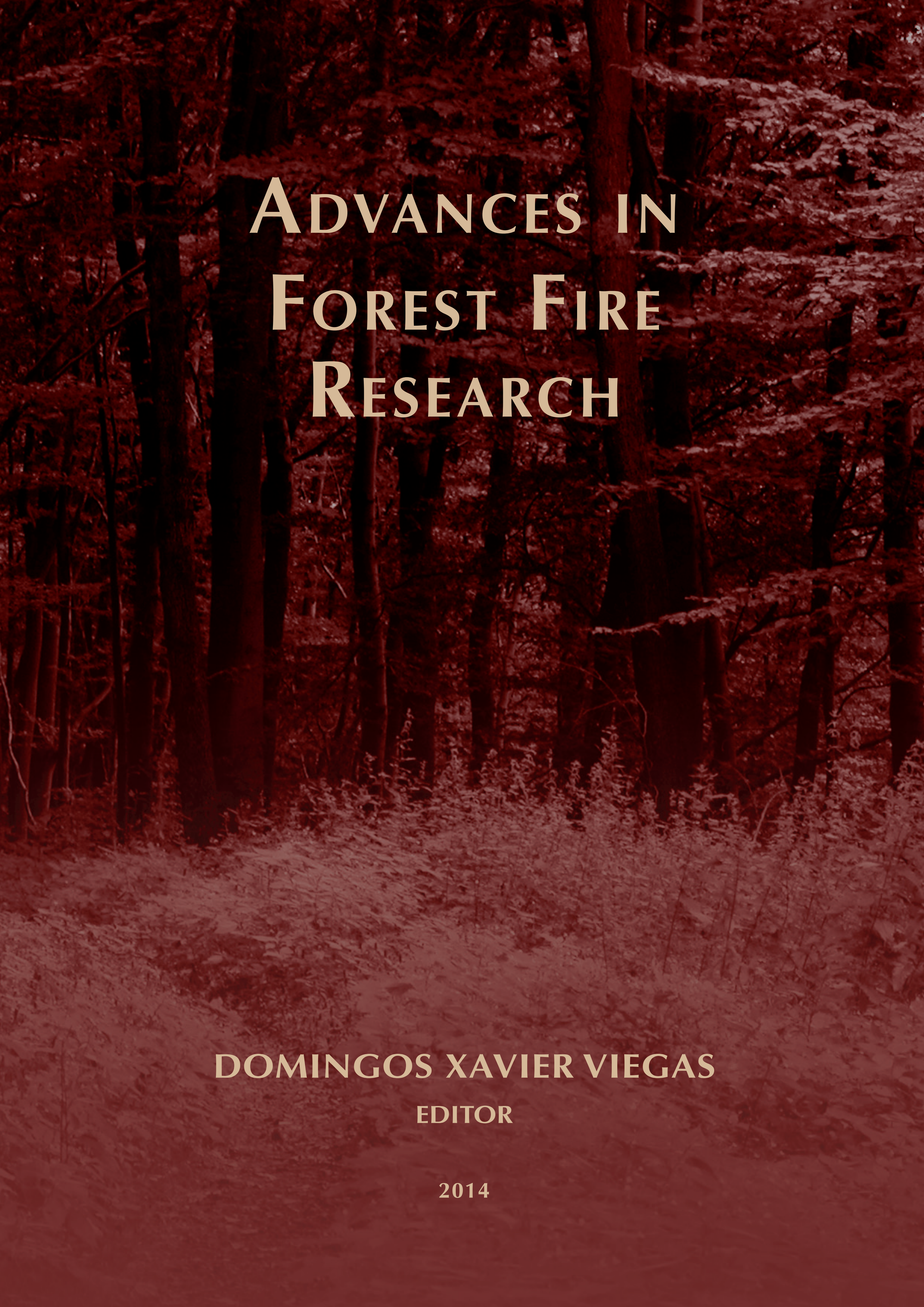

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The MODIS-based perpendicular moisture index as a tool for mapping fire hazard: indirect validation in three areas of the Mediterranean

