# AN APPLICATION OF THE PERPENDICULAR MOISTURE INDEX FOR THE PREDICTION OF FIRE HAZARD

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## ABSTRACT

Various factors contribute to forest fire hazard, and among them vegetation moisture is the one that dictates susceptibility to fire ignition and propagation. The scientific community has developed a number of spectral indices based on remote sensing measurements in the optical domain for the assessment of vegetation 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 spectral indices proposed so far fail 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, towards its application in a practical context. To this purpose, a data set of more than 7,700 fires recorded in Campania (13,595 km$^2$), Italy, between 2000 and 2008 was compared with *PMI* derived from MODIS images. Results show that there is no relationship between *PMI* and fire size, whereas a linear correlation was found between the spectral index and fire rate of spread.

## INTRODUCTION

Forest fires are a major environmental threat in the Mediterranean basin. In 2012 about 520,000 ha were burnt in Portugal, Spain, France, Italy and Greece, well above the average of the last twenty years (1). Fires have a negative impact on the productive potential of forests and surrounding lands, and consequently affect regional economies and population's life quality, especially in the economically depressed areas.

Remote sensing research has dealt with various aspects of the forest fires phenomenon, leading to several methodologies for fire detection, burnt scar mapping, and vegetation recovery monitoring. In Mediterranean countries, where fire managers' need for early detection is met by the spontaneous alerts provided by civilians thanks to the high population density, a major concern is about fuel condition and its variation with time. This information affects the ease of inception and fire propagation, and serves as a basis for fire prevention activities, but the establishment of a reliable methodology for the use of remote sensing data in fire hazard mapping demands for further research (2).

In order to spread a fire needs fuel moisture at an adequate level (3). Ideally, this information should be available daily and over vast areas, but this requirement can hardly be met only relying on ground measurements. With this in mind, the potential of remote sensing is significant, thanks to modern operational satellites that provide inexpensive measurements in the visible, near infrared (NIR) and short wave infrared (SWIR) with a spatial resolution of 250-1000 m and a revisit time as low as one day.

Vegetation moisture affects radiometric properties of vegetation in a distinguishable way (4). This led to the definition of several broadband spectral indices based on a rational function of near infrared (NIR) and SWIR reflectance, e.g. the Normalised Difference Infrared Index (5), the Normalised Difference Water Index (6), and the Global Vegetation Moisture Index (7). These indices are good predictors of vegetation moisture measured as equivalent water thickness (EWT), defined as the mass of water in leaf tissues per unit of leaf area. However, fire models rely on vegetation moisture measured as live fuel moisture content (*LFMC*), defined as the percentage mass of liquid water

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over the dry leaf mass, and these spectral indexes generally do not provide the same level of accuracy in estimating *LFMC* (8,9). Indeed, to date the only operational fire danger model that relies on satellite imagery uses this source solely for the evaluation of relative greenness, and integrates this estimate with a number of other ground measured parameters (10,11). This approach acknowledges the complex nature of the problem of fire hazard mapping, but does not exploit remote sensing observations to their full potential.

To overcome some of the limitations of the traditional broadband spectral indices of vegetation moisture, the perpendicular moisture index (*PMI*) was recently introduced (12). Based on MODIS spectral characteristics, the *PMI* is a direct measure of *LFMC*, although its accuracy in the estimation of this parameter decreases when vegetation density is lower. The *PMI* was validated against leaf moisture content from the LOPEX93 (Leaf Optical Properties Experiment 1993) data set of leaf optical and biophysical measurements (13). However, its application in the evaluation of fire hazard is still unexplored, i.e. it is not known whether maps of *PMI* would provide information relevant to fire managers.

The objective of this research was to understand the potential and limitations of the *PMI* in predicting fire hazard towards its application in an operational context. An empirical approach was adopted by comparing a data set of fire occurrences in Campania, Italy, against *PMI* values calculated from MODIS imagery acquired in the days prior to the event.

