

Technical Note

Easy-To-Interpret Procedure to Analyze Fire Seasonality and the Influence of Land Use in Fire Occurrence: A Case Study in Central Italy

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Received: 21 July 2020; Accepted: 24 August 2020; Published: 26 August 2020



Abstract: Fire frequency and fire seasonality are among the main components of the fire regime. In the Mediterranean Basin, climate directly drives fire occurrence, controlling fuel flammability and determining the fire-prone conditions, so that intense fires prevail during the dry and warm season of the year. However, humans also play a direct role in wildfire regimes, severely altering fuel features, fire policies and land-use management, as well as the timing and location of fire ignitions, to such an extent that anthropogenic activities have overcome the role of climate in shaping fire regimes. The main purpose of this work is to propose a graphical tool capable of identifying the most fire-prone portions of the territory and to explore the differences between the summer and winter fire risk; to this end, we analyzed the seasonal fire risk in the Latium region (central Italy) and its drivers in terms of land-use types, by using a fuel phenology framework. The results demonstrated that climate is not the main cause of bimodal seasonality in fire occurrence and that the existence of two annual fire seasons in Latium is strongly correlated with how humans use fire as a land management tool. The proposed approach may represent an easy-to-interpret pyrogeographical framework applicable in any environment and updatable over time, useful for identifying spatial gradients, and for recognizing fire regime temporal patterns.

Keywords: bimodality; fire risk; pyrogeography; summer fires; winter fires

1. Introduction

In the last few decades, the fire regime has become a key concept in fire ecology; however, a clear understanding is still lacking [1]. Fire regimes have always changed through time, especially in relation to environmental variation and human activities [2–4]. Understanding both natural and anthropogenic controls on fire behavior is a challenge in assessing fire risk and, ultimately, human safety. Climate variations and topography, along with fuel moisture and load, are well-known contributors to increased fire probability [5]. Hence, fire distribution in the landscape is not random; in most cases, fires show a preference for certain land-use types depending on fuel presence and characteristics [6–8].

According to Keeley [9], fire frequency and fire seasonality are among the major components of the fire regime. Fire frequency depends on fire occurrence and it was defined as the total number of fires recorded over a given period and area [10]. The probability of a wildland fire occurring at a specified

location and under specific circumstances defines the fire risk, which therefore refers to the probability of ignition [11]. Fire seasonality consists of the annual cycle of both fire-free and -active periods within the year [12] and it is a key component of fire regimes. The climate, featuring pronounced wet and dry seasons, creates a distinct fire seasonality which can be expressed by the regular series of periods resulting from specific weather and fuel moisture conditions [13,14].

The relative roles of climate, vegetation, and humans are still debated [15–17]. In the Mediterranean regions, the incidence of fire is highly related to seasonality, where very hot and dry summer conditions make some areas more prone to combustion [6,8,12]. In these environments, the climate is probably one of the superordinate drivers of fires at regional scales by controlling fire weather [15]. However, in the Mediterranean region, human activity is one of the most frequent causes of fire ignition [18]. Up to now, human pressure has dramatically increased [18–21], by shaping fuel structure, type and continuity and by igniting and suppressing fires [4,6,22,23]. Bajocco et al. [24], analyzing different fire behaviors in time and space, noted a tendency of fires to select certain land-use types in different periods of the year, related either to anthropic pressure, and the presence of fine vegetation which dries more quickly and burns more easily, or to the presence of coarser fuel which leaks humidity more slowly. Humans, therefore, play a direct role in wildfire regimes, severely altering fuel features, fire policies and land-use management, as well as the timing and location of fire ignitions, to such an extent that anthropogenic activities have overcome the role of climate in shaping fire regimes [3,25,26].

Lately, due to fast population growth and consequent land-use changes, the significance of human activity has increased, specifically changing the climate-based seasonality of fires [27,28]. As a consequence, an annual fire bimodal distribution was observed in specific regions worldwide, thus featuring two distinctive fire seasons per year [29]. However, both the environmental and anthropogenic factors, which are spatiotemporally driving bimodal fire regimes, remain underexplored, also due to the human–fire complex interaction [12].

