et al. 2009). Several authors (Davis 1990; Hammer et al. 2004; Theobald and Romme 2007; Zhang et al. 2008; Badia et al. 2011) stressed the importance of estimating not only the current extent of WUI areas but also their trend in expansion, since it allows to minimize their impact, to estimate trends and patterns of WUI expansion in the future, and to make decisions on future land use planning. More recently, also European scientists have increasingly turned their attention on wildland-urban interface issues, with particular care to WUI characterization and mapping, and wildfire risk estimation (assessment) in WUI areas (Camia et al. 2002; Lampin-Maillet et al. 2009, 2010; Caballero and Quesada 2010). Temporal pattern and recent rate of expansion of WUI have been rarely documented in Mediterranean countries. Analysis and mapping of temporal changes of WUI in Mediterranean countries is also one of the main topics of the European project FUME (FP7). The main aim of the present paper is to show the first results of the research activity we carried out in Sardinia island, Italy, with the purpose of analyzing WUI dynamics and landscape change of wildland urban interface in a typical tourist area located in the northeastern part of the island over the period 1954-2008.

2. MATERIAL AND METHODS

2.1. Study area

The study area is located within the territory of Golfo Aranci municipality, in northeastern Sardinia (Figure 1). This area, extended 37.26 km^2, is primarily covered by evergreen sclerophyllous shrubs and sub-shrubs. The climate is Mediterranean with water deficit conditions occurring from May through September and precipitations mainly concentrated in autumn and winter. Historic fire records show that wildfires occurring in the study area are concentrated during the period from May to September.

2.2. Data

For the purpose of analyzing the temporal evolution of WUI areas, a set of aerial photographs from the period 1954-2008 were acquired and georeferenced using a set of ground control points. Six temporal steps (1954, 1968, 1977, 1987, 1998, and 2008) were used for obtaining the spatial themes needed to perform the WUI analysis. The aerial photographs were photointerpreted and digitalized, and a map of dwellings and roads for each time step, with the exception of the last one, was developed. For the last time step spatial themes were obtained from a geodatabase of the Regional Administration of Sardinia containing different sources of data at scales ranging from 1:2000 to 1:10000.

Only residential buildings with a surface area larger than 50 m^2, and therefore more related to fire risk, were included in the analysis.

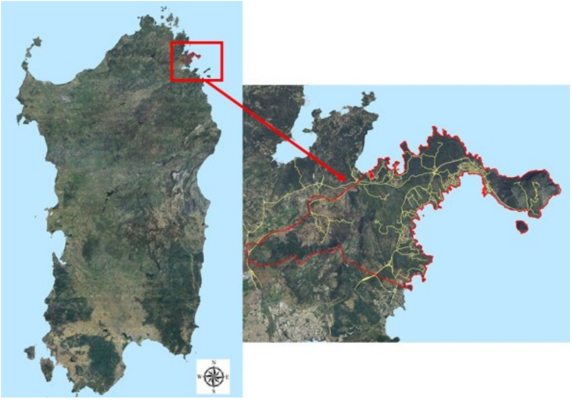

Figure 1. Study area

Characterization and mapping of WUI areas were made using the approach proposed by Lampin-Maillet et al. (2009, 2010), based on the identification of three different housing type configuration: isolated (3 houses less than 100 m apart), scattered (4-50 houses) and clustered (>50 houses). Housing type classification was obtained using a buffer area extending 50 m around the houses. Then, overlapping buffer zones were merged for calculating the number of polygons (houses) inside each buffer, the mean house surface, and the mean house volume. For the purpose of calculating the extension of WUI boundaries, a buffer zone extending 200 m around each identified feature was set up, and the following two additional metrics were calculated: house densities, and extension of the WUI boundary per house. Maps of housing configuration were developed for each time step, and the temporal variation of the different WUI indicators were analysed by calculating the percentage difference between time steps. In addition, for the purpose of defining additional useful information on fire risk assessment, the variations of dwelling residents in the area during the last 60 years were derived from the national census of population (National Institute for Statistics, ISTAT), and compared with the summer season population estimated from house volumes.