## MATERIALS AND METHODS

### The perpendicular moisture index

In the spectral plane representing measurements in MODIS channels 2 (0.86 µm) and 5 (1.24 µm), points with the same value of *LFMC* lie along straight parallel lines (12). The perpendicular moisture index (*PMI*) measures the distance of a reflectance measurement in this plane from the reference line of completely dry vegetation according to:

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

where $R2$ and $R5$ are reflectance measurements in MODIS channels 2 and 5, respectively. The *PMI* increases with increasing values of *LFMC*.

The soil line is parallel to the isolines of *LFMC*. When the vegetation cover is less dense, the soil is exposed to the sensor's view, and reflectance measurements are shifted towards the soil line, which results in a reduction in the *PMI*, and thus in an underestimation of vegetation moisture. The *PMI* shares this sensitivity to *LAI* with the other spectral indices based on SWIR reflectance (14).

### Study area

The research was performed on the study area of Campania (13,595 km$^2$), Italy. The interest in this region is given by the diversity of the landscape and land use/land cover it embraces, which are representative of wider areas throughout the Mediterranean. Campania is among the most populated regions of Mediterranean Europe: The anthropic pressure is high and almost all fires are triggered by human activities (15).

### Fire data

The Italian Forest Corps (*Corpo Forestale dello Stato*, CFS) provided a data set of more than 7,700 fire records covering the years between 2000 and 2008. Data included date and time, coordinates of the centroid of the burnt area, duration and extent of each event. The data set covered a range of fire seasons that were considered safe (year 2002) to critical (2007), in both number of fires and burnt area. On average, 850 events are recorded each year, leading to the loss of more than 6,300 ha of natural areas. Most fires (82%) occur in the summer season, i.e. June to September.

### MODIS data

This research was performed on MODIS reflectance data retrieved from the Land Processes Distributed Active Archive Center (LP DAAC) hosted by the United States Geological Survey (USGS)

(16). The data set consisted of all 8-day composite images acquired by Terra-MODIS (product MOD09A1, collection 5) between June and September in years 2000-2008.

### Production of PMI maps and validation of the spectral index

The production of *PMI* maps and the subsequent analysis of fire occurrence were performed within the GRASS GIS environment (17). Maps were masked basing on CORINE Land Cover classes (18) corresponding to forests and natural areas, and on the quality assessment layer of MOD09A1 product. For each fire in the data set, the value of the *PMI* was sampled from the *PMI* map corresponding to the MOD09A1 compositing period previous to the date of the event.

The indirect validation of the *PMI* was performed by comparing *PMI* values at fire locations to fire sizes and rates of spread. The latter parameter was computed from fire size and duration in the hypothesis of a circular fire over a plain terrain. It does not give any information about the actual rate of spread; however, it provides information of “how fast” the area affected by the fire was burnt.

## RESULTS

Maps of *PMI* show clear seasonal trends as well as year-to-year variability. In Figure 1, four maps produced from the MOD09A1 data of the 208th day (composite of days 201-208) of years 2002, 2003, 2004 and 2005 clearly show how spatial patterns of *PMI* vary for the same compositing period on a yearly base. Although not shown, similar observations can be drawn from other compositing periods of the summer season.

Figure 2 shows four successive 8-day maps of *PMI* of the year 2007. The *PMI* appears to capture the evolution of vegetation conditions during the summer (dry) season towards conditions of lower moisture content.

Fire size and rate of spread are affected by various factors of different nature, e.g. topography, vegetation type and amount, local winds, human intervention, presence of obstacles. To isolate the role of vegetation moisture (as estimated by the PMI) from that of all the other factors, the PMI values associated to fires were divided into bins delimited by their 0th, 10th, …, 100th percentiles. Within each bin, the mean values of the fire size and rate of spread were associated to the corresponding median value of *PMI*.

There is no clear pattern between fire size and *PMI* (Figure 3), which means that other factors are more relevant in influencing this parameter. On the other hand, the relationship between *PMI* and rate of spread is evident (Figure 4). A linear regression law relates the two parameters: Higher *PMI* values imply a lower rate of spread, as would be expected in conditions of higher moisture content in leaf tissues.