To disentangle this complexity, many authors proposed indices or modeling tools for understanding fire risk distribution [30]; however, such studies often require complex computations [31], site-specific applicability [32], or the constraint of using land cover maps [33].

In this perspective, the main purpose of this paper is to propose an easy-to-apply tool to analyze the bi-seasonal dynamics of fire ignition risk and the influence of land use in fire occurrence at the landscape scale and in every environment. A landscape classification scheme based on fuel phenology was used as a framework in this study given that fuel temporal flammability patterns may affect the seasonal behavior of anthropogenic fires directly shaping the distribution of fire ignitions across the landscape [24]. The rationale is hence to develop a modeling tool able to identify wildfire hotspot distribution through time and space, their drivers and to relate them with the phenological dynamics of fuels. To this purpose, we used the case study of Latium, a region of Central Italy showing two clearly distinct annual fire peaks, where we aimed (i) to identify the most vulnerable zones during the different fire seasons and (ii) to test the role of the different land-use types on summer and winter fire risk.

2. Materials and Methods

2.1. Study Area

The Latium region (Central Italy) has an elongated shape in NW-SE direction along the Tyrrhenian coast of central Italy. The region covers an area of 1720 km² (Figure 1). The territory is morphologically heterogeneous, predominantly mountainous/hilly, with 26.1% mountains, 53.9% hills and 20% plains. Latium is characterized by a large climatic and environmental variability. The highest elevation is 2458 m a.s.l.

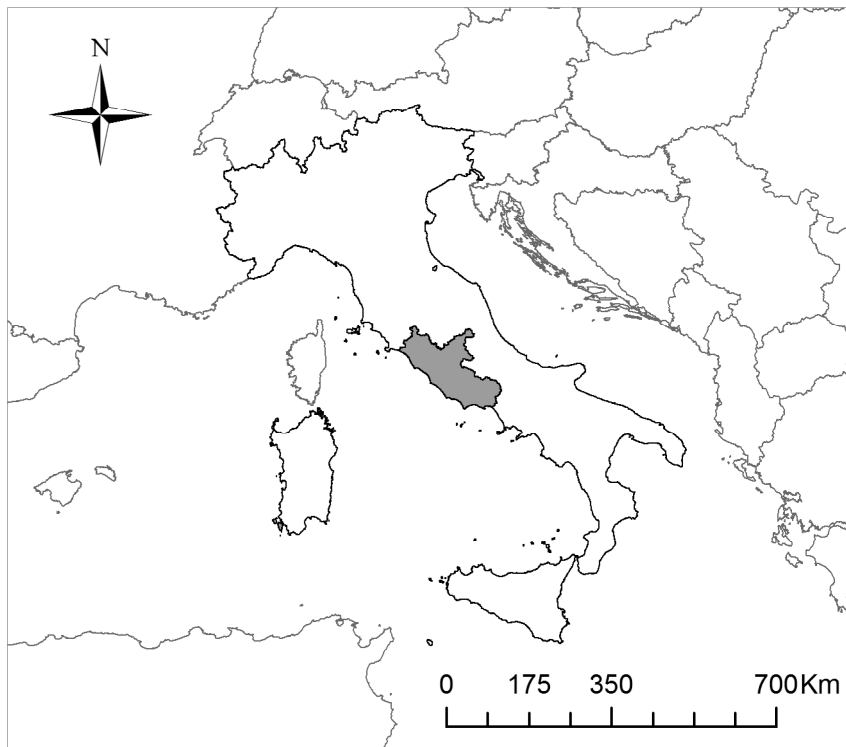


Figure 1. Location of the study area.

In the most mountainous areas of the Apennines, the climate is mainly temperate. Rainfall is very abundant, and temperatures drop below zero in the winter and do not exceed 20 °C in the summer. On the contrary, the Mediterranean zone along the coast experiences a mild winter and marked summer dryness. Average annual rainfall is very variable (700–1600 mm). The rainiest season occurs in autumn–winter. The temperature shows an inverse tendency to that of the precipitation recording the lowest values in autumn–winter and the highest values in summer–spring. Average annual temperatures range between 5 °C and 17 °C.