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Abstract
Several spectral indices based on measurements in the optical domain have been proposed for the estimation of equivalent water thickness (EWT), which is defined as the mass of liquid water per unit of leaf surface. However, fire models rely on the live fuel moisture content (LFMC) as a measure of vegetation moisture. LFMC is defined as the ratio of the mass of the liquid water in a fresh leaf over the mass of oven dry leaf, and traditional vegetation moisture spectral indices are not as effective in capturing LFMC variability. Recently, the perpendicular moisture index (PMI), based on MODIS, was proposed to overcome this limitation and provide a direct measure of LFMC. The aim of this research was to understand the potential and limitations of the PMI in predicting fire hazard. To this purpose, more than 19000 fire records in Provence-Alpes-Côte d'Azur (31400 km^2), France, Toscana (22994 km^2), Italy and Campania (13595 km^2), Italy, over heterogeneous periods between 2000 and 2012 were compared against PMI derived from MODIS reflectance images. Results show that PMI maps capture both year-to-year variability of vegetation condition and its evolution during the advancement of the dry season. The PMI appears to be correlated with mean rate of spread and mean number of fires.

Keywords*: MODIS; Live Fuel Moisture Content; Perpendicular Moisture Index; Fire hazard.*

1. Introduction

The remote-sensing community has developed a number of spectral indices based on broadband satellite measurements in the optical domain for the assessment of vegetation water content measured as equivalent water thickness (EWT), which is defined as the mass of liquid water per unit of leaf surface (e.g. Hunt and Rock 1989; Gao 1996; Pinty *et al.* 2002). However, fire models rely on the live fuel moisture content (LFMC) as a measure of vegetation moisture (Yebra *et al.* 2013). LFMC is defined as the ratio of the mass of the liquid water in a fresh leaf over the mass of oven dry leaf, and spectral indices proposed so far are not as effective in capturing LFMC variability as with EWT (Danson and Bowyer 2004; Caccamo *et al.* 2012).

In a recent paper (Maffei and Menenti 2014), the perpendicular moisture index (PMI) was introduced to exploit MODIS spectral characteristics and to overcome some of the limitations of the traditional vegetation moisture spectral indices. The PMI is a direct measure of LFMC, but its potential in the evaluation of fire hazard is unexplored.

The objective of this research was to understand the potential and limitations of the PMI in predicting fire hazard, i.e. in providing relevant information on the characteristics of fires that might occur in a certain area. To this purpose, three large study areas were selected, and MODIS-derived maps of PMI were evaluated against fire occurrence records. The relationship between the PMI, the average fire propagation speed and the mean number of fires was investigated.

2. Materials and methods

2.1. Study areas

The research was performed on three study areas of the Western Mediterranean basin (Figure 1):

- Provence-Alpes-Côte d'Azur (PACA, 31400 km^2), France;
- Toscana (22994 km^2), Italy;
- Campania (13595 km^2), Italy.

Figure 1. Study areas.

2.2. Fire data

Fire records from different sources were used in this research:

- PACA: a collection of more than 9400 fires between 2000 and 2012 extracted from the Prométhée database ("Prométhée: Forest fires database for Mediterranean area in France");
- Toscana: a database of more than 2300 fires records between 2000 and 2007, provided by the Regional Administration of Toscana;
- 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).

2.3. MODIS data

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 for the near-real-time delivery of derived products. For this research, 8-day composites of Terra-MODIS reflectance data (product MOD09A1) were retrieved from the Land Processes Distributed Active Archive Center ("LP DAAC") hosted by the United States Geological Survey (USGS). All composites covering June to September were selected, for the years corresponding to the availability of fire data in each study area.

2.4. The perpendicular moisture index

The perpendicular moisture index (PMI) was developed from the observation that, in the spectral plane spanned by MODIS channels 2 (0.86 μm) and 5 (1.24 μm), points characterised by the same value of LFMC lay on straight parallel lines. This led to the definition of a measure of vegetation moisture as the distance of a reflectance point in this plane from a reference line, according to equation:

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

where R2 and R5 are reflectance measurements in MODIS channels 2 and 5 respectively.

2.5. Indirect validation of the PMI

Maps of PMI were calculated from MODIS data, and masked basing on CORINE Land Cover (CLC) classes. Due to a difference in the way the Italian and French fires databases were constructed, CLC mask for the Italian sites included all forests and natural areas classes, whereas in France it also included agricultural lands.

For each fire in the data sets, the value of the PMI was sampled from the PMI map corresponding to the MODIS 8-day compositing period previous to the date of the event. PMI values at fires' locations were compared to fire rate of spread. This parameter was computed from fire size and duration, and in this sense it does not give any information about the actual rate of spread; however, it provides information on "how fast" the area affected by the fire was burnt.