3. RESULTS

During the last fifty years, the study area has been characterized by large changes in presence and extension of WUI. The temporal trend of WUIs shows clearly the change from a prevailing agro-pastoral economy to an economy based mainly on tourism. At the end of 50s clustered interface was completely absent in the study area, which was almost completely uninhabited. House number gradually increased until the 80s when the quick tourism development led expansion of different WUI types. An intensification of WUI clustered interface, mainly represented by tourist villages and resorts, occurred near the coast (Figure 2). In particular, the number of buildings increased more or less gradually during the whole period analysed both for WUI-isolated and WUI-scattered classes, whereas WUI-clustered buildings showed two rapid rises during the 70s (from 61 to 350) and the 90s (from 470 to 890) (Figure 3a). The length of road network length rose in conjunction with house number. To estimate the fire risk related to housing development, changes in total WUI perimeter length was also calculated. It is well known that the higher the WUI perimeter length the higher the cost for protecting houses from fire.

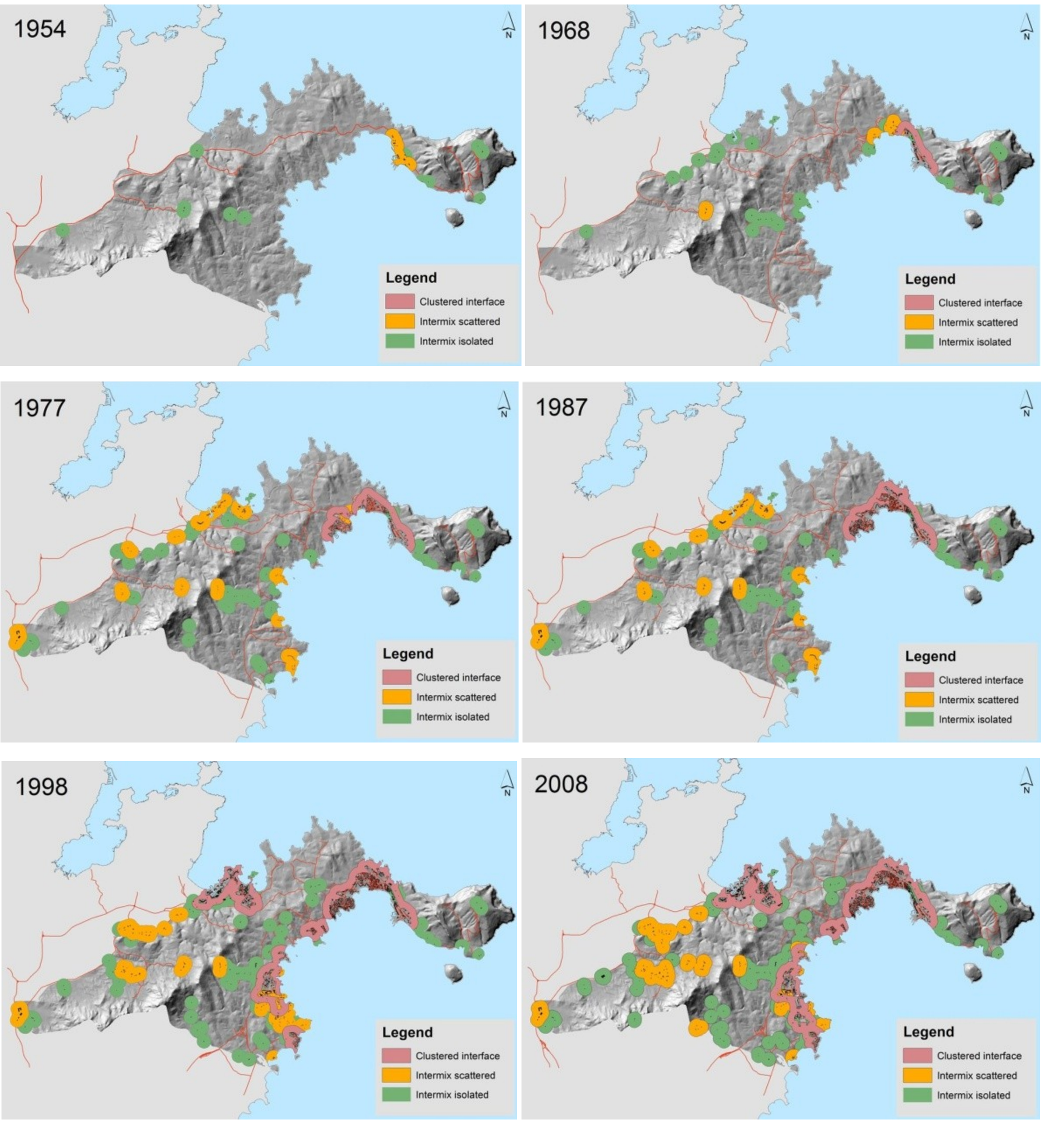

Figure 2. Temporal evolution of WUI classes in the study area during the period 1954-2008

As reported in Figure 3b, a sharp increase of WUI perimeter length was observed throughout the years (from 13 to 111 km). As expected, the largest increase occurred for isolated houses (from 11 to 61 km). WUI isolated class requires higher cost for protection not only because his highest surface exposed to fire but also because roads are often too much small for allowing rescuers to easily reach houses. On the other hand, although edges of WUI clustered are relatively easy to be protected, in this WUI type the fire risk is made worse by population load, which is another important component in determining fire risk, and is higher than in WUI isolated classes.

The temporal building evolution due to the high tourism development in the study area has also caused an increase of dwellers. According to census data from ISTAT, dweller number tripled from 1951 (about 830) to 2010 (about 2400). In addition, population load grows sharply in summer when potential population load can be 1000 times greater than in the other seasons (Figure 3c). The potential population load in summer showed an increment from 2000 people in 1968 to about 23000 people in 2010. In case of dangerous situation determined by wildfire, protection operation aimed at protecting and saving people can become problematic, especially if road network is not developed enough to sustain so high population load.