2.2. Data

Information on the coarse-scale vegetation phenology of Latium was obtained from the 16-day MODIS 250 m Enhanced Vegetation Index (EVI) product (MOD13Q1). According to Huete [34], EVI data proved to be effective in measuring dense vegetation regions, like Latium territory. From 2004 to 2015, 23 EVI images per year were acquired (i.e., 276 images totally). We next generated a mean annual EVI profile for each pixel by averaging the EVI values of each 16-day image over the period 2004–2015. On this basis, we segmented the study area and obtained landscape units (LUs) homogeneous in terms of vegetation phenology, i.e., with pixels showing similar EVI temporal patterns.

Previous work [24,35] has shown that remotely sensed vegetation phenology represents a relevant functional driver of fire occurrence regarding fuel load and flammability. Therefore, EVI images can be effectively used to identify homogeneous landscape units with distinctive pyrological behavior, which in turn reflects underlying differences in land cover and climate [35]. Understanding the geographic distribution of vegetation phenology may be key for planning effective firefighting and prevention strategies, since regions with similar fuel availability patterns are regions where similar management policies should be applied [35].

Fire data were provided by the National Forest Service and contain 4719 forest fires that occurred in Latium between 2004 and 2015 (Figure 2). For each fire record, the dataset includes information on the date and the coordinates of fire ignition, and a field estimate of the burned area. Using the same time intervals of the EVI images, we constructed a fire profile for each landscape unit, showing the

total number of fires over each 16-day span from 2004 to 2015. For statistical reasons, we discarded all LUs with fewer than one fire event per year on average. The final dataset consisted of 4623 fires belonging to 39 LUs.

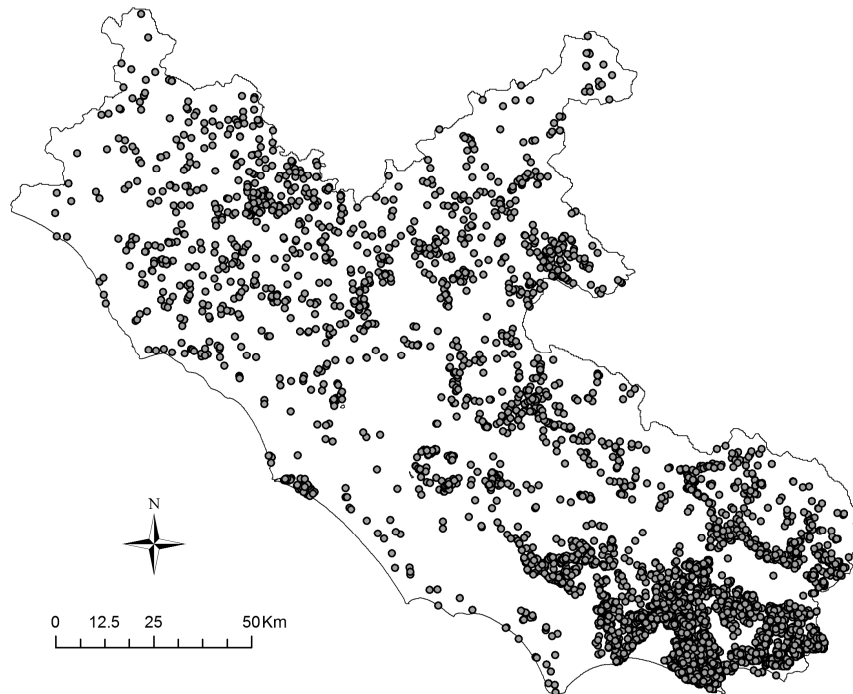


Figure 2. Distribution of the fire ignition points throughout the study area.

2.3. Methods

Given the pronounced bimodality of temporal fire occurrence in Latium, the annual fire profiles were divided into two separate fire seasons, from Julian day 337 (3 December) to Julian day 144 (24 May), hereafter referred to as winter fires, and from Julian day 145 (25 May) to Julian day 336 (2 December), hereafter referred to as summer fires. In particular, the limit between the winter and the summer fire season corresponds to the start of the summer dry season in most parts of Latium.