To understand the relationship between the number of fires and the PMI values, within each intermediate administrative unit (departments in PACA, provinces in Toscana and Campania), the median PMI in an 8-day compositing period was calculated and the fires in the following compositing period counted. This led to the construction of a number of couples of values of PMI and number of fires that were grouped by regular intervals of PMI; in each group, the mean number of fires was calculated and assessed against PMI values.

3. Results

Maps of PMI show clear seasonal trends as well as year-to-year variability. In Figure 2 four maps produced from the MOD09A1 data of the 208th day (composite of days 201-208) of years 2003, 2004, 2005 and 2006 in PACA clearly show how spatial patterns of PMI vary for the same compositing period on a yearly base. Similar considerations can be drawn in Toscana (Figure 3) and Campania (Figure 4).

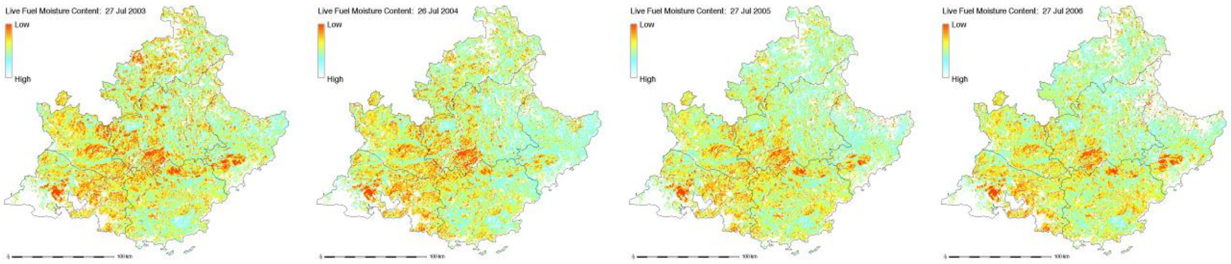

Figure 2. Maps of PMI in the same date of four successive years in the study area of PACA.

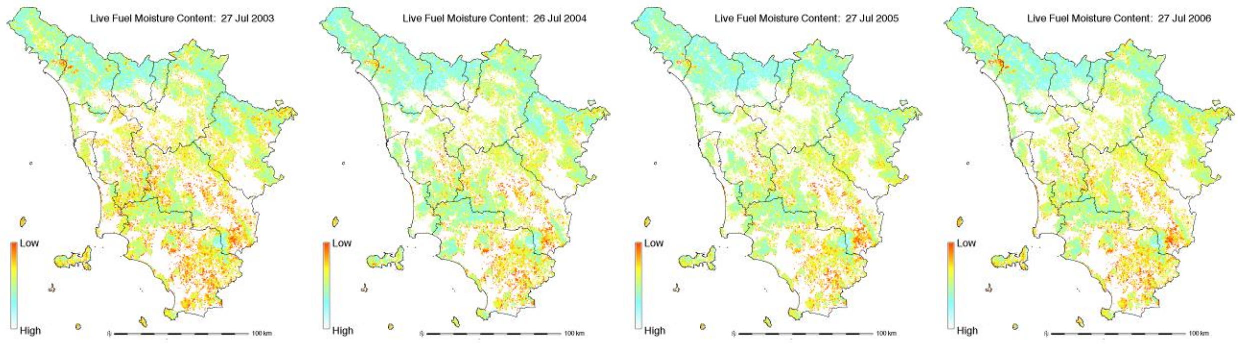

Figure 3. Maps of PMI in the same date of four successive years in the study area of Toscana.

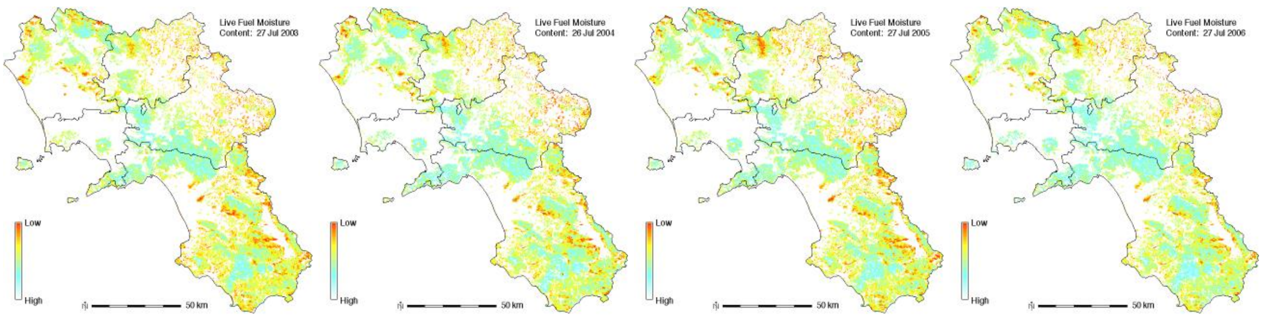

Figure 4. Maps of PMI in the same date of four successive years in the study area of Campania.

