



Modelling fire occurrence at regional scale: does vegetation phenology matter?

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Abstract

Through its influence on biomass production, climate controls fuel availability affecting at the same time fuel moisture and flammability, which are the main determinants for fire ignition and propagation. Knowing the role of fuel phenology on fire ignition patterns is hence a key issue for fire prevention, detection, and development of mitigation strategies. The objective of this study is to quantify, at coarse scale, the role of the vegetation seasonal dynamics on fire ignition patterns of the National Park of Cilento, Vallo di Diano and Alburni (southern Italy) during 2000-2013. We applied a habitat suitability model to compare the multitemporal NDVI profiles at the locations of fire occurrence (the used habitat) with the NDVI profiles of the entire study area (the available habitat). Results demonstrated that, from May to October, wildfires occur preferentially at sites where the remotely-sensed NDVI observations have on average lower values than the available habitat. On the other hand, in the period November-April, wildfires tend to occur at sites where the corresponding NDVI observations have higher values than the available habitat. From a practical viewpoint, the proposed method can be implemented using many different ecogeographical variables simultaneously, thus integrating remotely sensed imagery with socioeconomic data, land cover, physiography or any landscape features that are thought to influence fire occurrence in the study area.

Keywords: Ecological niche, fuel phenology, fire probability, NDVI profiles, remote sensing.

Introduction

Human factors are known to be the principal cause of wildfire events in Mediterranean countries such as Italy [Barbati et al., 2015], Spain [Martínez et al., 2009], Portugal [Catty et al., 2009] and Greece [Koutsias et al., 2012]; nonetheless climate still plays an essential role in characterizing fire behavior. Through its influence on biomass production, climate controls fuel availability affecting at the same time fuel moisture and flammability, which are the main determinants for fire ignition and propagation [Bajocco et al., 2010; Moreira et al., 2011].

Flammability of living vegetation is influenced by several factors including structural properties and vegetation composition, i.e. fuel type, and chemical properties and moisture content, i.e. fuel status [Pellizzaro et al., 2007; van Altena et al., 2012]. In Mediterranean areas, live fuels represents the main component of the available fuel to fire [Sun et al., 2006; Pellizzaro et al., 2007]. In this view, fuel moisture content is one of the most critical parameter affecting fire ignition and propagation because its variations are related to both environmental conditions and ecophysiological characteristics of plant species [Castro et al., 2003; Pellizzaro et al., 2007]. At the landscape scale, fuel availability and flammability are closely related to the phenological status of living vegetation, which directly affects wildfire pattern in time and space [Bajocco et al., 2015]. Therefore, analyzing wildfire distribution in Mediterranean ecosystems in relation to coarse-scale vegetation phenology can help to identify the main bioclimatic drivers of fire occurrence and their temporal dynamics.

Phenology is defined as the study of the timing of recurring biological events [Lieth, 1974] and examines the causes and consequences of biotic and environmental interactions [Gu et al., 2010]. Although the merit of in situ phenological observations is unquestionable [Menzel et al., 2006; Ma et al., 2013], up-to-date only remote sensing can offer effective and repeatable synoptic information on ecosystem phenology and productivity over several temporal scales [Ivits et al., 2013]. This is even more so because environmental changes are especially noticeable at the ecosystems level [Vitousek et al., 1997].

While in situ phenological data are generally scarce in many parts of the world [Chen and Pan, 2002], several studies have used remotely sensed phenological indices, such as the normalized difference vegetation index (NDVI), for monitoring vegetation dynamics from regional to global scales [i.e. Zhou et al., 2001; de Beurs and Henebry, 2005; Jeong et al., 2011; Fensholt et al., 2012; Ivits et al., 2012]. Since the pioneer work of Rouse et al. [1974] extensive research has shown that NDVI is indicative of plant photosynthetic activity through its direct relationship with ecophysiological parameters, such as absorbed photosynthetically active radiation and leaf area index [Stoms and Hargrove, 2000; Liang et al., 2005]. In addition, as far as fire occurrence is concerned, variations in NDVI values over time are assumed as good indicators of changes in water and nutrient availability, plant disease, and other stress factors, which are in turn indicators of a marked vulnerability of the vegetation to fire [Fiorucci et al., 2007]. For a detailed review, see Lasaponara [2005]. The main objective of this work is thus to apply a habitat suitability model to fire occurrence data for analyzing the relationship between fire ignition and the multitemporal NDVI profiles of the vegetation of the National Park of Cilento, Vallo di Diano and Alburni (southern Italy) during 2000-2013. The working hypothesis is that, given the direct relationship between NDVI and the coarse-scale phenological status of the vegetation, the shape of the annual NDVI profiles associated to different environmental conditions and vegetation types may be a good predictor of fire occurrence in the study area.

