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Research paper

Relating wildfire seasonality to remotely sensed fuel phenology: a tool for a new pyrogeography?

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ABSTRACT In the Mediterranean region, notwithstanding the high human pressure, fire activity is essentially drought-driven, such that fuel moisture represents the main determinant for sustaining fire ignition and spread. Seasonal variations in remotely sensed vegetation indices, such as the Normalized Difference Vegetation Index (NDVI), proved to be indicative of variations in fuel amount and moisture content and associated fire risk. This study aims to propose a general method to represent the combined pattern of remotely sensed vegetation indices and fire ignitions throughout the year, as potential tool to classify terrestrial ecosystems at local to global scale. To jointly visualize the temporal dynamics of remotely sensed vegetation indices and annual fire density, we propose to log-transform the 'annual fire density' (AFD) values, thus expressing the temporal dynamics of fire ignitions in orders of magnitude and producing a pyrophenological diagram in which both quantities vary approximately in the same range. The methodological approach proposed in this study proved to be independent of the local characteristics and applicable with any available remotely sensed vegetation index. The combined NDVI-fire diagrams may contribute to the global pyrophenological classification and mapping of terrestrial ecosystems based on the integrated monitoring of remotely sensed vegetation phenology and fuel seasonality.

KEYWORDS: Fire behaviour, fire regime, NDVI, pyrophenology, remote sensing.

Introduction

Fire activity and distribution is determined by the interactions of three main environmental constrains: natural and anthropogenic ignitions sources, fuel characteristics, and climate-weather conditions that favor combustion (Moritz et al. 2005, Archibald et al. 2013, Bradstock 2010, Flannigan et al. 2016, Ruffault and Mouillot 2017, Clarke et al. 2020). The influence on fire of such constrains vary across ecosystems and climate types, resulting in significant global to local scale heterogeneity in fire regimes (Chuvieco et al. 2008, Le Page et al. 2010, Giglio et al. 2013, Pausas and Ribeiro 2013, Benali et al. 2017, Clarke et al. 2020).

Seasonality is a major element of fire regimes. It is usually accepted that the annual fire cycle is described by the alternation of a fire-free and a fire-active season, which is controlled by favorable weather conditions, fuel moisture and the availability of ignition energy (Benali et al. 2017). However, humans also influence fire seasonality, typically by igniting fires in suboptimal fire weather conditions (Le Page et al. 2010, Benali et al. 2017).

In the Mediterranean region, this complexity is one of the major sources of uncertainty for the understanding of actual and future fire scenarios (Martìnez et al. 2009, Moreira et al. 2011, Ruffault and Mouillot 2017). Climate affects fire occurrence both indirectly through its long-term effects on vegetation (i.e., fuel) distribution, and directly through the short-term effects of weather conditions on fire regimes (Bradstock 2010, Ruffault and Mouillot 2017). In regions with marked climate seasonality, like the Mediterranean, although the fire-weather relationships are largely shaped by human practices (Marlon et al. 2008, Ruffault and Mouillot 2015), fire activity is essentially drought-driven, such that fuel moisture represents the main determinant for sustaining fire ignition and spread (Wotton et al. 2010, Flannigan et al. 2016). Therefore, fires are most likely to ignite and spread when vegetation drought and meteorological fire-prone conditions co-occur (Ruffault and Mouillot 2017).

Understanding the effects of human pressure and vegetation conditions on fire occurrence is thus critical especially under climate change, which can alter the seasonal patterns of fuel moisture and hence the length and severity of the fire season (e.g., Flannigan et al. 2009, Westerling 2016, Vega-Nieva et al. 2018). Seasonal variations in remotely sensed vegetation indices (VIs), such as the Normalized Difference Vegetation Index (NDVI) proved to be indicative of variations in vegetation productivity and moisture content (Wang et al. 2003). Therefore, the use of temporal NDVI patterns has been proposed by many authors to assess vegetation fire-proneness as they represent the main proxy for potential fuel load and flammability (Lasaponara 2005, De Angelis et al. 2012, Fares et al. 2017, Bajocco et al. 2017). For example, Manzo-Delgado et al. (2004, 2009) proved the potential of NDVI time-series as indicators of fuel drought and associated fire risk in Central Mexico, while Bajocco et al. (2017) related the spatial and temporal distribution of wildfires hotspots in Sardinia (Italy) to NDVI temporal profiles. Vega-Nieva et al. (2019) showed that the relationships between temporal trends in a satellite fuel greenness index and fire density change across regions and vegetation types. A detailed understanding of the relationship between fire occurrence and the remotely sensed seasonal conditions of fuels in different regions is thus nec-