To quantify the seasonal fire behavior in each LU, an index of fire ignition risk (σ) was derived according to Bajocco and Ricotta [6] for both fire seasons as follows:

$$\sigma = \frac{pF - pA}{pF + pA} \quad (1)$$

where pF represents the proportion of fires in each landscape unit (i.e., number of fires in that LU/total number of fires in all LUs) and pA is the proportional area of that landscape unit in the study site (i.e., surface of that LU/total surface of all LUs). This “normalized selectivity index” ranges from -1 to 1 . If all LUs were equally as fire prone, fire ignitions would occur randomly across the landscape, such that the number of ignitions within a given landscape unit would be nearly proportional to the relative area of that unit. In this case, the values of fire selectivity would be close to zero. Values larger than zero indicate LUs where fires occur more frequently than expected by a random process of fire ignition; values lower than zero indicate LUs where fires occur less frequently than expected [35]. For each landscape unit, fire risk was separately calculated for summer fires ($S\sigma$) and winter fires ($W\sigma$) and then plotted $S\sigma$ vs. $W\sigma$. Two maps of fire ignition risk for the summer and the winter fire season were also produced.

Finally, the relationship between winter and summer fires with the main land cover types in each landscape unit was examined. The different land cover types represent a synthetic expression of the

socioeconomic and land management drivers at the landscape scale, as well as of the available fuel load and typology [24]. We selected seven land cover classes derived from CORINE land-cover (CLC) map updated for the reference year 2012: urban areas, arable land, permanent crops (mainly olive groves), heterogeneous agricultural areas, forests, grasslands and pastures and shrublands. Due to the relative homogeneity in the amount and spatial continuity of fuel load within each class, these classes were considered adequate to study fire occurrence patterns at the landscape scale [6]. For each landscape unit, we first calculated the proportion of fires in each CLC class (i.e., number of fires in that class/total number of fires in the LU) over the period 2004–2015. Next, to analyze the relationship between seasonal fire occurrence and the distribution of fire ignitions within the different land cover types, for each fire season, a multiple forward stepwise linear regression between fire risk and the proportion of fires in each CLC class was performed.

3. Results

Figure 2 shows the fire ignition points distribution over Latium. In general, fire ignitions show a marked tendency to concentrate in the southern part of Latium, while the other areas feature more dispersion. The mean annual pattern of fire ignitions occurring over the 2004–2015 time period (Figure 3) shows a clear biseasonal behavior with two major peaks in summer and late winter–early spring.