Study area

The National Park of Cilento, Vallo di Diano and Alburni (hereafter National Park of Cilento) covers an area of roughly 181000 ha south of the city of Napoli (Fig. 1). The Park extends from the coast of the Tyrrhenian Sea with a typical Mediterranean climate to the inner mountain areas with a temperate climate. Maximum elevation is 1899 m at Mount

Cervati. Mean annual precipitation ranges from approximately 980 mm along the coast to 1900 mm in the inner regions. Mean annual temperatures are comprised between 18° and 10 °C. The Park is characterized by a high geological and morphological heterogeneity that gives rise to a wide variety of habitats and a rich floristic diversity [Moggi, 2001]. In the coastal areas land cover is dominated by agriculture (mainly olive trees, vineyards and chestnuts), sclerophyllous shrubs and Holm oak forests. In the inner areas, vegetation is composed of mixed forests of deciduous oaks, beech forests and grasslands.

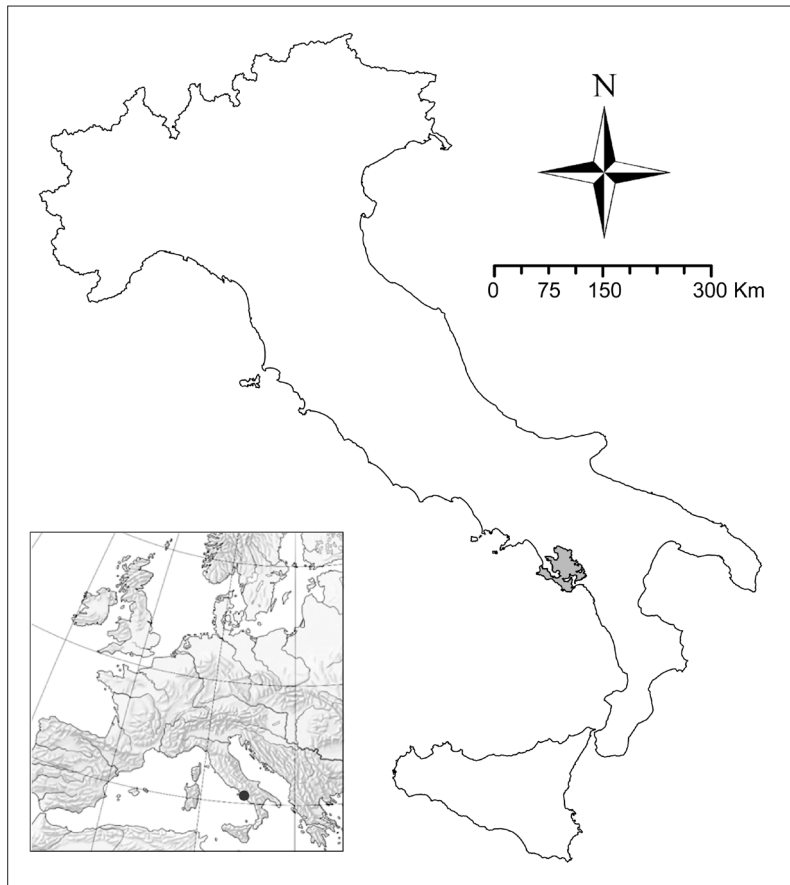


Figure 1 - Location of the study area.