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essary to identify patterns of fire occurrence, support fire management strategies and foresee future trajectories of fire regimes.

In climatic studies, combined patterns of precipitation and temperature have been often analyzed by means of graphs or diagrams. A common way to describe the climatic conditions of a given location in a graphical way is to use so-called Walter and Lieth diagrams (Walter and Lieth 1967). On Walter-Lieth diagrams, average monthly precipitation (P) and mean temperature (T) are plotted for each month of the year while scaling the data in such a way that 10°C on the temperature scale always correspond to 20 mm of rain on the precipitation scale. Climate diagrams are thus a graphical representation of mean annual climatic regimes. Originally aimed at visualizing the dynamics of those climatic variables that are particularly relevant for the vegetation distribution, these diagrams represent the starting point for a global climatic classification of terrestrial ecosystems (e.g. Walter and Lieth 1967, Walter and Box 1976).

Similar to Walter-Lieth diagrams, in this study we propose a general method to represent the combined pattern of remotely sensed vegetation indices and fire ignitions throughout the year. A preliminary assessment of the proposed method was performed by analyzing the mean annual profiles of NDVI and fire ignitions for two fire hotspots with distinct fire regimes in two Mediterranean regions of Italy: Sardinia and Latium.

Methods

The number of fires and the burned area are processes driven by different factors and should be analyzed separately (Lloret et al. 2002, Bajocco et al. 2008): while the amount of fuel mainly drives fire ignition (Moreira et al. 2001), fuel spatial distribution mainly explains propagation, because the discontinuity of fuel load produces changes in fire-propagation rates (Cumming 2001). We focused our work on the NDVI-based fuel load as ignition energy, so we considered only the number of fires; yet the procedure could be adapted and extended to fire size.

Notwithstanding the existence of several *ad hoc* moisture content indices, we decided to use NDVI for monitoring drought stress mainly because: (*i*) RED and NIR are very common spectral bands, contrary to other ones like SWIR; (*ii*) the spatial resolution of RED and NIR is usually higher with respect to other bands like SWIR; (*iii*) NDVI is a ready-to-use product of several satellites, like MODIS or Sentinel-2, computed, corrected and validated, contrary to other indices like NDWI, for instance; (*iv*) many works demonstrated the effectiveness of using NDVI as proxy for vegetation responses to drought-related stress (Dutta et al. 2013, Benedict et al. 2021, Gaikwad et al. 2022, Zhan et al. 2022).

The main challenge in combining the annual profiles of the number of fire ignitions and remotely sensed vegetation indices is that, unlike the vegetation indices like NDVI, which are usually bounded between -1 and 1, the number of fires is a cumulative variable that increases with the observed area and the sampled time interval. This makes it impossible to compare fire ignition profiles sampled in regions of different size or with different time intervals without an appropriate data normalization.

