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Remote sensing evaluation of fire hazard: towards operational tools for improving the security of citizens and protecting the environment

Carmine MAFFEI,[1,2] Carmine GAMBARDELLA,[3] Massimo MENENTI[4]
(1) BENECON scarl, Aversa, Italy
carmine.maffei@unina2.it
(2) Department of Geoscience and Remote Sensing, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, Netherlands
c.maffei@tudelft.nl
(3) Department of Architecture and Industrial Design, Seconda Università degli Studi di Napoli, Aversa, Italy
carmine.gambardella@unina2.it
(4) Department of Geoscience and Remote Sensing, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, Netherlands
m.menenti@tudelft.nl

Abstract
Forest fires are a threat for both the environment and the security of citizens. This is particularly relevant in the Mediterranean, where the population density is high, and long dry summers drive vegetation into fire-prone conditions. Policy makers underline the key role of prevention over damage reparation, and indeed efforts are conducted at regional, national and international level to develop tools supporting fire managers' activities. The preventive allocation of intervention resources is based on fire hazard maps; these should be updated frequently throughout the fire season. In this framework satellite remote sensing can play a key role, providing daily measurements in the optical domain for the determination of vegetation water content, a key parameter for the prediction of fire hazard. This paper outlines current practices adopted in Mediterranean Europe, analyses how earth observation data are used, and underlines areas of improvement. Strengths and weaknesses of algorithms for the retrieval of vegetation water content are discussed. Examples are provided with the production of remote sensing maps of vegetation moisture in three different areas of the Mediterranean: Campania (Italy), Tuscany (Italy) and Provence-Alpes-Côte d'Azur (France). Finally, a brief review describes current and forthcoming Earth Observation missions with the potential to support fire prevention activities.

Keywords: Fire danger rating systems; Mediterranean; MODIS; Perpendicular Moisture Index; Copernicus Sentinels program.

1. Introduction
Forest fires are a major threat for both the security of citizens and the environment (**Fig. 1**). In the Mediterranean more than 290000 hectares were burnt in 2013, of which 72000 hectares belonged to Natura2000 sites of the European Union [1]. On average, about 50000 fires are recorded annually, burning between 700000 and 1000000 hectares [2]. Fires cause loss of human lives [3], have a negative impact on the productive potential of forests and surrounding lands, and affect regional economies and population's life quality, especially in the economically depressed areas.
The phenomenon is mainly dictated by climatic conditions. Prolonged summers with poor precipitations and high temperatures increase water loss through evaporation and transpiration, causing a reduction in live and dead fuels moisture content and an increase in forests susceptibility to fires. About 95% of fires are man-caused. Fire fighting activities employ 30000 workers every summer, rising to 50000 in the most hazardous years. About 300 aircrafts are used for suppression. The observed increase of the fire phenomenon in recent decades is due to changes in land use and climate. Predicted change in climate points towards increased temperatures and reduced summer rainfalls, thus leading to an increase in fire risk [1].


Fig. 1: Forest fires in Italy in the summer of 2007 (Source: NASA).

Strategies for the reduction of potential damage include early warnings and optimal allocation of resources. The former is ensured by the spontaneous alerts provided by the civilians, thanks to the high population density in the Mediterranean area. Therefore, the main concern of fire managers is about fuel condition and its variation with time, i.e. with fire hazard. This property affects the ease of inception and fire propagation, and serves as a basis for fire prevention planning. To allow for effective use, maps of fire hazard should be updated frequently thoughout the fire season. In this framework satellite remote sensing can play a key role, providing daily measurements in the optical domain useful for the determination of vegetation water content, a key parameter for the prediction of fire hazard.
The need for an efficient and advanced method to assess and monitor forest fire hazard is clearly acknowledged by the European Union. In 2006 the European Parliament has adopted resolution P6_TA(2006)0349 on “Forest fires and floods,” further reinforced by resolutions P7_TA(2009)0013 on “Forest fires in the summer of 2009,” P7_TA(2012)0147 on “A better environment for a better life,” and P7_TA(2012)0223 on “A resource-efficient Europe.” These resolutions recognise that forest fires not only affect Spain, Portugal, Greece, France, Italy and Cyprus, but also member States traditionally considered less at risk (such as The Netherlands, Ireland, Lithuania, UK, Austria, Sweden, Czech Republic and Poland), and that the phenomenon can only be handled efficiently at Community level. They underline the key role of prevention over damage reparation, and call for scientific improvements and exchange of experience in fire risk evaluation technologies.