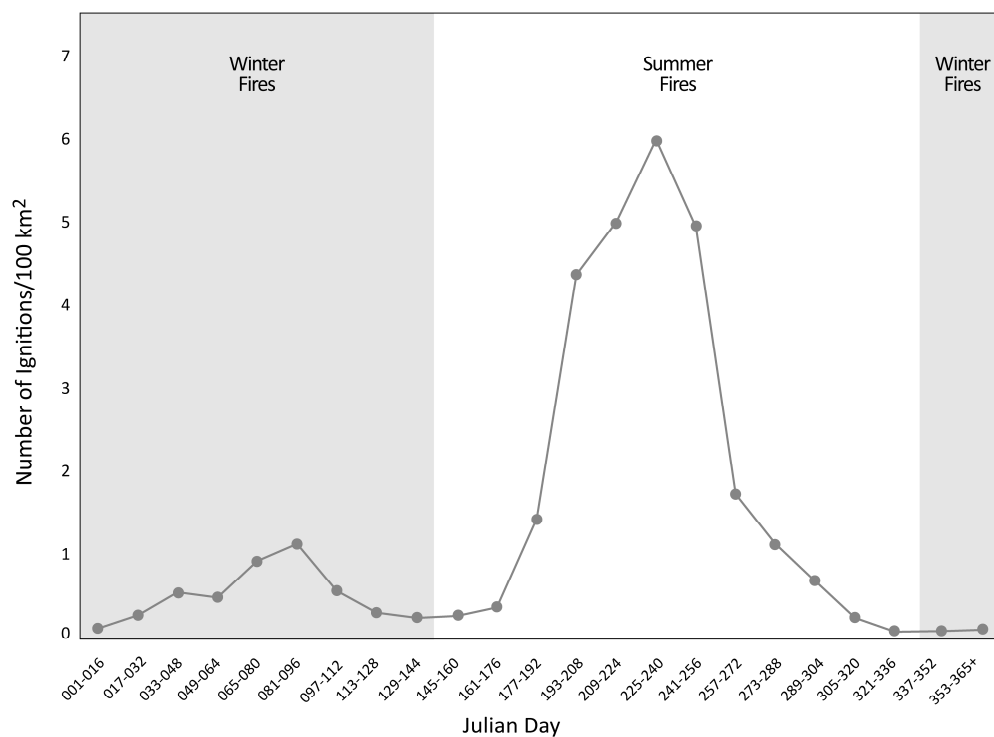


Figure 3. Cumulative fire profile of Latium from 2004 to 2015, using the same 23 16-day time intervals of the MODIS images.

Figure 4 shows summer selectivity ($S\sigma$) vs. winter selectivity ($W\sigma$) for the 39 landscape units of the study area. All LUs above the main diagonal (dashed line) have higher risk values in summer than in winter, whereas all points below the main diagonal have higher risk values in winter than in summer.

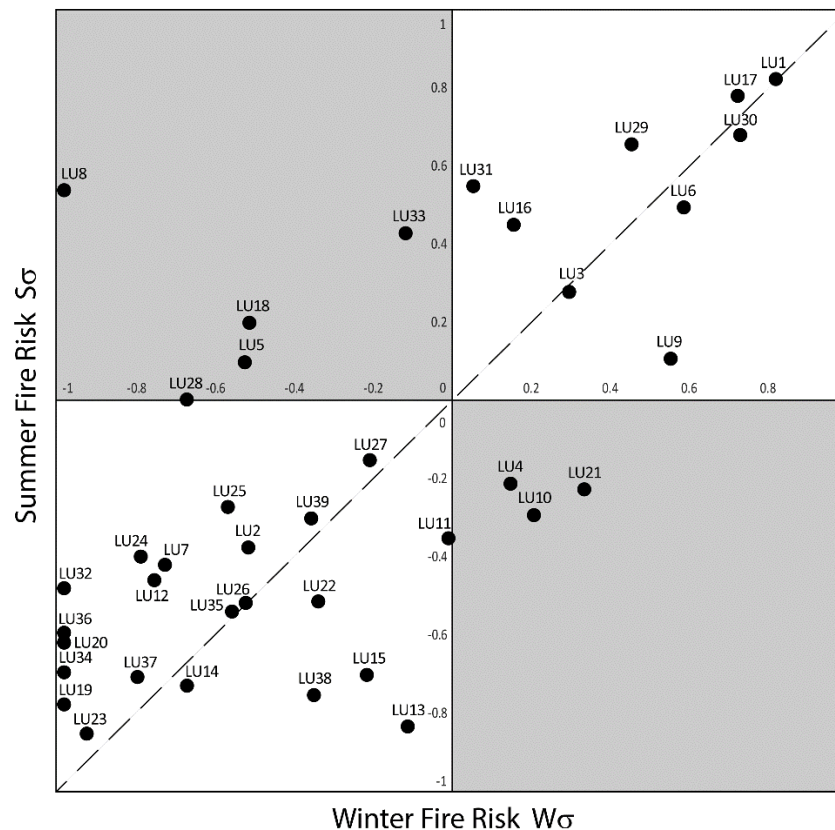


Figure 4. Plot of summer fire risk ($S\sigma$) vs. winter fire risk ($W\sigma$) for all LUs of the study area over the period 2004–2015.

The correlation coefficient between $S\sigma$ and $W\sigma$ is $R = 0.686$ ($p < 0.001$) meaning that there is a general tendency for LUs with high summer risk to show also high winter selectivity and vice versa. Accordingly, most LUs are concentrated in the lower left quadrant of Figure 4, which contains the polygons with negative summer and winter selectivity, and in the upper right quadrant, which contains the polygons with positive summer and winter selectivity. Specifically, in all polygons in the upper right quadrant, most of which are located in the south-eastern part of Latium, fires occur more frequently than expected by chance alone both in summer and in winter. Therefore, they represent the major fire hot spots of the study area.