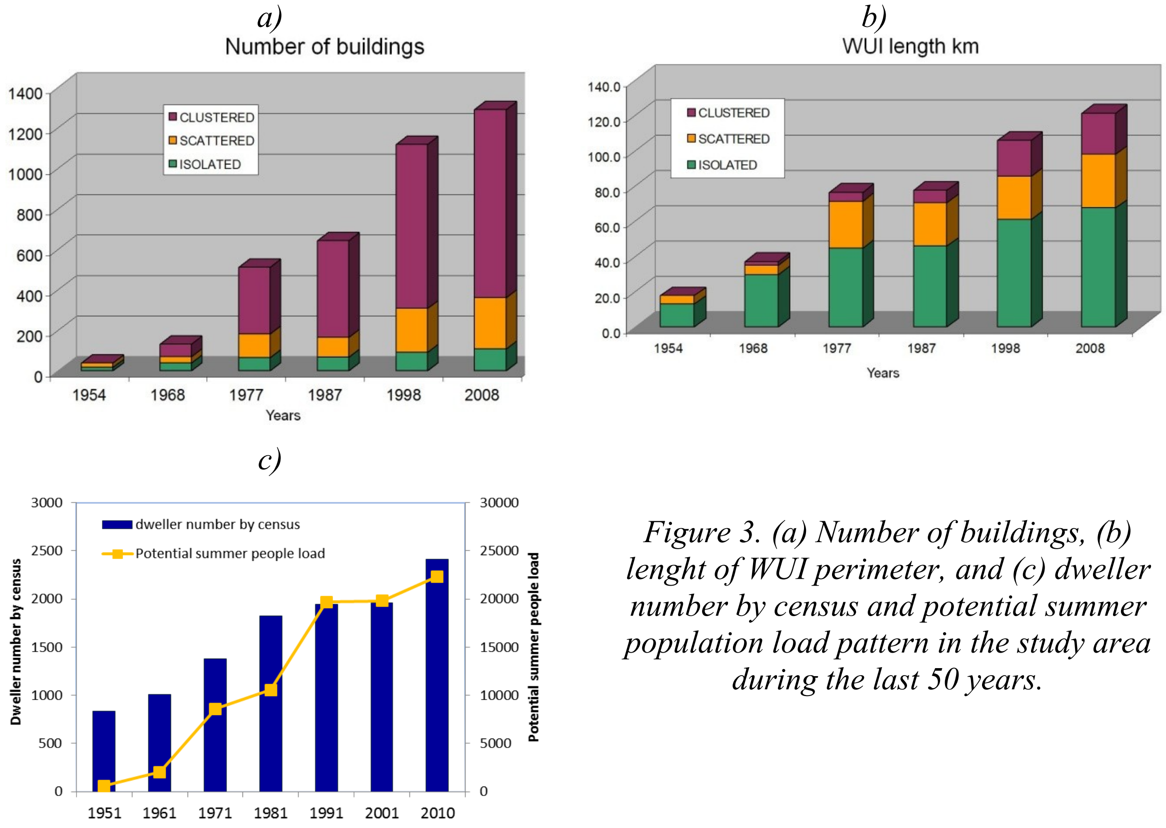

Figure 3. (a) Number of buildings, (b) lenght of WUI perimeter, and (c) dweller number by census and potential summer population load pattern in the study area during the last 50 years.

4. CONCLUSION

In this paper we analysed, at landscape level, housing growth occurred during the last 50 years in an area of North East Sardinia. We showed how some factors affecting fire risk can change due to WUI expansion. Our first results showed that this approach allows to estimate the potential evolution of fire risk in this kind of areas. Knowledge of potential future fire risk associated with housing and population growth at landscape level can help public land management to develop strategies and planning policies taking into account also wildland fire risk.

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Multiscale modelling of forest fire smoke emissions impact on urban air quality at the pedestrian level

Amorim J.H.[1]; Miranda A.I.[1]; Sá E.[1]; Martins V.[1]; Ribeiro C.[2]; Coutinho M.[2]; Borrego C.[1]

[1]CESAM and Department of Environment and Planning, University of Aveiro, Portugal;
[2]IDAD – Instituto do Ambiente e Desenvolvimento, Aveiro, Portugal

amorim@ua.pt

Abstract

Forest fires are known to have serious consequences on air quality levels both at local and regional scales due to the heavy emission of particles, and several gaseous compounds, to the atmosphere. Currently, one of the most critical air pollution problems is associated with the high concentrations of particulate matter in the atmosphere, which causes approximately three million deaths per year in the world. This work addresses the numerical modelling of the spatial distribution of particles with less than 10 μm in equivalent aerodynamic diameter (PM10) at the pedestrian level, applying a meso- to microscale approach. The study case is a fire occurred in northern Portugal, close to the town of Trofa, that consumed 93 ha of forest and shrublands during a period of 18 hours. The implemented methodology was based on a three stage process: (1) the estimation of smoke emissions taking into account the