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Original Articles

Linking fire ignitions hotspots and fuel phenology: The importance of being seasonal

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ABSTRACT

Fire ignitions tend to be aggregated in time and space creating a clustered spatio-temporal pattern that is mainly driven by climatic factors and the availability of ignition sources. The aim of this work is to identify the spatio-temporal distribution of wildfires hotspots in Sardinia (Italy) during 2000–2013 and to relate their dynamics with remotely-sensed NDVI-based fuel phenology patterns. We considered eleven bi-weekly time frames (TFs) and used kernel density (KD) estimation to spatialize the corresponding fire ignitions. Then, to identify zones of fire occurrence concentration, we performed a quartile classification of the KD values for each TF considered. Finally, we analyzed the spatio-temporal association between the ignitions hotspots and the remotely-sensed fuel phenology patterns by means of a correspondence analysis and a selectivity ratio. We found that wildfires hotspots are strictly related to anthropogenic pressure and to the spatio-temporal variation of fuel conditions in terms of both load and moisture: areas with less fires concentration proved to be mainly associated to coarse fuels with low seasonal NDVI variability; to the contrary, the fire hotspots resulted strictly correlated to fine fuels with high seasonal NDVI variability. Understanding the association between the seasonal distribution of wildfires hotspots and fuel phenology may allow the projection of fire ignition patterns to future, especially under changing climatic scenarios.

1. Introduction

Wildfires exhibit a marked seasonal cycle which is mainly driven by climatic factors and the availability of ignition sources. Interactions between climate, fuel and fire are complex, although it is widely demonstrated that climate is one of the key natural factors influencing both vegetation distribution and burning regime characteristics (Pourtaghi et al., 2016). While single fires may be caused by a number of different reasons (for instance for agricultural purposes like pasture renewal and crop stubble clearing), general fire regimes are primarily climate-driven (Bekker and Taylor, 2010). In the long term, climate affects fire regime in terms of fuel type and distribution (Marlon et al., 2012). In the short term, variations in precipitation, temperatures, and drought periods have a direct effect on vegetation growth (i.e. fuel load) and flammable conditions (i.e. fuel moisture) (Archibald et al., 2013; Sarris and Koutsias, 2014).

In Mediterranean areas, live fuels represent the main component of the available fuel to fire (Pellizzaro et al., 2007). Flammability of living vegetation is influenced by several factors including the chemical properties of plants, moisture content and vegetation composition and structure (Van Altena et al., 2012). 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. Accordingly, fire occurrence is generally characterized by a strong annual cycle associated to the temporal patterns of environmental conditions and vegetation phenology (Ganteaume et al., 2013).

A number of studies have used remotely-sensed indices, such as the Normalized Difference Vegetation Index (NDVI), for monitoring the seasonal dynamics of vegetation from regional to global scales (Jeong et al., 2011; Fensholt et al., 2012; Ivits et al., 2012). NDVI is generally considered as a good proxy for vegetation primary productivity and biomass (Li et al., 2013; Piao et al., 2014). Accordingly, NDVI time series have been extensively used for monitoring coarse-scale vegetation dynamics (Ahl et al., 2006) and for providing information on key aspects of vegetation functionality, such as seasonality, productivity and inter-annual variability (Bajocco et al., 2015).

Fire seasonality, which is the sole component of fire regime in which climate has a greater impact than human activities, plays a crucial role in the impact of wildfire on ecosystem structure and function (Zhang et al., 2014; Huesca et al., 2009). However, anthropogenic land use

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management practices may also influence the temporal dynamics of wildfires (see Archibald, 2016). In agriculture, fire is used world-wide for soil fertilization (pre-seeding fires), or for burning crop residues (post-harvest fires; Yevich and Logan, 2003; Korontzi et al., 2006). In anthropogenic fire regimes, like in the Mediterranean region, fire ignitions also tend to be spatially aggregated due to the spatial autocorrelation of human activities (Caldarelli et al., 2001; Gonzalez-Olabarria et al., 2012). In these regions, identifying areas with very high probability of fire occurrence or "fire hotspots" may provide effective information for optimizing fire-fighting strategies and resources allocation (Carmel et al., 2009).

Forest fires hotspots are usually identified as real-time or daily satellite-based active fires detection (Csiszar et al., 2006; Hantson et al., 2013; Armenteras et al., 2016). Such approach is mainly focused on the single events detection, overlooking the general perspective of the phenomenon. To the contrary, some recent studies investigated the regional distribution patterns of wildfires hotspots relating them with driving factors (Kalabokidis et al., 2007), causes of ignitions (Gonzalez-Olabarria et al., 2012) and future fire regime scenarios (Salis et al., 2014).

In spatial analysis buffer impact areas are called "hotspots" and are determined by means of density clustering methods. One of the most commonly used method for visualizing multi-scale spatial variations in the frequency of point-based observations, such as fire ignition points, is kernel density (KD) estimation (Gonzalez-Olabarria et al., 2012; Koutsias et al., 2016). The flexibility of kernel methods has been previously demonstrated by many studies dealing with wildlife habitat and movement (Worton 1989). Kernel methods have been also used for spatializing point-based fire data, converting them into continuous surface representations and deriving maps of fire ignition density. The main advantage of using a continuous fire density layer is the possibility to integrate it with other types of spatially explicit data in order to estimate their driving factors, their geographic trends and their influence on the neighborhood (Podur et al., 2003; Koutsias et al., 2004; Amatulli et al., 2007).