2. Current fire hazard mapping practices in Europe

For a fire to spread it is required that fuel moisture and temperature are at an adequate level [4]. A forest fire hazard index synthesises this information into a set of indicators, or even a single value, providing a measure of ignition probability. Several fire danger rating systems have been into operational use since the first half of the 20th century, most of them adopted on a national basis. Those developed and currently used in Portugal, France, Italy, Canada and Australia are essentially based on meteorological input [5]. In these models, weather conditions over a period of time are used to produce indirect estimates of the moisture content of dead fuels. However, information on live fuel status and fuels temperature is disregarded. The

National Fire Danger Rating System (NFDRS) used in the Unites States uses meteorological information in conjunction with maps of fuel types and of vegetation relative greenness [6], [7]. The latter is retrieved from time series of vegetation vigour calculated from satellite remote sensing measurements in the visible and in the near infrared. Vegetation vigour is a measure of forests' health, and its variation with time is used as a proxy for live vegetation moisture. NFDRS maps have a resolution of 1 km.
To harmonise fire information systems within the European Union, the Joint Research Centre (JRC) established the European Forest Fire Information System (EFFIS). As part of the Regulation (EC) 2152/03, EFFIS develops and delivers services supporting fire prevention. In 2007 EFFIS adopted the Canadian Fire Weather Index (FWI) System as a unified method for fire danger mapping. Fire hazard maps are processed from meteorological data and distributed to forest services and civil protection agencies. Currently, these maps have a resolution of 10, 16 or 25 km. Although valuable at national and international scale, they are inappropriate at regional level, where fire management decisions are usually made, and a spatial resolution of 1 km or better is needed.

3. Considerations on the use of Remote Sensing

Remote sensing research has dealt with various aspects of the forest fires phenomenon, leading to well established methodologies for fire detection, burnt scar mapping, and vegetation recovery monitoring. Remote sensing applications for fuel status and fire hazard mapping are still under development [8]. Indeed, current fire danger mapping methods make little use of remote sensing data. The only exception is the NFDRS, although satellite imagery is only used for the evaluation of a property that is indirectly related to vegetation moisture. Nevertheless, existing satellite Earth observation instruments have been launched in the last 15 years that potentially allow for the direct retrieval of live vegetation moisture content of both alive and dead fuels temperatures [9], [10].
This outlines a clear need for further research to fill the gap between knowledge and application, towards the operational use of remote sensing for fire hazard mapping. Given the complementary information they carry, meteorological fire indexes and satellite retrievals of vegetation moisture may be used synergistically to construct a comprehensive model of fire hazard [11], [12].

4. Remote sensing of vegetation moisture content

Vegetation moisture can be expressed in two different ways. The Remote Sensing research community is familiar with the concept of equivalent water thickness (EWT), which measures the mass of water per unit of leaf area. EWT is not suitable for use in fire danger models, since the key variable related to fire ignition and rate of spread is live fuel moisture content (LFMC), and the two parameters are not exchangeable. LFMC is defined as the mass of water per unit of leaf dry mass.
Water content in leaf tissues affects their optical properties in the shortwave infrared. This characteristic has been exploited to estimate EWT through several spectral indexes [13]–[16], i.e. simplified arithmetic models for the translation of earth observation measurements into estimates of water content. However, these indexes are not good estimators of LFMC [17], [18]. In recent papers [9], [19] the perpendicular moisture index (PMI) was introduced to exploit the spectral characteristics of MODIS sensor on board Terra and Aqua satellites of NASA Earth Observing System (EOS) programme and provide an estimate of LFMC.