## CONCLUSIONS

The recently introduced perpendicular moisture index (*PMI*) tries to solve the limitations of the previously developed spectral indices of vegetation moisture in the estimation of live fuel moisture content (*LFMC*). However, like the other spectral indices based on short wave infrared (SWIR) reflectance, the *PMI* is sensitive to *LAI*. When the vegetation cover is less dense, the soil is exposed to the sensor’s view, thus displacing spectral measurements towards the soil line, which results in a reduction of the measured *PMI* and thus in an underestimation of *LFMC* (12). Due to the coarse resolution of this instrument, this effect may be more evident when using MODIS data for the prediction of vegetation moisture.

The objective of this research was to understand, whether the PMI computed from MODIS imagery was able to predict fire hazard despite the outlined limitations. To this purpose, maps of *PMI* were computed from 8-day composites of Terra-MODIS reflectance (product MOD09A1) and compared with summer fires (June to September) recorded between 2000 and 2008 in Campania, Italy.

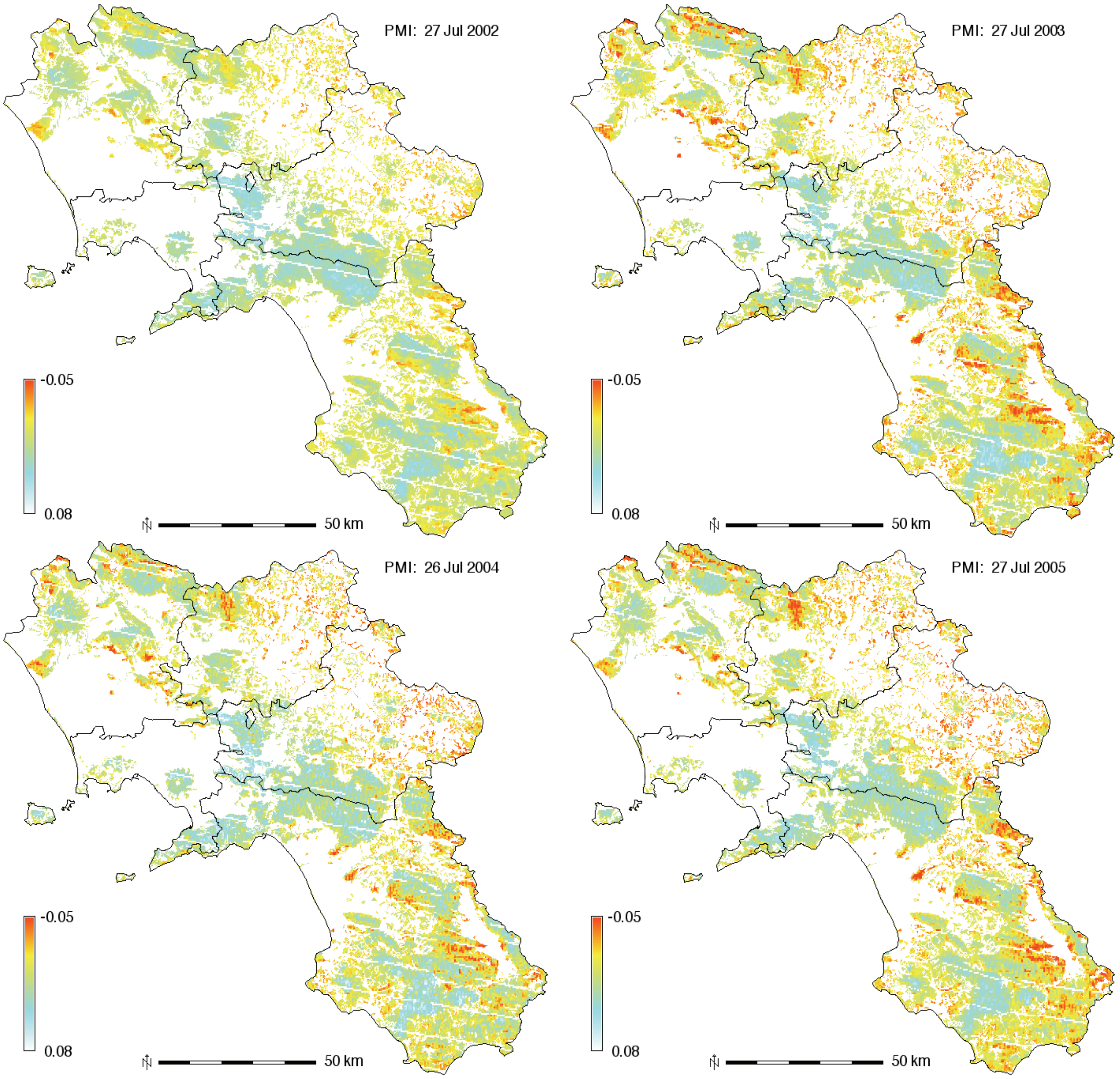

*Figure 1: Maps of PMI in the study area, computed from MODIS 8-day composites of reflectance data of the 208th day of years 2002-2005.*

When observing data of the same period of the year, maps of PMI clearly show year-to-year variability (an example is reported in Figure 1). During the single year, *PMI* maps are also able to observe the evolution of vegetation towards conditions of lower water content with the advancement of the dry season (an example is reported in Figure 2).

The computed maps *of PMI* assume both positive and negative values. Low values of *LAI*, as well as fragmented vegetation cover within an image pixel, shift points towards the soil line well beyond the reference line used in the definition of the *PMI*. The soil line and the dry vegetation line are parallel (12). This means that it is not possible to introduce modifications to the *PMI* in order to make it robust to *LAI* variations.

The *PMI* does not appear to have any relationship with fire area (Figure 3), whereas it has a clear effect on rate of spread (Figure 4). In this research, rate of spread is a measure of how fast a fire consumed the burnt area. Apart from the burnt area rate, the comparison was made with the fire front rate of spread, since this parameter is actually related to *LFMC* (3). In our experiment, rate of spread and *PMI* indeed appear to be clearly linked, showing the ability of *PMI* in predicting fire hazard.