For a given study area, we thus need to refer the number of fire ignitions observed in a given time period to a fixed unit area and temporal interval. For the purposes of our study, this is best obtained with the 'annual fire density' (AFD) by standardizing the observed number of fires to an areal unit of 10 square kilometers and to a temporal interval of one year. The AFD is calculated as follows: 1. First, we calculate the number of fires per unit area in each 16-day interval (the same interval of the NDVI observations). 2. Next, we express the AFD in a given interval as the number of fires per unit area that we would observe in one year if these events would occur throughout the year with the same constant rate observed in that interval. This is tantamount saying that the number of fires per unit area in each 16-day interval is multiplied by a constant coefficient of 23 for all 16-day intervals. The reason for this operation is twofold: first, in this way we rescale the observed fire density over one year of observations, rather than to an a-priori defined 16-day interval. This enables to express AFD always using the same measurement unit independently of the duration of the time intervals using for constructing the annual NDVI profiles. Second, by changing the order of magnitude of the measurement unit of the AFD, we render it commensurable after log-transformation with the range of the NDVI values [0, 1] and hence to plot them together on the same graph. The resulting 'annual fire density' (AFD = number of fires/10 km^2 yr.) represents the number of fires per unit area that we would observe in one year if these events would occur throughout the year with the same constant rate. For example, if in the first decade of August we observe in a given region 0.2 fires /10 km^2, assuming a constant rate of events throughout the year, this would correspond to an annual fire density of 0.2 x 36.5 = 7.3 fires/10 km^2 yr.

Also, while in vegetated areas NDVI and other normalized difference indices range approximately from 0.2 to 1.0, the annual fire density may range over more than two orders of magnitude. Therefore, to jointly visualize the temporal dynamics of remotely sensed vegetation indices and annual fire density, we propose to log-transform the AFD values, thus expressing the temporal dynamics of fire ignitions in orders of magnitude.

This operation produces a diagram (hereafter PyroPhenological diagram) in which both quantities, log AFD and the vegetation index, vary approximately in the same range, thus allowing their combined visualization in graphical way. The ability of the proposed diagrams for highlighting relevant aspects of the relationship between remotely sensed fuel load and fire seasonality is illustrated with actual examples on the fire regimes of two fire hotspots, i.e., areas with the highest number of fires, in Sardinia and Latium (Italy).

Worked example

Sardinia

The island of Sardinia (Fig. 1) covers roughly 24,100 km² and has a typical Mediterranean climate characterized by dry hot summers and a significant water deficit from May to September. Annual precipitations range from less than 500 mm along the coast to 1,200 mm on the mountains in the inner part of the island. The highest elevation is 1,834 m a.s.l. The mean annual temperature follows the same altitudinal gradient and ranges from 13 to 18°C.

Land use along the coast and in the main plains is dominated by agriculture that covers about 45% of the island. In the interior areas, forest stands combined with pastures and shrublands prevail. The principal forest types include *Quercus ilex* L. and *Quercus suber* L. forests. At higher elevations the sclerophyllous oak forests merge with broadleaved forests of Quercus *pubescens* Willd. and *Castanea sativa* Mill.

Previous work of Bajocco et al. (2015, 2017) has shown that remotely sensed vegetation phenology represents a significant driver of fuel load and flammability. Accordingly, NDVI images can be effectively used to identify homogeneous landscape units with distinctive pyrological behavior. To relate fire occurrence with fuel seasonality we used the phenological map of Sardinia produced by Bajocco et al. (2015). In this map, Sardinia is classified into phenologically homogeneous units that were obtained by segmenting the mean annual NDVI profiles of each pixel over the 2000-2012 period (https://doi.org/10.6084/m9.figshare.20980027.v1; Bajocco et al. 2015).

Fire data from 2000 to 2015 were obtained from the regional Forest Service of Sardinia (https://www.sardegnaambiente.it/corpoforestale). For each fire record, the database provides information on the date of ignition, the coordinates of the ignition point, and a field estimate of fire size. For the phenological unit with the highest fire occurrence (i.e., hotspot), we constructed a pyrophenological diagram using the 16-day MODIS 250m NDVI images (MOD13Q1, https://lpdaac.usgs.gov/products/mod13q1v006/) over the period 2000-2015, together with the fire ignition points that occurred in the same period of time.