Contrary to this general trend, the LUs located in the upper left quadrant show positive summer selectivity and negative winter selectivity, while the LUs located in the lower right quadrant show negative summer selectivity and positive winter selectivity, meaning that in these polygons fires occur more frequently than expected only in winter, whereas summer fires occurrence is lower than expected by a random null model.

Figures 5 and 6 show throughout the study area the spatial distribution of summer and winter fire risk, respectively, and in accordance with Figure 4, they confirm that the southern part of the Region has the highest fire risk both in summer and in winter.

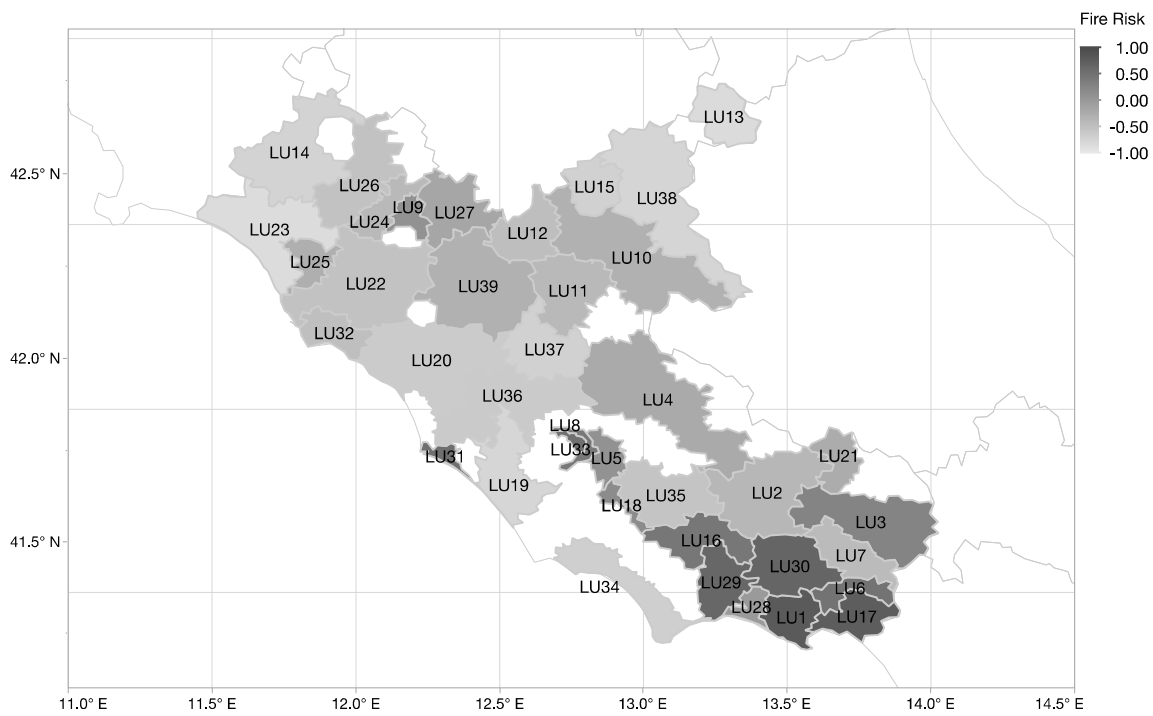


Figure 5. Maps of summer fire risk in Latium over the period 2004–2015.