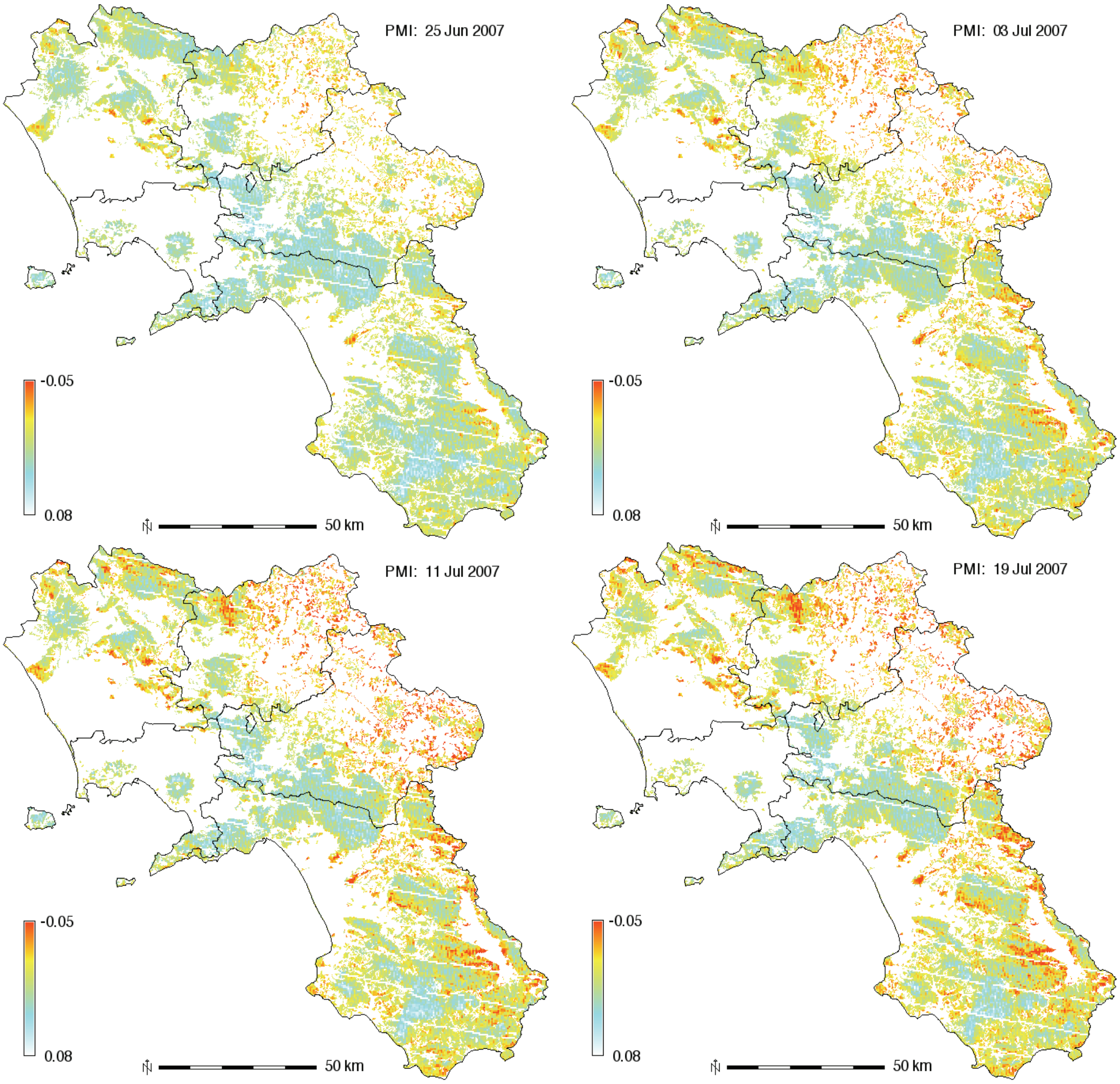

*Figure 2: Maps of PMI in the study area, computed from MODIS 8-day composites of reflectance data of 25 June, 3, 11 and 19 July 2007.*

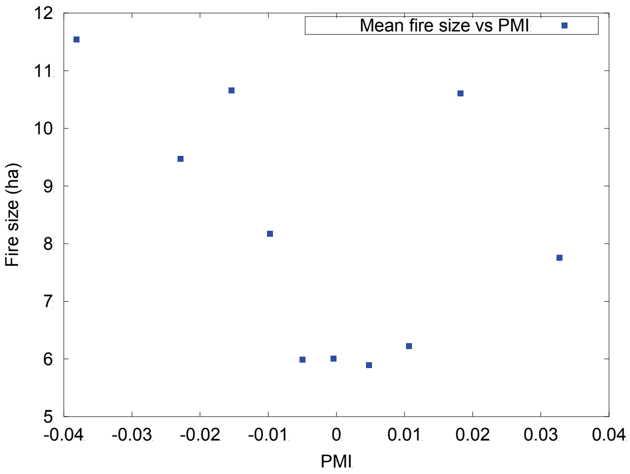

*Figure 3: Relationship between mean fire size and PMI, from MODIS 8-day composites of reflectance data and fire events.*

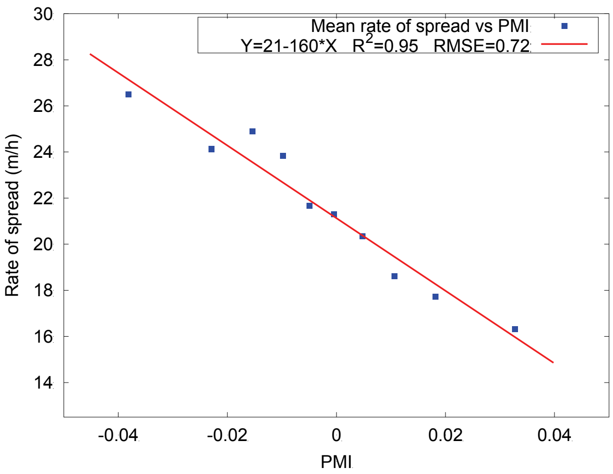

*Figure 4: Relationship between mean rate of spread and PMI, calculated from MODIS 8-day composites of reflectance data and fire events.*