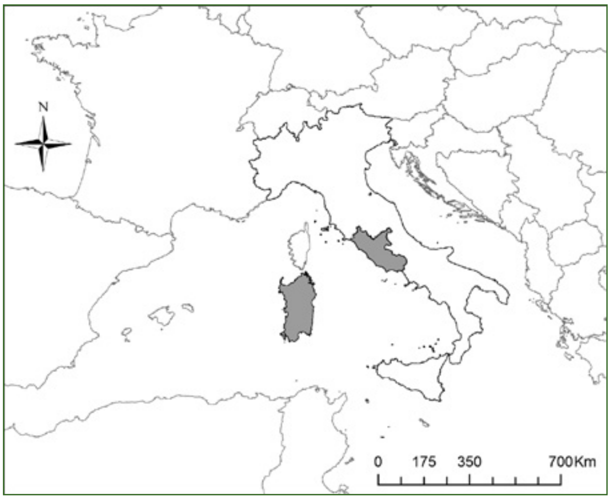
First, for each pixel of the hotspots, we generated a mean annual NDVI profile by averaging the NDVI values of each 16-day image from 2000 to 2015. Next, we derived a mean annual NDVI profile for the selected phenological unit by averaging all pixel values belonging to that unit for each 16-day NDVI image. Finally, we constructed the seasonal fire profile of the selected phenological unit by calculating the mean annual fire density (AFD) over the period 2000-2015 for the same time intervals of the 16-day NDVI images.

Latium

Latium is a region of 17,200 km² located on the Tyrrhenian coast of central Italy (Fig. 1). The region has an elongated shape in the NW-SE direction and is characterized by a prevalently mountainous-hilly topography and high heterogeneity in geological and morphological features. The coastal area is characterized by a Mediterranean climate. The inner areas, up to 2,458 m a.s.l., have more temperate climatic features with cooler and more humid weather conditions. Average annual rainfall ranges from less than 600 mm along the coast to 1,600 mm in the inner mountainous regions. Mean annual temperature ranges from 5 to 17°C. Vegetation along the coast is dominated by sclerophyllous shrubs and *Quercus ilex* forests. At higher elevations the vegetation ranges from mixed forests of deciduous oaks to *Fagus sylvatica* L. forests and grasslands.

Information on the coarse-scale vegetation phenology of Latium was obtained from the 16-day MODIS 250m NDVI images (MOD13Q1) over the period 2004-2015. We first generated a mean annual NDVI profile for each pixel of Latium by averaging the NDVI values of each 16-day image from 2004 to 2015. By means of an object-oriented classification, the resulting 16-day mean NDVI images were used for segmenting the territory of Latium into phenologically homogeneous landscape units showing similar temporal patterns in the NDVI values of the constituting pixels (https://doi.org/10.6084/m9.figshare.20980756.v1; Bajocco et al. 2020) . Using a fire database of Latium over the same 2004-2015 period provided by the National Forest Service, we identified the main fire hotspot in the southern coastal part of the region and we derived its seasonal fire profile by calculating the mean annual fire density (AFD) over the period 2004-2015 for the same time intervals of the 16-day NDVI images and we next constructed the correspondent pyrophenological diagram.

Figure 1 - Study area.



Results

The pyrophenological diagrams of the fire hotspots in Sardinia and Latium are shown in Figure 2. The fire hotspot of Sardinia covers an area of 3,060 km². Land cover in this area is prevalently agricultural with scattered remnants of sclerophyllous shrublands and forests.

Climate is typically Mediterranean with pronounced summer drought.

Over the period 2000-2015, this area experienced an average of 1,057 fires per year, which corresponds to a mean AFD of 3.45 fires/10 km^2 yr. The mean annual NDVI profile shows a U-shaped pattern with a peak of vegetation activity in spring and a marked decrease during the summer dry period. The unimodal pattern of fire occurrences is inverse of that of NDVI, showing a clear direct connection between remotely sensed vegetation condition and fire seasonality (see Bajocco et al. 2017). The highest fire occurrence corresponds to the lowest NDVI values. Wildfires are mainly concentrated during the summer months, from May to October, with a peak of ignitions in June-July, while relatively low activity was observed from late fall to early spring.

The fire hotspot of Latium covers an area of 926 km^2. Land cover is composed of a mosaic of extensive agriculture, olive groves, pastures and forests. Climate is Mediterranean, although with less pronounced summer drought than in Sardinia.