Figure 5 shows four successive 8-day maps of PMI of year 2003 in PACA. The PMI appears to capture the evolution of vegetation condition during the summer (dry) season, toward conditions of lower moisture content. Also in this case, similar considerations can be drawn in Toscana (Figure 6) and Campania (Figure 7).

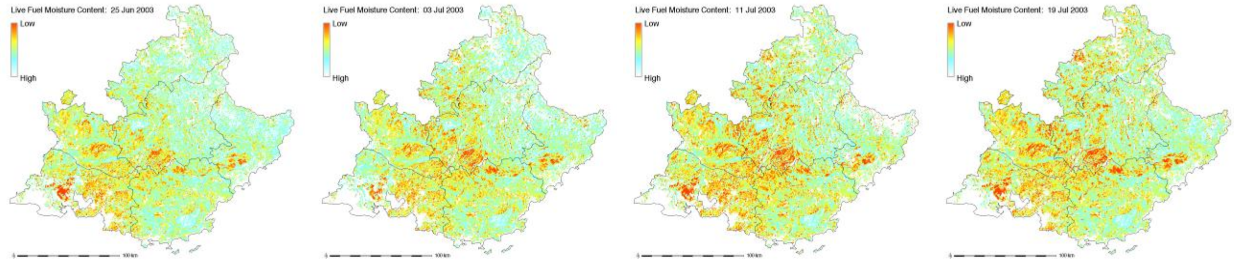

Figure 5. Maps of PMI in four successive compositing periods of the same year in the study area of PACA.

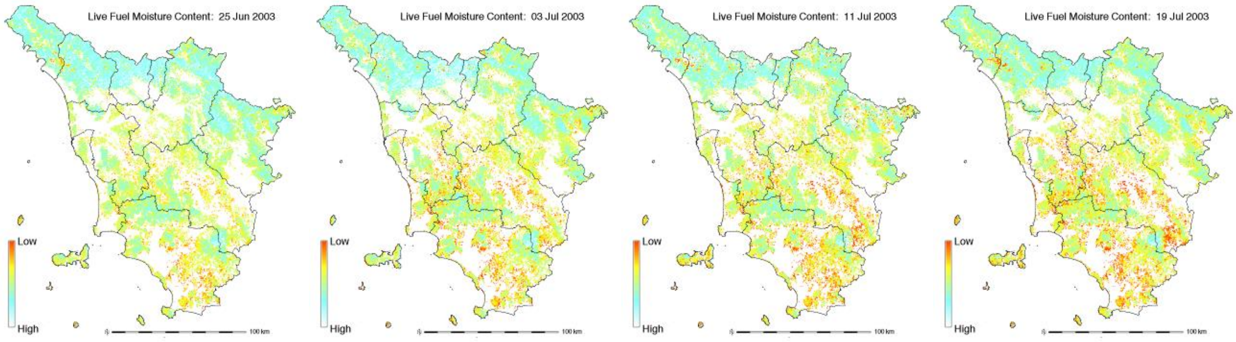

Figure 6. Maps of PMI in four successive compositing periods of the same year in the study area of Toscana.

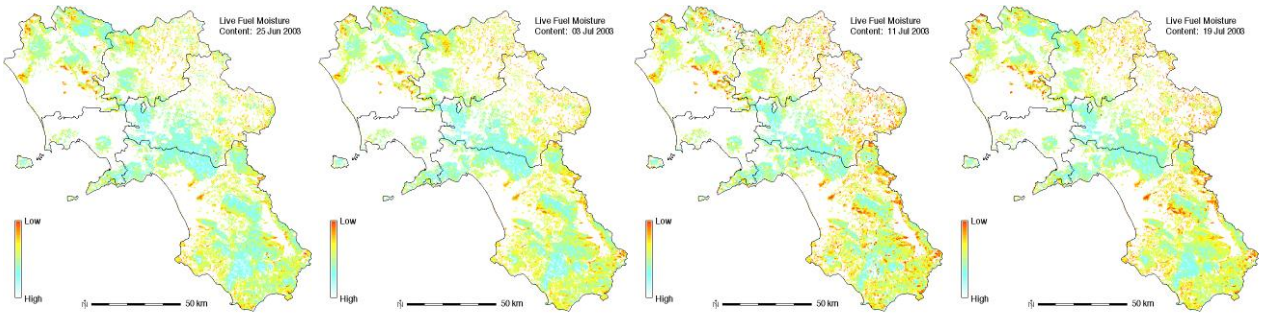

Figure 7. Maps of PMI in four successive compositing periods of the same year in the study area of Campania.