specificities of southern-European fuels and climate, (2) the application of TAPM model to a forest fire accounting for the temporal discretization of the area burned, and (3) the use of TAPM outputs as boundary/initial conditions for the application of the Computational Fluid Dynamics (CFD) model FLUENT. Regarding emissions, in average and comparing with road traffic emissions, the fire contributed with 85% of the mass of particles at five different spots in the city during the period of simulation. The CFD simulations reveal the complex characteristics of the windflow inside the city, resulting from the synergies between the configuration and positioning of buildings and trees and the synoptic wind. Highly ventilated zones were identified, allowing an efficient removal of particles, in opposition to others where decreased wind speed and the formation of recirculations leads to the formation of air pollution hot-spots. However, the PM10 limits established by the air quality directive for the protection of human health (2008/50/EC) were not exceeded. This work provides spatially and timely detailed PM10 concentrations in a typical southern European town facing a medium-size forest fire and therefore contributes to the understanding of the potential impacts of forest fires on short-term human health and the definition of emergency action plans, meeting the growing need of data for smoke impact management in urban areas.

Keywords: forest fire emissions, urban air quality, numerical modelling, multi-scale approach

1. INTRODUCTION

Nowadays, one of the most critical air pollution problems is associated with the high concentrations of particulate matter in the atmosphere. Estimates from the European Environment Agency [EEA 2003] indicate that the human exposure to PM causes approximately 3 million deaths per year in the world. In this context, forest fire events are particularly relevant because of the heavy production of particles and several gaseous compounds, which have impacts at global scale through climate change, at regional scale due to photochemical pollution, and at local scale through severe air quality degradation.