Over the period 2004-2015, this area was subjected to an average of 170 fires per year, which corresponds to a mean AFD of 1.83 fires/10 km^2 yr. The resulting pyrophenological diagram shows a bimodal fire pattern in log-AFD space with a primary peak in summer and a secondary peak in late winter-early spring. These peaks are separated by a period of low fire occurrence from late April to early June that corresponds to the highest annual NDVI values.

Discussion

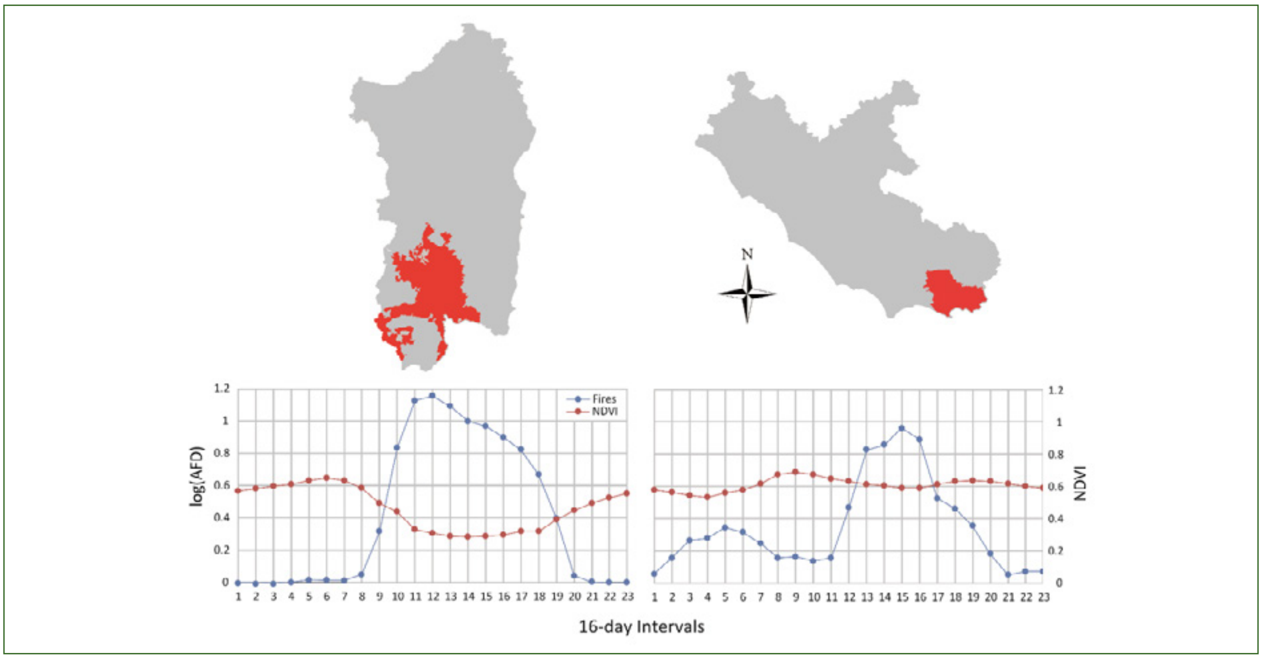
Understanding the complex interactions of climate, fuel conditions and anthropogenic activities in shaping fire regimes is a major concern to reliable fire management strategies, especially under increased global warming, which in some regions may lead to increasing drought conditions, and consequently to increasing fire frequency and severity (Flannigan et al. 2009, Woolford et al. 2014).

Accordingly, several studies analyzed the effects of climate and fuel conditions on fire regimes for specific sites and regions (e.g., Díaz-Avalos et al. 2001, Botequim et al. 2013, Oliveira et al. 2013, Ager et al. 2014, Vega-Nieva et al. 2019). However, none of them proved to be capable of providing a general model to cover the broad variability of environmental conditions of the Earth surface. This led Platt et al. (2015) to suggest that the most appropriate fire-weather models are likely to be local, or at most regional in scale.