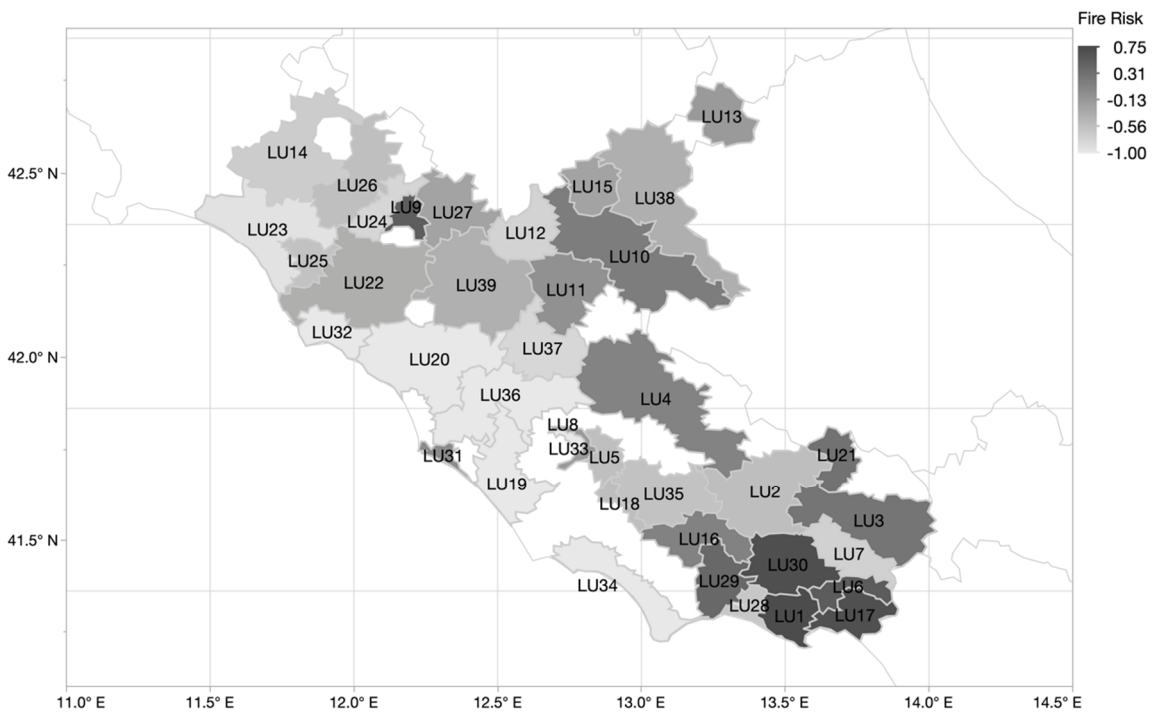


Figure 6. Maps of winter fire risk in Latium over the period 2004–2015.

For all landscape units, the correlation coefficients of $S\sigma$ and $W\sigma$ vs. the proportional abundance of fires in all CLC types are shown in Table 1. Overall, both summer and winter fire risks are positively correlated to fire occurrence in grasslands and shrublands and negatively correlated to fire occurrence in arable lands. Summer fire occurrence is also negatively correlated to fire occurrence in forests. From the multiple regression analysis, the model suggests that fire occurrence in arable land and grasslands were the most relevant predictors for summer fire risk $S\sigma$ (Adjusted $R^2 = 0.670$; $p < 0.001$).

The same two variables were also the most relevant predictors for winter fire risk $W\sigma$ (Adjusted $R^2 = 0.432$; $p < 0.001$). In good agreement with the highly significant correlation coefficient between $S\sigma$ and $W\sigma$, these results stress a similar fire pattern during the two fire seasons in which the most fire-prone land cover types remain the same both in the summer and winter season. The fact that summer and winter fires display the same model, i.e., grassland, is because the majority of fire ignitions in Latium occur in the Aurunci area (south-eastern Latium). This area is dominated by grasslands of *Ampelodesmos mauritanicus*, which is a species that keeps flammability throughout the year, i.e., sustain fire initiation and transmission in both winter and summer since it contains a large dead/live ratio [36]. Notable exceptions to this general tendency are the landscape units in the upper left and lower right quadrants of Figure 4.

Table 1. Correlation coefficients (R) of summer fire risk $S\sigma$ and winter fire risk $W\sigma$ vs. the proportional abundance of fires in the selected CORINE land-cover (CLC) types. Asterisks indicate significant values: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. The variables selected by the forward stepwise linear regression models are shown in italic. The equations of both models are: $S\sigma = -0.344 - 0.006 \times$ Arable land + $0.026 \times$ Grasslands (Adjusted $R^2 = 0.670$) and $W\sigma = -0.260 - 0.013 \times$ Arable land + $0.016 \times$ Grasslands (Adjusted $R^2 = 0.432$).