The main objectives of the current work are the following:

- to contribute to the understanding of the potential impacts of forest fires on urban air quality;
- to provide spatially and timely detailed PM10 concentrations in a typical southern European town facing a medium-size forest fire.

But, how to simulate the transport/dispersion of the smoke plume from the emission source through the city boundaries with the required spatial resolution? This is one of the questions addressed by this paper.

2. METHODOLOGY

The methodology applied in this research, with the objective of obtaining the concentration of particles with less than 10 μm in equivalent aerodynamic diameter (PM10) at the pedestrian level, is based on the application of a multi-scale air quality modelling approach that can be structured into the following stages:

(1) smoke emission estimation taking into account the specificities of southern-European fuels and climate,

(2) mesoscale smoke dispersion modelling applying the mesoscale air quality model TAPM and accounting for the temporal discretization of the area burned,

(3) microscale smoke dispersion modelling using TAPM outputs as boundary/initial conditions for the application of the Computational Fluid Dynamics (CFD) model FLUENT.

The case-study for this work is the forest fire event occurred in the 23rd of August 2009 in Northern Portugal, close to the town of Trofa, which consumed 93 ha of forest and shrublands during an 18 hours period.

2.1. Smoke emissions estimation

Smoke emissions were estimated based on the product of the emission factor for PM10, the burning efficiency, the fuel loading and the area burned. Except for the area burned, which was obtained for the official report, the other data were compiled by Miranda (2004) and were selected as the most suitable values representing south European ecosystems, namely the Portuguese fuel types (see Table 1).

Table 1. Fuel load, burning efficiency and emission factors (Miranda 2004).

Forest type	Fuel load ($kg.m^{-2}$)	Burning efficiency	PM10 emission factor ($g.kg^{-1}$)
Shrubs	1.00	0.80	10
Resinous	8.60	0.25	10
Deciduous	1.75		13
Eucalyptus	3.90		13

2.2. Downscaling technique

The simulation of the processes in which the smoke plume undergoes in the atmosphere (transport, dispersion, deposition, chemical reaction) was carried out through the application of the three-dimensional prognostic model TAPM version 3.0 (for details on the numerical formulation and parameterizations, including the numerical methods used to solve the model equations, see Hurley et al. [2005]). TAPM was applied to Northern Portugal region, with a horizontal domain of 900×900 km^2, as shown in Figure 1, with nested resolutions of 30, 10, 3 and 1 km and a vertical grid of 8000 m and 25 levels, with the first level 10 m above the ground. The information on meteorology and PM10 concentration was then used to prescribe the local scale boundary conditions of the CFD model FLUENT, version 6.1.18 for UNIX platforms. The CFD simulation area has 1.3×1.3 km^2, with a spatial grid resolution varying between 0.01 and 1100 m^3, in a total of approximately 5 million computational cells. The downscaling technique is schematically shown in Figure 1, conjointly with a perspective of the 3D domain generated for the CFD simulation.