In good agreement with Platt et al. (2015), our preliminary results highlighted a direct, though highly local and non-linear relationship between the annual patterns of NDVI and fire occurrence. This is not surprising, as NDVI is generally considered a complex non-linear indicator of the amount of remotely sensed vegetation, its moisture content and related flammability, and its local management practices, together with the associated risk of fire occurrence (Lozano et al. 2008, Chuvieco et al. 2010, Yebra et al. 2013, Bajocco et al. 2017).

For example, 'human-engineered' fire regimes are generally assumed to be characterized by two distinct fire seasons per year with at least one of these seasons occurring under suboptimal fire weather conditions (Benali et

Figure 2 - Location of the fire hot spots of Sardinia and Latium with the corresponding pyrophenological diagrams. The 16-day intervals used for constructing the diagrams are: 1–16 Jan (1), 17 Jan–1 Feb (2), 2–17 Feb (3), 18 Feb–5 Mar (4), 6–21 Mar (5), 22 Mar–6 Apr (6), 7–22 Apr (7), 23 Apr–8 May (8), 9–24 May (9), 25 May–9 June (10), 10–25 Jun (11), 26 Jun–11 Jul (12), 12–27 Jul (13), 28 Jul–12 Aug (14), 13–28 Aug (15), 29 Aug–13 Sept (16), 14–29 Sept (17), 30 Sept–15 Oct (18), 16 Oct–31 Oct (19), 1–16 Nov (20), 17 Nov–2 Dec (21), 3–18 Dec (22), 19–31 Dec (23).



al. 2017). Therefore, the bimodal fire seasonality observed in Latium can be considered the fingerprint of strong anthropogenic influence on fire regimes. Note however that, while from a climatic viewpoint late winter-early spring is only a suboptimal period for fire occurrence, this secondary fire peak is associated to the lowest NDVI values throughout the year. Hence, at least in terms of fuels, the observed winter peak is not completely decoupled from remotely sensed vegetation conditions that promote fire occurrence. Therefore, it might be hypothesized that to get a fire season under sub-optimal fire weather, favorable fuel conditions and intense fire-promoting activities (such as burning agro-forestry, or the use of fire for pasture renewal) are needed to compensate for the unfavorable climate. Note also that the logarithmic scale used to represent annual fire density in Latium allowed us to highlight a marked (NDVI-driven) biseasonal trend in fire occurrence which would have been much less evident using a linear scale.

More generally, although the relationship between NDVI and fire occurrence is highly context-dependent, the methodological approach proposed in this study does not depend on the local characteristics of the study area and can be applied with any available remotely sensed vegetation index. Therefore, it may provide valuable information on the seasonal patterns of fire occurrence and their relationships with remotely sensed fuel phenology in any type of vegetation and climatic region based on available fire records and remotely sensed data.

Conclusions

With this work, we are proposing a descriptive empirical approach that can be replicated with everyone's own data, sensu Bagnouls-Gaussen diagram (1957). As this latter diagram can represent a useful method to highlight the climatic limitations that may negatively influence the applied agricultural techniques in a given site, our NDVI-fire diagram may represent a tool to identify the fuel amount conditions that favor or limit the wildfire occurrence. Due to their general applicability, these combined NDVI-fire diagrams may thus contribute to the global pyrophenological classification and mapping of terrestrial ecosystems based on the integrated monitoring of remotely sensed vegetation phenology and fuel seasonality. At the same time, they may represent a reference point for exporting local fire-weather models in other regions with similar vegetation types, phenology and management practices, thus contributing to an integrated knowledge of fire seasonality and its most relevant drivers. It should be considered that, at moderate-to-coarse scale, as in our case, the climatic drivers weigh more than the land use management, while, at finer scale, the landscape structure, in terms of land use/land cover, should be taken into account. Specific additional experimental designs could be investigated in future research studies to evaluate tool sensitivity to different geographic areas (e.g., in terms of heterogeneity) and to assess inter-annual variability.

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