5. Examples in Italy and France

The Moderate Resolution Imaging Spectroradiometer (MODIS) sensors mounted on Terra and Aqua satellites from NASA view the entire Earth's surface almost on a daily basis, recording radiance in 36 spectral channels ranging from the optical to the thermal domains. MODIS data are free of charge, and can be downlinked and processed at ground stations worldwide for the near-real-time processing and delivery of services. These characteristics make this sensor ideal for the production of fire hazard maps.
To show the potential of the PMI to produce maps of LFMC derived from MODIS imagery, three large areas in the Mediterranean were selected: Campania (13595 km^2), Italy; Tuscany (22994 km^2), Italy; Provence-Alpes-Côte d'Azur (PACA, 31400 km^2), France. Campania is an economically depressed area listed in the European Convergence Regions. It embraces a diversity of the landscape and land use/land cover (e.g. scrubland on coasts and internal hills, evergreen and deciduous woods, agricultural plains, mountains, inland cereals cultivations, a variety of abandoned rural areas) that are representative of wider areas throughout the Mediterranean. Tuscany is characterised by extremely heterogeneous morphological and land cover features. Its climate ranges from Mediterranean to temperate warm or cool following the altitudinal and latitudinal gradients and the distance from the sea. Forests cover about half of the region and are mostly placed in the inner hilly and mountainous areas. PACA is one of most densely wooded regions of France, hosting a high biodiversity. Its Mediterranean climate is characterized by wet and mild winters, while the summers are hot and dry.
Fire records from different sources were used:

- Campania: a database of more than 7700 fire records covering years between 2000 and 2008, provided by the Italian Forest Corps (*Corpo Forestale dello Stato*, CFS).
- Tuscany: a database of more than 2300 fires records between 2000 and 2007, provided by the Regional Administration of Tuscany.
- PACA: a collection of more than 9400 fires between 2000 and 2012 extracted from the Prométhée database [20].

From a qualitative point of view, maps of PMI show clear annual variability in its spatial pattern. An example of this can be noticed in **Fig. 2**, where four maps represent the values of the LFMC estimated from the PMI in the same day (the 208th) of years 2003, 2004, 2005 and 2006 in Campania. Similar observations can be drawn from LFMC maps in Tuscany (**Fig. 3**) and PACA (**Fig. 4**) [21].

Maps of satellite-derived LFMC also show clear seasonal trends. **Fig. 5** shows the example of four successive dates (every eight days) in Campania. The maps exhibit decreasing values of LFMC, capturing the evolution of vegetation condition during the dry season. Although not shown here, this pattern was observed in every year under consideration. Also in this case, similar results can be reproduced for Tuscany (**Fig. 6**) and PACA (**Fig. 7**) [21].

Fire rate of spread is affected by several factors of different nature. To isolate the role of vegetation moisture (as estimated by the PMI) from that of all the other factors, the median PMI values associated to the fires in a study area were plot against the mean value of the rate of spread (**Fig. 8**). The plots show evidence of a linear relationship between PMI and fire rate of spread [21]. Higher PMI values (and thus higher LFMC values) imply a lower rate of spread, as it would be expected in conditions of higher moisture content in vegetation. Although the regression is linear in both study areas, the regression differs, due to the different environmental and climatic conditions in the two regions. This observation was only performed in Tuscany and Campania, since the Prométhée database does not contain information on fire duration.