	Urban Areas	Arable Land	Permanent Crops	Heterogeneous Agriculture	Forests	Grasslands	Shrublands
$S\sigma$	-0.050	-0.491 ***	0.127	-0.049	-0.354 *	0.802 ***	0.463 **
$W\sigma$	-0.197	-0.569 ***	0.164	-0.190	0.085	0.556 ***	0.373 *

4. Discussion

This paper presented a simple methodological procedure to analyze fire seasonality and the influence of land use in fire occurrence within a fuel phenology zoning framework. The detection of geographic clusters of seasonal fire occurrence may represent an effective support tool for identifying high-risk areas, selecting sites for more intensive analyses, optimizing fire prevention strategies and efficiently allocating firefighting resources [24,37].

To this end, we identified the most vulnerable zones in Latium during the different fire seasons and tested the role of the different land-use types on summer and winter fire risk. Similar to previous studies [12], our results confirm that climate is not the main cause of bimodal seasonality in fire occurrence, since part of the vegetation burns during the wet winter–spring season (i.e., outside the dry climate-driven burning season), and winter and summer fires burn the same land cover types, regardless of the climate-related fuel flammability conditions. This is in agreement with the fact that, in the short term, the weather is the main driver of fire occurrence, and its effects are regional; however, when considering larger time periods, the probability of fire occurrence is highly driven by human activities and land management practices, which is consistent with the presence of local structural risk factors independent of the season or weather condition [38,39]. These results also match with previous studies done in the Mediterranean regions [8,40,41], which found direct relations between population density and fire occurrence.

The presence of two annual fire seasons in Latium is strongly correlated with how humans use fire as a land management tool, therefore bimodal fire regimes are an expression of a marked anthropogenic activity. Accordingly, fires occur predominantly in shrublands and grasslands, where the fire is commonly used as a well-established tool to manage vegetation, grazing and plant species richness [23]. The early fire season occurs between March and April, i.e., under sub-optimal climate conditions (Figure 2), while the late fire season occurs between June and September, during the dry period of the year. In the late dry season, fires are ignited by humans for land clearing and renewing pastures, to obtain fresh and nutritious understory vegetation for cattle grazing [42,43]. In this framework, the complex fire–human patterns in Latium represents the key factor that contributed to shaping the bimodal seasonality of the fire regime.

Our results provided statistical evidence for spatio-temporal fire patterns throughout the territory, mainly related to fire probability, weather, and landscape variables, that are different in terms of ignition number, but similar as for location and fuel type. This differentiation between landscape units jointly in terms of fire risk and seasonality may serve as indicators for diverse applications, like, for instance, fire regime classifications [44]. Furthermore, a better knowledge of landscape factors (e.g., land-use types) as drivers of fire occurrence could be helpful for prevention and suppression strategies, and for predicting fire behavior under changing landscape composition.

Finally, the plot developed in Figure 4 may represent an easy-to-interpret graphical tool, useful for (i) categorizing different land units according to both fire-proneness and fire seasonality, (ii) identifying spatial gradients, and (iii) recognizing fire regime temporal patterns. The fire temporal pattern is an important feature of a fire season in addition to its length and onset and termination dates [38]. Discerning where and when a fire occurs and how humans use fire as a land management tool improves our comprehension of how fire practices and land management strategies may change in the near future and it is particularly helpful for fire agencies in their efforts to plan and implement specific fire prevention measures. Recognizing and reckoning how human activities modify the fire seasonal patterns represent a major concern for advancing our understanding of local to global trends in fire activity, seasonal carbon emissions, fuel availability, and climate change impacts.

In conclusion, the proposed methodology provides a modeling tool to identify wildfire hotspot distribution through time and space and to relate them with the phenological dynamics of fuels at the landscape scale. It is applicable to every type of land unit, both functional (e.g., phenological categories or fuel types) and structural (land-use classes, administrative units, etc.). Further implementations of this tool should include information about the fire size and causes in addition to fire ignitions, in order to obtain a complete view of fire behavior across seasons and take into account the whole spectrum of fire regime components.

Author Contributions: Conceptualization, C.R. and S.B.; methodology, C.F. and D.G.; writing—original draft preparation, S.B.; writing—review and editing, C.F.; supervision, C.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: We would like to thank the referees of this note for the fruitful suggestions.

Conflicts of Interest: The authors declare no conflict of interest.

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