Data

Fire data

We compiled a wildfire time series of the National Park of Cilento containing 2274 records on individual fires from 2000 to 2013. The database contains all fires that were recorded by the Regional Forest Service; for each record the database includes the date of ignition, the geographic coordinates of the ignition point, and a field estimate of the burned area. Fire size spans several orders of magnitude from 0.01 to > 700 ha and the total surface burnt

during 2000-2013 is 13571 ha. Although most of the recorded fires are human-caused, fire occurrence is largely controlled by climate, whose role is testified, on one hand, by the high wildfire seasonality with a concentration of events during the dry and hot months [Keeley and Fotheringham, 2003; Pausas, 2004; Bajocco and Ricotta, 2008] and, on the other hand, by the strong correlation between fuel flammability conditions and the associated wildfire regimes [De Angelis et al., 2012].

Like in most Mediterranean areas, in Cilento fire is strongly seasonal with more than 70% of fires occurring in the summer months (Fig. 2).

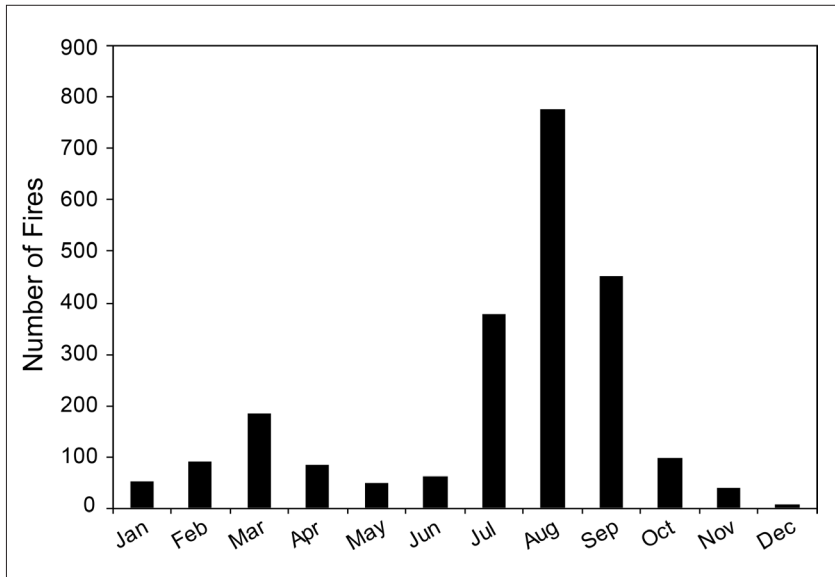


Figure 2 - Monthly fire distribution in the National Park of Cilento in the period 2000-2013.

Remotely sensed data

Remotely sensed NDVI time series have been usually considered a reliable indicator of vegetation dynamics and ecosystem phenology over large geographic areas [Alcaraz et al., 2006; Wessels et al., 2011; Ma et al., 2013; Bartoszek et al., 2015]. In this paper, information on the remotely sensed vegetation phenology of the study area was extracted from the 16-day MODIS-AQUA 250 m NDVI maximum value composite product (MYD13Q1). Twenty-three NDVI images per year from July 2002 to December 2012 were acquired, resulting in a total of 242 MODIS images. For each image pixel we derived a mean annual NDVI profile composed of 23 mean 16-days observations by averaging all NDVI values of each 16-day composite over the period 2002-2012.

Methods

For analyzing the relationship between fire occurrence and the mean annual NDVI profiles we used the Ecological Niche Factor Analysis (ENFA) [Hirzel et al., 2002], an exploratory

analysis tool originally developed by zoologists for characterizing the multidimensional ecological niche of a given species. Hutchinson [1957] defined the ecological niche as the hypervolume in the multidimensional space formed by a set of environmental variables where the species can potentially maintain a viable population. Adapting the niche concept to every spatially explicit ecological process and not only to living organisms, the niche modeling can be applied for understanding the patterns of fire occurrence, considering wildfires like ‘herbivores’ with variable preferences for different resources [Moreira et al., 2001; Bond and Keeley, 2005]. Hence, in this paper, we refer to the ‘niche’ of wildfires as to the subset of conditions in multivariate NDVI space, where wildfires are most likely to occur [Ricotta and Di Vito, 2014].