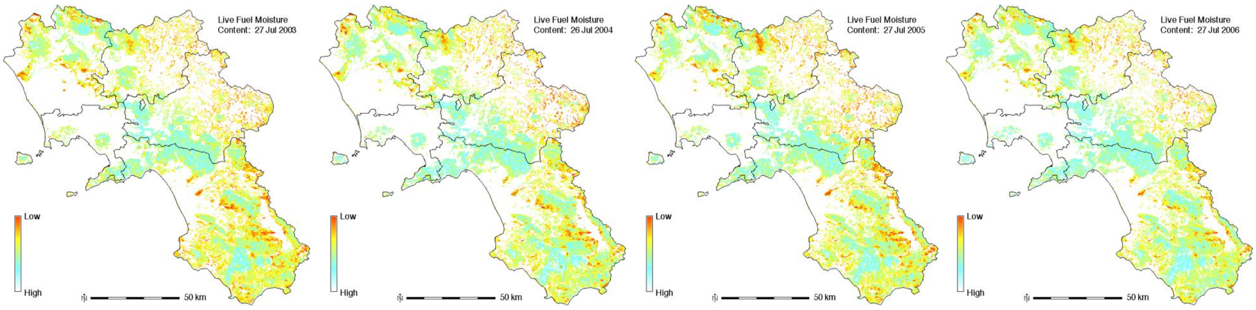

Fig. 2: Maps of estimated live fuel moisture content in the same date of four successive years in Campania, Italy.

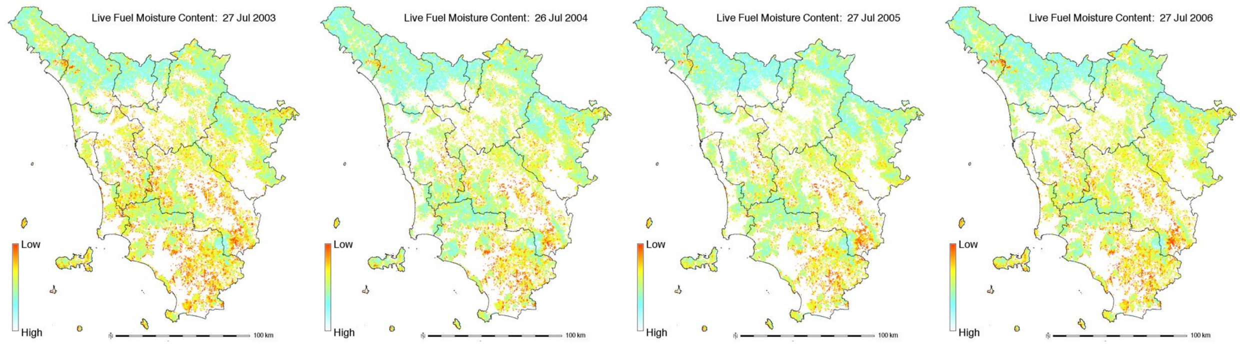

Fig. 3: Maps of estimated live fuel moisture content in the same date of four successive years in Tuscany, Italy.

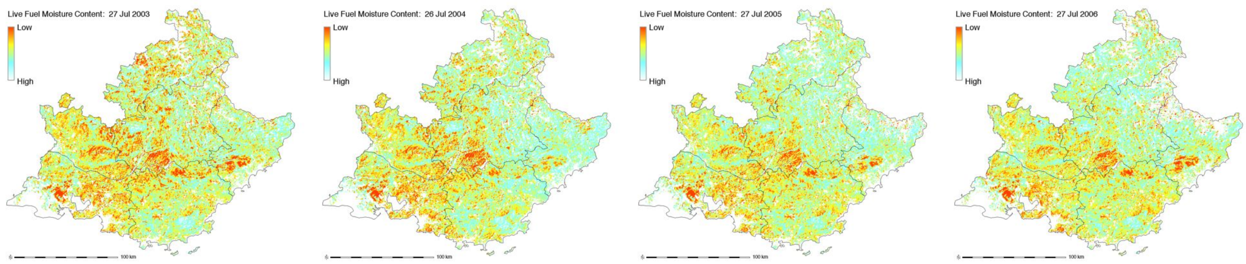

Fig. 4: Maps of estimated live fuel moisture content in the same date of four successive years in PACA, France.