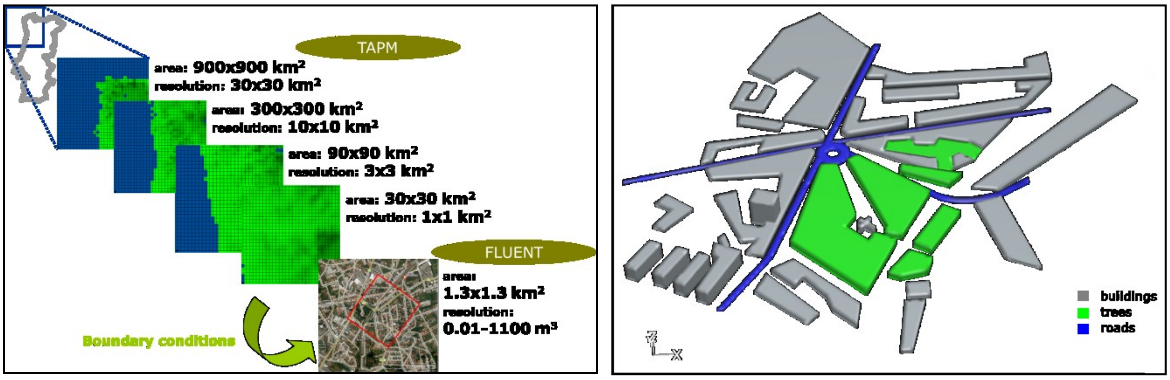

Figure 1. Regional to local scale downscaling technique (left) and virtual domain of Trofa city center generated with FLUENT's preprocessor Gambit (right).

FLUENT is a general-purpose CFD model widely applied in the simulation of diverse types of flows and transport phenomena in varied scientific and engineering branches. Its application in the simulation of urban air quality under the influence of a forest fire was validated by Miranda et al. (2008). The 3D windflow is computed by solving the Reynolds Averaged Navier-Stokes (RANS) equations, with a specific module that accounts for the aerodynamic effects of trees (Amorim et al. 2010), using the standard k-ε turbulence model.

Particles dispersion is calculated applying an Eulerian approach. Road traffic emissions are estimated with TREM model (Borrego et al. 2003).

3. MODELING RESULTS

Hourly average results for wind velocity and PM10 concentration in the study area are presented in the following sub-sections.

3.1. Windflow

Taking as example any of the images presented in Figure 2, it can be seen that significantly distinct ventilation capacities of the different street-canyons in the study area were obtained due to the effect of buildings and trees over the windflow. Along the simulation period there was also a modification of the windflow patterns, as a response to the change of the synoptic conditions.

The windflow behaviour shapes the trajectory of the smoke particles through the urban canopy (buildings and trees). In this sense, the spatial resolution provided by the CFD model is crucial for the detailed understanding of the interaction between the meteorological conditions and the configuration/positioning of the urban elements.

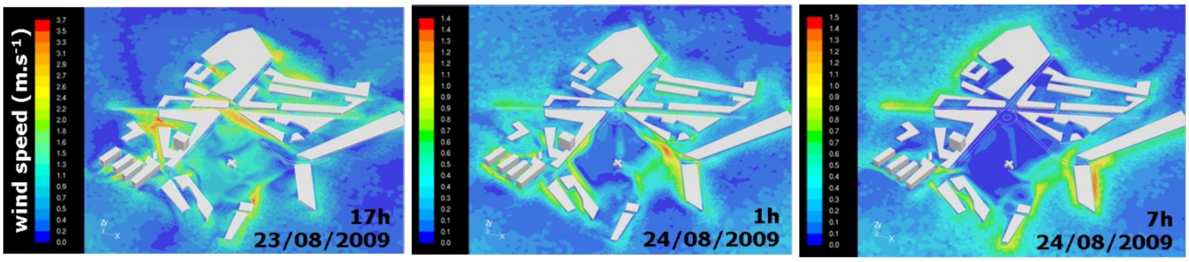

Figure 2. Horizontal plane (at 3 m high) of wind speed in the study area, obtained with FLUENT for 3 hourly periods with distinct inflow meteorological conditions. For simplicity, the porous volumes representing the trees are not shown.

3.2. PM10 concentration

According to the simulations, there was a consistent increase of PM10 concentrations until 1 h, as shown in Figure 3, which is associated with the decrease of wind speed. As expected, it is for a W-SW wind direction, responsible for the transport of the smoke plume towards the city, that the air quality levels are more significantly affected. The red line in the Figure represents both the contribution of fire and traffic emissions, while the grey line accounts only for traffic. It can be inferred that comparing with road traffic, the fire contributed with 85% of the mass of particles at the selected 5 spots.

Additionally, Figure 4 represents the horizontal contours of PM10. Highly ventilated zones were identified, which allow an efficient removal of particles, in opposition to others where decreased wind speed and the formation of recirculations leads to the formation of hot-spots (higher concentration areas).