The input data used by ENFA are a set of quantitative raster maps describing the environmental conditions of the study area (in our case, the mean biweekly NDVI observations for the period 2002-2012). ENFA then compares the NDVI profiles at the locations of fire occurrence (the used habitat) with the NDVI profiles of the entire study area (the available habitat). ENFA is essentially an ordination method, such as principal component analysis (PCA), which is aimed at reducing the redundancy in multispectral images searching for directions in the multivariate data space so that most of the available information is condensed into a few relevant factors [Basille et al., 2008]. However, unlike in PCA, the resultant factors of ENFA have a biological interpretation, which defines relevant aspects of the ecological niche of wildfires [Ricotta and Di Vito, 2014].

The most important factor calculated by ENFA is the ‘marginality’, a measure of the deviation (either positive or negative) of the mean environmental conditions of the used habitat from the mean environmental conditions of the available habitat [Hirzel et al., 2002]. The marginality vector is defined as the vector from the centroid of all pixels of the study area in multivariate NDVI space to the centroid of the distribution of burned pixels (i.e. the optimum NDVI conditions for fire ignition in the study area), and its squared norm, which is usually termed global system marginality, quantifies the squared Euclidean distance between both centroids. The marginality thus measures the degree of habitat selection by wildfires with respect to the mean NDVI conditions of the whole study area; its size is related to the strength of habitat selection, and its direction shows which variables contribute most to the deviation of the environmental conditions of the used habitat from the conditions of the available habitat [Calenge et al., 2005; Basille et al., 2008].

The global marginality index usually ranges between 0 and 1 (although in extreme conditions the value can exceed one; see Hirzel et al. [2002]). If the burned cells were randomly distributed across the landscape, the resulting marginality would be close to zero, meaning that there is no difference between the mean environmental conditions of the whole study area and the ecological conditions associated to fire occurrence. The higher the marginality, the more the conditions of the used habitat deviate from the conditions of the available habitat. The marginality coefficients (i.e. the coordinates of the marginality vector normed to 1; see Basille et al. [2008]) range from -1 to $+1$. The higher the absolute value of a given marginality coefficient, the larger the difference between habitat use and availability for the corresponding NDVI observation.

For additional details on ENFA, see Hirzel et al. [2002] and Basille et al. [2008]. ENFA is contained in the BIOMAPPER package freely available at <http://www.unil.ch/biomapper/>.

Results and discussion

After the influential paper of Moreira et al. [2001], a number of authors have generalized the concept of habitat selection to every spatially distributed ecological process. In this framework, we applied ENFA [Hirzel et al., 2002], a multivariate ordination method used by ecologists for the exploration of habitat selection by animals, for summarizing the ‘ecological niche’ of fire incidence in the National Park of Cilento based on remotely sensed NDVI profiles.

The spatial patterns of fire ignitions have been studied by many authors using various landscape classification schemes based either on land use/land cover types [Lloret et al., 2002; Nunes et al., 2005; Bajocco and Ricotta 2008; Conedera et al., 2011], physiographic variables [Pezzatti et al., 2009; Sharples et al., 2012], or functional attributes [Podur and Martell, 2009; Bajocco et al., 2011]. The present study combines the spatial distribution of fire ignitions with the temporal dynamics of their remotely sensed phenological drivers, thus dealing with the coarse-scale functional aspects of the fuel bed.

Although in Mediterranean regions human activities represent the primary ignition source [Catry et al., 2009], fuel availability (i.e. biomass) and flammability (dryness) are among the most relevant factors influencing fire start and propagation. Accordingly, monitoring vegetation status in space and time is a major concern for understanding fire-related phenomena [Elmore et al., 2005]. In this framework, NDVI profiles of high temporal resolution may be a powerful tool for an accurate characterization of fuel types and fuel condition at the landscape scale [Chuvieco et al., 2003].