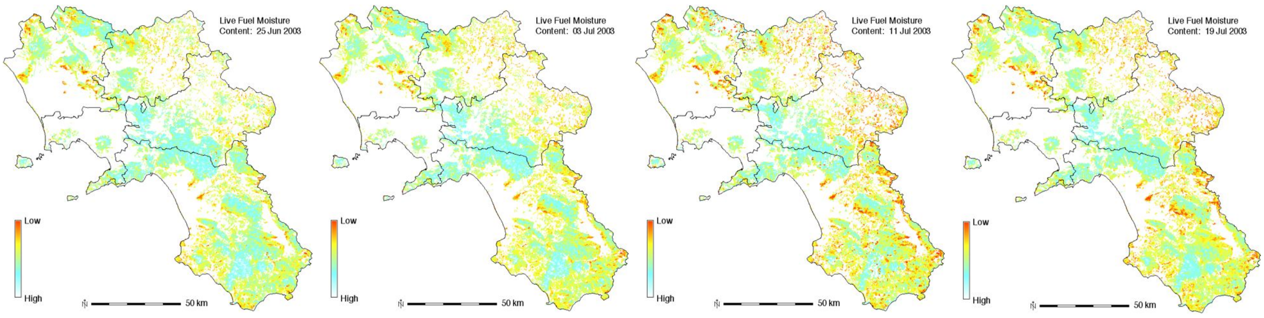

Fig. 5: Maps of estimated live fuel moisture content in four successive dates of the same year in Campania, Italy.

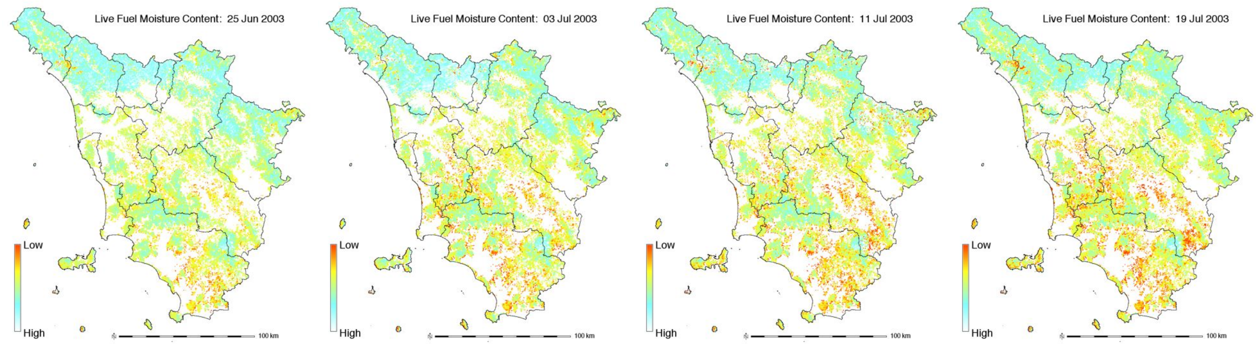

Fig. 6: Maps of estimated live fuel moisture content in four successive dates of the same year in Tuscany, Italy.

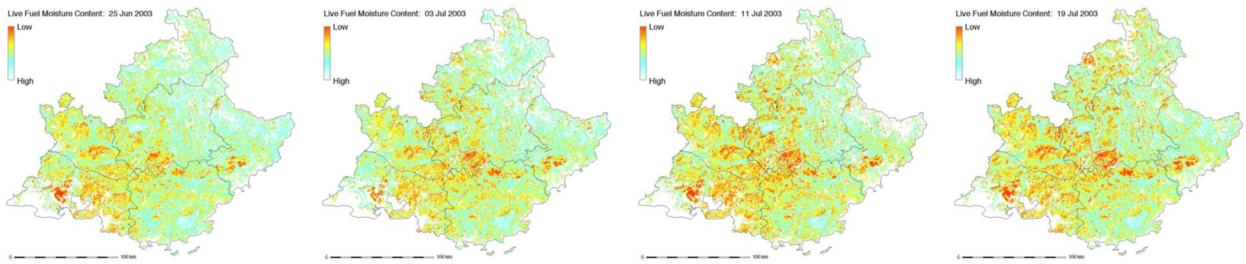

Fig. 7: Maps of estimated live fuel moisture content in four successive dates of the same year in PACA, France.