Different dispersion patterns were obtained according to the change on the prevailing wind direction. At 17h and 7h the traffic hot-spots are clearly visible, while for 1h, when the influence of fire is strongest, there is a much more homogeneous distribution of particles in the simulation area, which is the typical urban air quality pattern obtained under the influence of a forest fire (in agreement with the conclusions taken by Miranda et al. 2008).

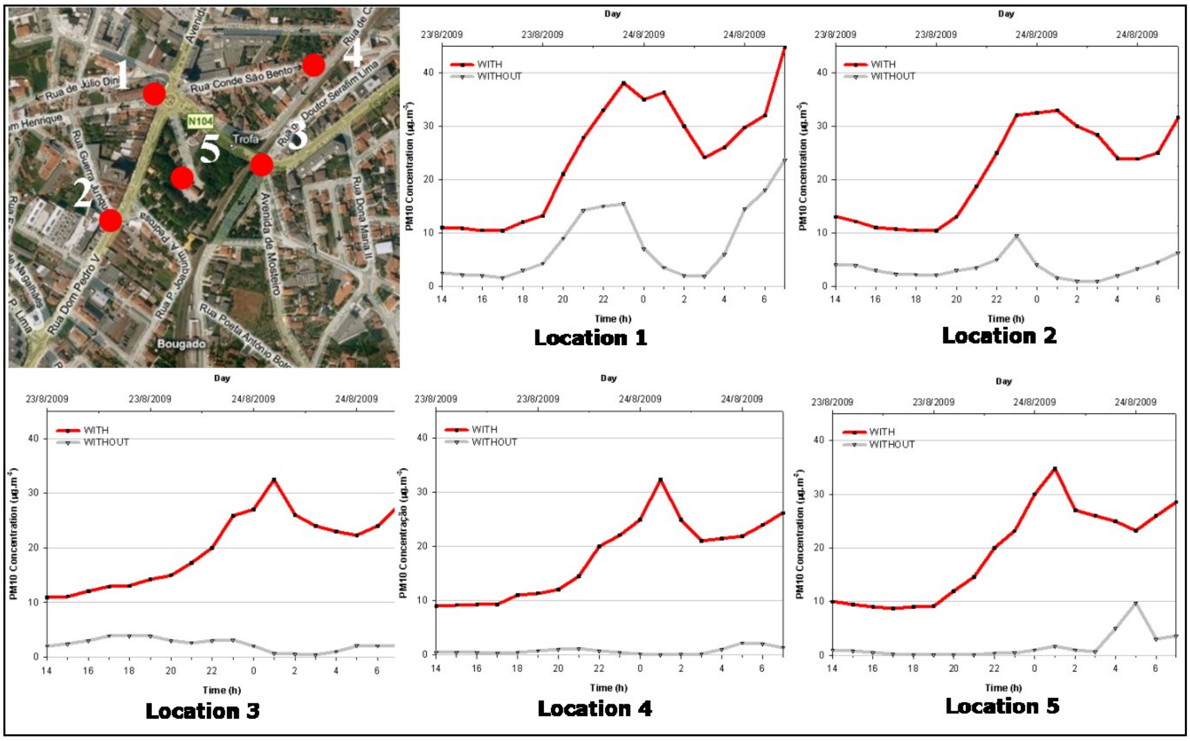

Figure 3. Temporal evolution of hourly average PM10 simulated with FLUENT at 5 selected spots, with and without the presence of smoke.