The aim of this study was to investigate the spatio-temporal patterns of forest fire events occurred in Sardinia (Italy), a fire-prone area experiencing thousands of human-driven wildfires every year. The working hypothesis is that the spatial distribution of wildfires in Sardinia is not stable throughout the year, but rather changes as a function of the spatial patterns of fuel phenology. The first objective was hence to identify wildfires occurrence hotspots based on burning events recorded during 2000–2013 using kernel density interpolation techniques. The second objective was to explore the relationship between the seasonal dynamics of the identified wildfires hotspots and their remotely-sensed fuel phenology.

2. Study area

The island of Sardinia (Italy) is located in the western part of the Mediterranean Basin, between 38° 51′ N and 41° 15′ N latitude and 8° 8′ E and 9° 50′ E longitude and covers 24090 km^2 (Fig. 1). Sardinia has a complex topography; the average elevation is 338 m a.s.l. and the highest point is Punta la Marmora with 1834 m a.s.l. in the center of the island (Salis et al., 2015). The climate is characterized by mild rainy winters, dry hot summers and a remarkable water deficit from May to September. Most of the annual rainfall occurs in fall and winter; annual precipitation ranges from 500 mm along the southern coastlines to 1200 mm in the mountains on the eastern side of the island. The mean annual temperature follows the same geographical pattern and ranges from 13 °C to 18 °C. During the summer season the daily maximum temperatures exceed 30 °C. The average wind speed is moderate–high in both winter and summer seasons; west and north-west are the most frequent wind directions.

Sardinia has 1.7 million inhabitants, mostly concentrated in the cities of Cagliari and Sassari. The vegetation is influenced by both physical factors and a long history of anthropogenic pressure (fires, grazing, urbanization, agriculture, etc.). Forests cover about 16% of the island, and are mainly composed of *Quercus ilex, Q. suber, Q. pubescens* and *Q. congesta.* At higher elevations *Q. pubescens* forests are the most widespread oak formation. Pine plantations cover only 3%, mainly in the coastal areas, and include *Pinus pinea* and *P. halepensis*. Large areas (28%) are covered by shrublands (Mediterranean maquis and garrigue), comprised primarily of *Pistacia lentiscus*, *Arbutus unedo*, *Erica arborea*, *Myrtus communis*, *Olea europea*, *Phyllirea* spp., *Juniperus* spp., *Cistus* spp. and *Euphorbia* spp. Urban areas cover 3% of the island, while 50% of Sardinia is composed of anthropogenic land uses, such as agricultural lands, grasslands, pastures, vineyards and orchards (Salis et al., 2015).

3. Data

3.1. Fuel phenology data

To relate fire occurrence with fuel seasonality, we used the phenological map of Sardinia produced by Bajocco et al. (2015). To realize the map, remotely sensed NDVI images from 2000 to 2013 were used. NDVI is calculated as the normalized ratio of red and near-infrared (NIR) surface reflectances: (NIR − RED)/(NIR + RED); it ranges between −1 and 1. The images were extracted from the 16-days NDVI maximum value composite product MOD13Q1 of the MODIS satellite at 250 m pixel resolution (https://lpdaac.usgs.gov/products/modis_products_table/mod13q1). Late fall and winter scenes revealed several low quality and noisy pixels regions due to bad weather events. Therefore, we focused only on late spring-early autumn scenes, i.e. eleven yearly MODIS NDVI images from Julian day 113 (April 23rd) to Julian day 273 (October 1st). The 16-days time frames (TFs) used for generating the map were: 23 April–8 May (TF1); 9–24 May (TF2); 25 May–9 June (TF3); 10–25 June (TF4); 26 June–11 July (TF5); 12–27 July (TF6); 28 July–12 August (TF7); 13–28 August (TF8); 29 August–13 September (TF9); 14–29 September (TF10); 30 September–15 October (TF11).

The phenological map is composed of 60 phenologically

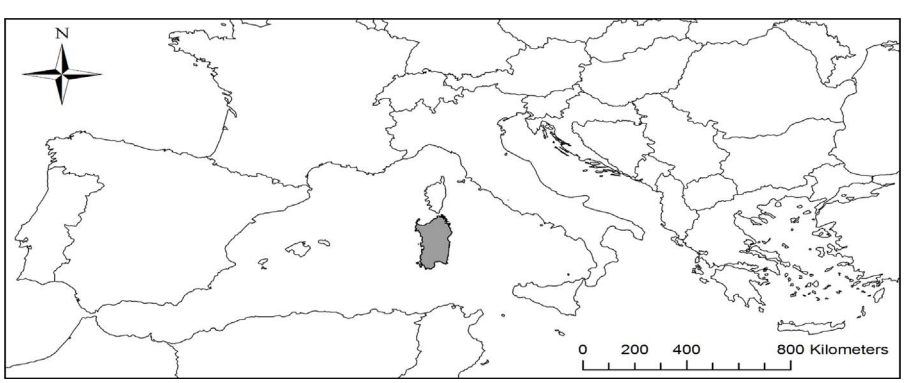

Fig. 1. Location of the study area.