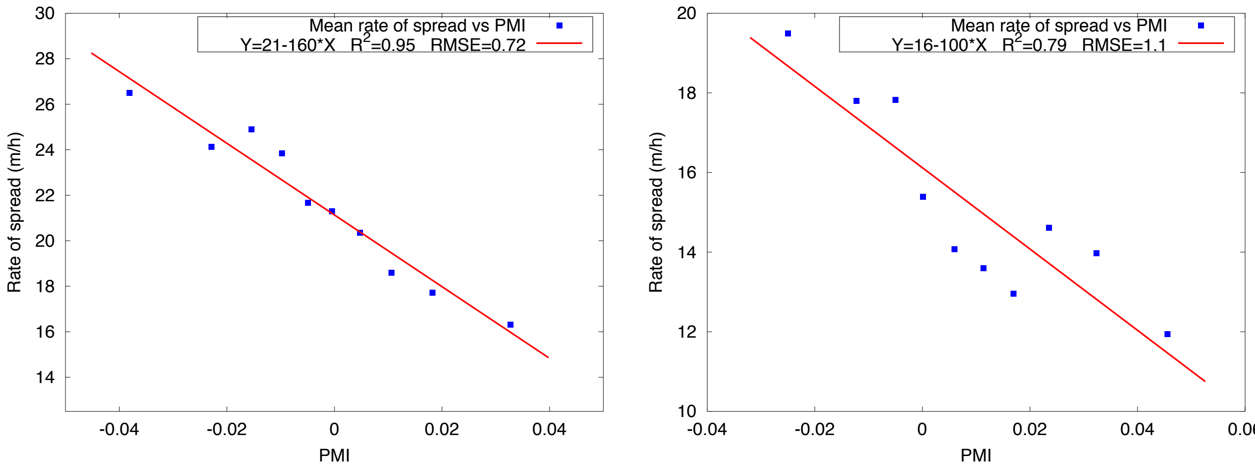

Fig. 8: Relationship between PMI and fire mean rate of spread in Campania (left) and Tuscany (right).

Vegetation water content also affects ease of inception, and indeed this results in clear trends in the number of fires with varying values of PMI. The median PMI value in 8-day compositing periods was compared against the number of fires occurred in the following compositing period, and mean tabular data were produced for each intermediate administrative unit (provinces in Campania and Tuscany, departments in

PACA) [21]. In Campania there is a clear variation of the mean number of fires with PMI (**Tab. 1**): when the vegetation moisture content is higher (the PMI is higher), a lower number of fires is observed. Similar results were found in Tuscany (**Tab. 2**) and PACA (**Tab. 3**).

6. Current and future operational instruments

The examples reported in section 5 are based on data from MODIS instrument. This choice was dictated by the need to develop the methodology against historical fire data on the longest available time frame. Nevertheless, similar results may be achieved using other sensors and satellite missions capturing the electromagnetic radiation in the wavelengths of the optical domain affected by the water content in vegetation tissues, thus providing the opportunity to directly quantify LFMC. In this section, a few of them will be described.

VEGETATION (VGT) is a family of sensors developed by European scientific and industrial partners with the aim of providing large-swath multispectral images of the land surface. VGT-1 and -2 are substantially identical instruments installed on board SPOT-4 (Satellite Pour l'Observation de la Terre-4, 1998-2013) and SPOT-5 (2002 to present) satellites respectively. They capture the reflected solar radiation in the blue, red, near infrared (NIR) and shortwave infrared (SWIR) with a swath of 2200 km and a ground sampling distance of 1 km. The two sensors allow a near to daily global coverage. VGT-P is a spectrally equivalent and much smaller sensor on board the PROBA-V (2013 to present) micro-satellite. It provides daily coverage of continental masses with a swath of 2285 km and a 300 m baseline ground resolution.

The Visible Infrared Imaging Radiometer Suite (VIIRS) is a multidisciplinary sensor capturing radiation from the visible to the thermal infrared in 22 bands. It was designed to provide long-term continuity to MODIS data and science products. The first VIIRS was launched on board the Suomi NPP (Suomi National Polar-orbiting Partnership) in 2011, jointly managed by NASA and NOAA. It provides a daily revisit of almost the entire globe, with a ground resolution of 370-740 m. A second specimen of VIIRS is planned to be launched on board JPSS-1 (Joint Polar Satellite System-1) in 2017.

Tab. 1: Relationship between the mean number of fires and the median PMI value in 8-day observation periods, for each province of Campania.