According to our results, remotely sensed landscape phenology represents an important functional driver of fire ignition. Table 1 shows the marginality coefficients of all mean biweekly NDVI observations, while Figure 3 shows the mean annual NDVI profiles of the available and used habitats. The ecological niche factor analysis provided a global marginality of $M=1.219$, meaning that, in Cilento, wildfire occurrence in multivariate NDVI space considerably differs from the average remotely sensed phenological conditions of the entire study area. As shown in Table 1, all marginality coefficients associated to the biweekly NDVI observations from May to October show negative values, while the remaining biweekly NDVI observations are all associated to positive marginality values. That is, in Cilento wildfires preferentially occur at sites where the biweekly NDVI values in the period May-October are on average lower than in the entire study area. On the other hand, from November to April, the NDVI values at sites of wildfire occurrence are on average higher than in the reference area (see also Fig. 3).

This results indicate that the NDVI profiles of the available and used habitats differ in terms of both, vegetation productivity, which is related to the absolute values of the 16-day NDVI composites [Glenn et al., 2008; Fensholt et al., 2012] and its seasonal variability, which expresses the transition from moist to dry vegetation [Bajocco et al., 2015].

Along the year, the used habitat shows a lower variability in the NDVI values than the available habitat, while during the main fire season, the used habitat is generally characterized by a lower fuel amount compared to the available habitat. As a consequence, during the fire season all marginality coefficients from May to October show high negative values (Tab. 1), meaning that wildfires occur preferentially at sites where the remotely-sensed biweekly observations have on average much lower NDVI values than the available habitat. On the other hand, the positive marginality coefficients in the period November-April denote that

wildfires tend to occur at sites where the corresponding NDVI observations have higher values than the available habitat.

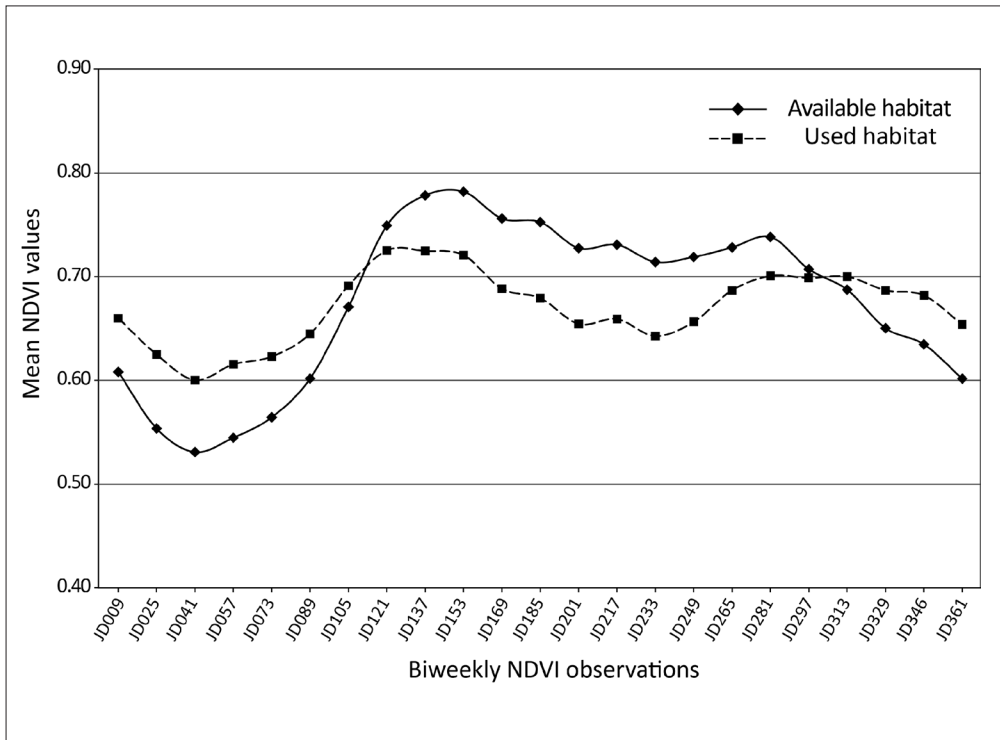


Figure 3 - Mean annual NDVI profiles of the entire study area (available habitat) and at sites of fire occurrence (used habitat). JD = Julian day.