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## REFERENCES

1 JRC, 2013. Forest Fires in Europe, Middle East and North Africa 2012. Joint Report of JRC and Directorate-General Environment. Report EUR 26048 EN, 118 pp. (last date accessed: 24 March 2014)

2 Yebra M, P E Dennison, E Chuvieco, D Riaño, P Zylstra, E R Hunt, F M Danson, Y Qi & S Jurdao, 2013. A global review of remote sensing of live fuel moisture content for fire danger assessment: Moving towards operational products. Remote Sensing of Environment, 136: 455-468

3 Rothermel R C, 1972. A mathematical model to predicting fire spread in wildland fuels. USDA Forest Service. Research Paper INT-115, 48 pp. (last date accessed: 24 March 2014)

4 Tucker C J, 1980. Remote sensing of leaf water content in the near infrared. Remote Sensing of Environment, 10: 23-32

5 Hardisky M A, V Klemas & M R Smart, 1983. The influence of soil salinity, growth form, and leaf moisture on the spectral radiance of *Spartina alterniflora* canopies. Photogrammetric Engineering and Remote Sensing, 49: 77-83

6 Gao B-C, 1996. NDWI – A normalized difference water index for remote sensing of vegetation liquid water from space. Remote Sensing of Environment, 58: 257-266

7 Ceccato P, N Gobron, S Flasse, B Pinty & S Tarantola, 2002. Designing a spectral index to estimate vegetation water content from remote sensing data: Part 1. Theoretical approach. Remote Sensing of Environment, 82: 188-197

8 Danson F M & P Bowyer, 2004. Estimating live fuel moisture content from remotely sensed reflectance. Remote Sensing of Environment, 92: 309-321

9 Caccamo G, L A Chisholm, R A Bradstock, M L Puotinen & B G Pippen, 2012. Monitoring live fuel moisture content of heathland, shrubland and sclerophyll forest in south-eastern Australia using MODIS data. International Journal of Wildland Fire, 21:257-269.

10 López A S, J San-Miguel-Ayanz & R E Burgan, 2002. Integration of satellite sensor data, fuel type maps and meteorological observations for evaluation of forest fire risk at the pan-European scale. International Journal of Remote Sensing, 23: 2713-2719

11 Preisler H K, R E Burgan, J C Eidenshink, J M Klaver & R W Klaver, 2009. Forecasting distributions of large federal-lands fires utilizing satellite and gridded weather information. International Journal of Wildland Fire, 18: 508-516

12 Maffei C & M Menenti, 2014. A MODIS-based perpendicular moisture index to retrieve leaf moisture content of forest canopies. International Journal of Remote Sensing, 35: 1829-1845

13 Hosgood B, S Jacquemoud, G Andreoli, J Verdebout, A Pedrini & G Schmuck, 1994. Leaf Optical Properties EXperiment 93 (LOPEX93). Joint Research Centre (Ispra), Report EUR 16095 EN, 46 pp. (last date accessed: 24 March 2014)

14 Wang L, J J Qu, X Hao & Q Zhu, 2008. Sensitivity studies of the moisture effects on MODIS SWIR reflectance and vegetation water indices. International Journal of Remote Sensing, 29: 7065-75

15 Italian Forest Corps, 2010. Forest Fires 2009. Corpo Forestale dello Stato (Roma), 102 pp.

16 https://lpdaac.usgs.gov/data_access/data_pool (last date accessed: 29 Jan 2014)

17 Neteler M, M H Bowman, M Landa & M Metz, 2012. GRASS GIS: A multi-purpose open source GIS. Environmental Modelling & Software, 31:124-130.

18 Büttner G, J Feranec & G Jaffrain, 2002. CORINE land cover update 2000: Technical guidelines. European Environmental Agency (Copenhagen), Technical Report No. 89, 56 pp. (last date accessed: 31 March 2014)