	Mean number of fires					
Province	PMI<-0.01	-0.01<PMI<0	0<PMI<0.1	0.01<PMI<0.02	0.02<PMI<0.03	PMI>0.03
Caserta	4.25	4.83	4.46	2.42	0.96	0.5
Benevento	6.80	7.56	2.58	1.57	0.14	-
Napoli	-	-	4.14	4.08	1.43	-
Avellino	6.37	9.11	7.45	1.14	1.17	-
Salerno	13.08	20.98	15.48	3.31	0.75	-

Tab. 2: Relationship between the mean number of fires and the median PMI value in 8-day observation periods, for each province of Toscana.

	Mean number of fires					
Province	PMI<-0.01	-0.01<PMI<0	0<PMI<0.1	0.01<PMI<0.02	0.02<PMI<0.03	PMI>0.03
Massa Carrara	-	-	2.37	2.28	1.28	0.69
Lucca	-	-	2.25	2.98	4.13	2.06
Pistoia	-	-	-	1.71	1.68	1.67
Firenze	-	4.73	4.83	3.43	1.75	0.67
Livorno	-	1.06	0.71	0.55	0.33	-
Pisa	-	2.26	2.51	1.70	0.64	-
Arezzo	-	4.18	4.40	1.61	1.71	-
Siena	2.81	1.79	0.93	0.36	-	-
Grosseto	3.68	2.48	1.79	0.64	-	-
Prato	-	-	-	0.70	0.69	0.72

Tab. 3: Relationship between the mean number of fires and the median PMI value in 8-day observation periods, for each department of PACA.

	Mean number of fires				
Department	PMI<-0.02	-0.02<PMI<-0.01	-0.01<PMI<0	0<PMI<0.01	PMI>0.01
Alpes-de-Haute-Provence	2.71	1.45	1.11	0.71	-
Hautes-Alpes	-	0.43	0.26	0.21	-
Alpes-Maritimes	-	4.75	5.53	4.48	4.00
Bouches-du-Rhône	9.86	10.41	7.19	7.25	-
Var	10.14	10.45	8.48	4.58	-
Vaucluse	1.34	1.80	1.47	1.11	-

“Copernicus” is the Earth observation programme established by the European Union and managed by the European Space Agency (ESA). The programme was initially known as GMES (Global Monitoring for Environment and Security), and was named after the 16th century astronomer Nicolaus Copernicus in 2012. Copernicus will be implemented through the launch of the Sentinel missions, a number of remote sensing satellites meant as the European contribution to the Global Earth Observation System of Systems (GEOSS).
The Sea and Land Surface Thermal Radiometer (SLSTR) is a wide swath sensor planned for launch on Sentinel-3A satellite by the end of 2015. A twin mission (Sentinel-3B) will be launched 18 months later. SLSTR builds on the experience of the Advanced Along Track Scanning Radiometer (AATSR) on board of the EnviSat satellite, whose peculiar characteristic was the availability of a dual-view camera almost simultaneously capturing radiation in two viewing directions. In the thermal infrared, this unique feature potentially allows the separation of vegetation and soil temperatures [10], [22]. SLSTR has a swath of 1400 km for the nadir-looking camera and 740 km for the oblique camera. This allows daily coverage of the globe with the nadir-viewing camera, and less than two days revisit time in dual-view mode. The sensor images the surface in 11 spectral channels from the visible to the thermal infrared with a ground resolution of 500 m in the visible, NIR and SWIR, and 1 km in the longer wavelengths.
The Sentinel-2 satellites A and B will carry the Multispectral Imager (MSI), a high-resolution optical sensor designed to provide long-term continuity to Landsat and Spot missions. MSI operates in 13 bands between the visible and the SWIR. Ground resolution is 10 m for visible and NIR bands, 20 m for red-edge and SWIR bands, and 60 m for atmospheric bands. Thanks to the ground swath of 290 km, the MSI will have a revisit time of 10 days. Sentinel-2A will be launched in June 2015, followed by Sentinel-2B about 18 months later. When both satellites will be operational, it will be possible to produce high-resolution fire hazard maps every 5 days.

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