These differences in the remotely sensed coarse-scale phenology are related to underlying differences in physiography, climate and land cover between available and used habitat: fire incidence is mainly associated to the most level areas along the coast where human impact is highest and climate is the most favorable to fire ignition. In this respect, most urban areas of the National Park of Cilento are located in the coastal region.

From a land cover perspective, fire incidence is mainly associated to agriculture, olive groves, evergreen sclerophyllous oaks, and pastures [Guglietta, 2013]. This latter class is located at higher altitudes with a less favorable climate for fire ignition. Nonetheless, due to their fine fuels, pastures are able to dry quickly and are therefore ready to burn after short periods of dry weather when the larger fuels are not yet dry enough to burn. In contrast, the land cover classes with a low fire incidence, such as broad-leaved deciduous forests, are mainly located in areas of low human impact and more temperate climate. Accordingly, this class is generally characterized by higher NDVI values during the main summer season and a higher annual variability due to the deciduous nature of these forests.

Table 1 - Marginality coefficients associated to the 23 mean NDVI biweekly observations used in this study, together with the corresponding NDVI values of the available and used habitats.

Biweekly NDVI observation		Mean NDVI values		Marginality coefficient
Day of the Year	Julian Day	Available habitat	Used habitat	
January 9	9	0.61	0.66	0.19
January 25	25	0.55	0.63	0.22
February 10	41	0.53	0.60	0.21
February 26	57	0.54	0.62	0.22
March 14	73	0.56	0.62	0.21
March 30	89	0.60	0.65	0.18
April 15	105	0.67	0.69	0.10
May 1	121	0.75	0.73	-0.16
May 17	137	0.78	0.73	-0.27
June 2	153	0.78	0.72	-0.27
June 18	169	0.76	0.69	-0.27
July 4	185	0.75	0.68	-0.26
July 20	201	0.73	0.65	-0.25
August 5	217	0.73	0.66	-0.25
August 21	233	0.71	0.64	-0.25
September 6	249	0.72	0.66	-0.24
September 22	265	0.73	0.69	-0.20
October 8	281	0.74	0.70	-0.20
October 24	297	0.71	0.70	-0.05
November 9	313	0.69	0.70	0.07
November 25	329	0.65	0.69	0.17
December 11	346	0.63	0.68	0.19
December 27	361	0.60	0.65	0.20

Conclusions

Knowing the role of fuel phenology on fire ignition patterns is a key issue for national authorities and fire managers towards fire prevention, detection, and development of mitigation strategies. In this framework, we proposed a methodology for quantifying the role of the vegetation seasonal dynamics in driving the spatial arrangement of fire ignition points.

According to our results, notwithstanding the triggering role of man, climate forcing directly affects fire occurrence patterns through the flammability conditions of fuel. In this view, due to their short revisit time, remotely-sensed products, like MODIS NDVI images, may represent a suitable basis for the development of a fuel modelling tool from regional to global scales. For instance, the NDVI of a given site mirrors the complex interactions between vegetation, land use and climate characteristics of that area such that multitemporal NDVI profiles are expected to represent an effective tool for modelling fire occurrence in time and space under current global changes scenarios.

From a practical viewpoint, the proposed method can be implemented using many different ecogeographical variables simultaneously, thus integrating remotely sensed imagery with all landscape features that are thought to influence fire occurrence in the study area, such as socioeconomic data, land cover or physiography [Ricotta and Di Vito, 2014]. Limitations

associated with the proposed methodology are linked with the coarse-resolution of the current remotely-sensed phenological data that may prevent its applicability at local scale where vegetation management and the intervention actions are carried out. Future research will advance the use of satellite time-series within the framework of data fusion in order to take advantage of the spectral and spatial resolution of different data sources.

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