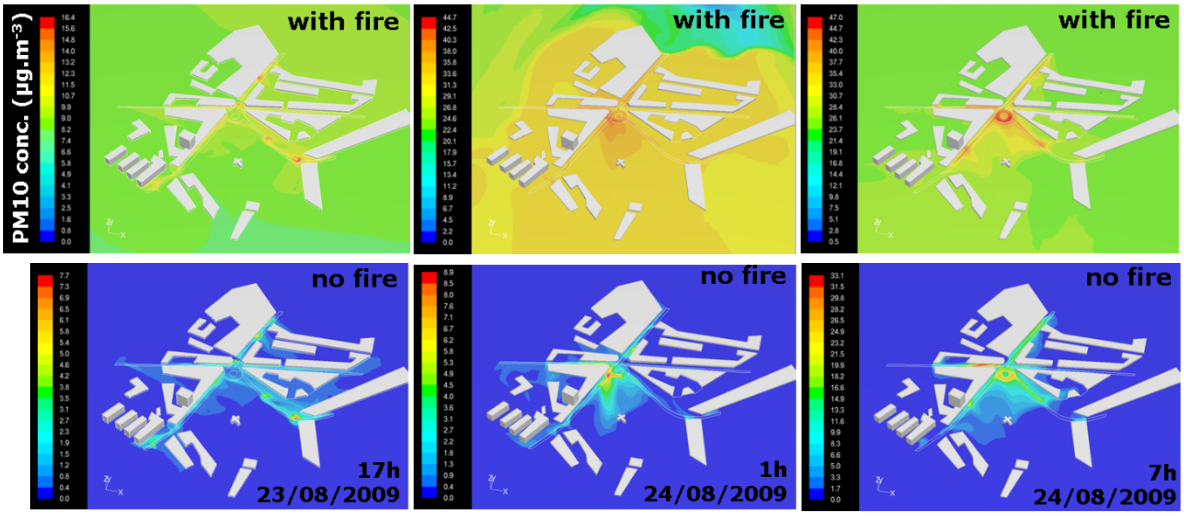

Figure 4. Horizontal plane (at 3 m high) of PM10 concentration in the study area, obtained with FLUENT for the same 3 hourly periods.

4. FINAL CONCLUSIONS

This work provides spatially and timely detailed PM10 concentrations at the pedestrian level in a typical southern European town facing a medium-size forest fire. Although the PM10 limits established by the air quality directive for the protection of human health (2008/50/EC) were not exceeded, the fire was responsible for a significant contribution to air pollution levels.

The multi-scale modelling approach can contribute to the understanding of the potential impacts of forest fires on short-term human health and the definition of emergency action plans, meeting the growing need of data for smoke impact management in urban areas.

5. ACKNOWLEDGMENTS

The authors would like to acknowledge the financial support of the Portuguese Ministry of Science, Technology and Higher Education, through the Foundation for Science and Technology (FCT), for the Post-Doc grant of J.H. Amorim (SFRH/BPD/48121/2008), and the PhD grants of E. Sá (SFRH/BD/60474/2009) and V. Martins (SFRH/BD/39799/2007).

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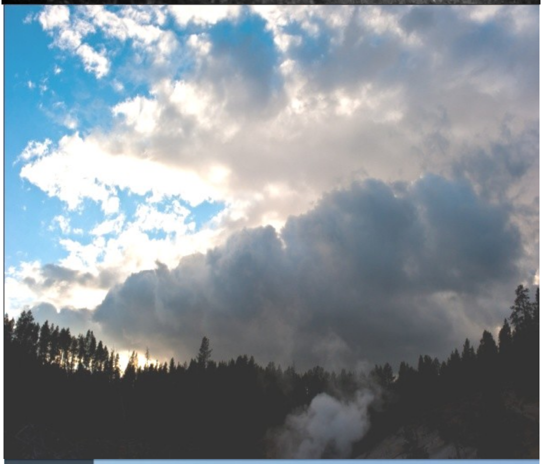
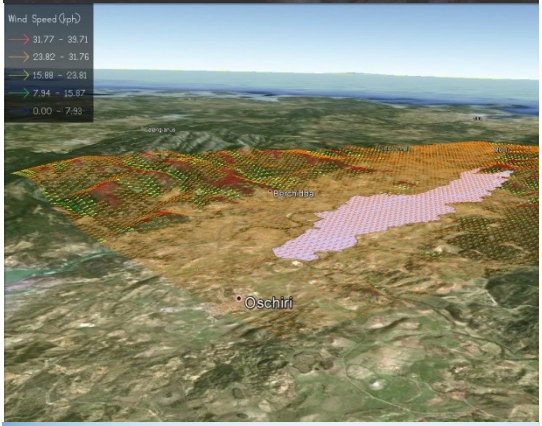
AUTHORS





ISBN 978-88-904409-7-7