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 PMI values associated to all fires in a study area were divided into bins delimited by their 0th, 10th, …, 100th percentiles. Within each bin, the mean value of the rate of spread was associated to the corresponding median value of PMI. This observation was only performed in Toscana and Campania, since the Prométhée database does not contain information on fire duration. Figure 8 shows evidence of the observed relationship between PMI and fire rate of spread. Higher PMI values imply a lower rate of spread, as would be expected in conditions of higher moisture content in leaf tissues. In both study areas the regression is linear; however, the dynamic range of the rate of spread differs.

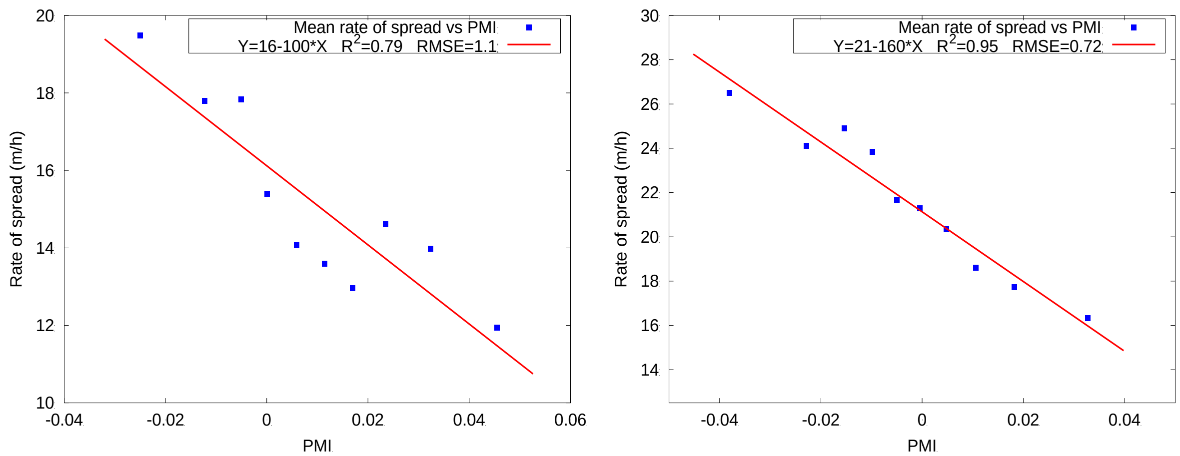

Figure 8. Relationship between PMI and mean rate of spread in Toscana (left) and Campania (right).

The variation of the mean number of fires with the median PMI value recorded in each department of PACA appears to follow a general trend (Table 1): when the vegetation moisture content is higher (the

PMI is higher), a lower number of fires is observed. Similar results were found in Toscana (Table 2) and Campania (Table 3).

Table 1. 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	-

Table 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

Table 3. 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	-

4. **Discussion**

The recently introduced PMI tries to overcome some of the limitations of the traditional broadband spectral indexes in the quantification of LFMC. Its main limitation is given by its sensitivity to the leaf aria index. It is expected that the PMI underestimates vegetation moisture when vegetation cover is less dense. Its application to fire hazard mapping was here evaluated in three large study areas in France and Italy.

From a qualitative point of view, the PMI appears to capture the seasonal variation of vegetation moisture, exhibiting decreasing values of PMI during the evolution of the dry season (Figures 5, 6, 7). Although not shown here, this pattern was observed in every year under consideration. Similarly, the proposed spectral index shows clear year-to-year variability for any selected compositing period (examples shown in Figures 2, 3, 4).

More quantitative observations lead to the clear identification of a linear relationship between PMI and average fire rate of spread (Figure 8). However, it must be noted that the regression lines are different in Toscana and Campania, suggesting that landscape factors may affect it.
Clear trends are observed between median PMI value calculated at department / province level and the mean number of fires in each 8-day observation period (Tables 1, 2, 3). No assumptions were made on the actual distribution of the number of fires in each observation period, as this is part of further investigations.

5. Acknowledgements

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