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Are Wildfires Knocking on the Built-Up Areas Door?

Leone D. Mancini [1] , **Mario Elia** [2,*] , **Anna Barbati** [1], **Luca Salvati** [3], **Piermaria Corona** [3] ,
Raffaele Lafortezza [2] **and Giovanni Sanesi** [2]

[1] Department for Innovation in Biological, Agro-Food and Forest Systems (DIBAF), University of Tuscia,
Via S. Camillo de Lellis snc, I-01100 Viterbo, Italy; leone.mancini@unitus.it (L.D.M.);
barbati.sisfor@unitus.it (A.B.)

[2] Department of Agricultural and Environmental Sciences, University of Bari 'Aldo Moro',
Via Amendola 165/A, I-70126 Bari, Italy; raffaele.lafortezza@uniba.it (R.L.); giovanni.sanesi@uniba.it (G.S.)

[3] CREA, Research Centre for Forestry and Wood, Viale Santa Margherita 80, I-52100 Arezzo, Italy;
luca.salvati@crea.gov.it (L.S.); piermaria.corona@crea.gov.it (P.C.)

* Correspondence: mario.elia@uniba.it

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Abstract: Human-started fires represent the vast majority of wildfires in Mediterranean countries. The current expansion of human settlements into fire-prone territories has led to the creation of landscapes where anthropogenic developments merge with wildland areas. In this context, understanding the role of distance from built-up areas in shaping coarse-scale wildfire spatial patterns is a major concern. Proximity to cities has become an important factor that may increase the probability of wildfires in wildland-urban interfaces. To this issue, we developed an assessment of wildfire distribution in Italy over an 8-year period (2007–2014) to quantify fire occurrence and recurrence as a function of distance from built-up areas. Our findings suggest a positive relationship between the distance from built-up areas and fire incidence (i.e., ratio between burnt forest area and total forest area), whereas a negative relation was found between distance from built-up areas and fire frequency and recurrence; thus, there are more recurring yet smaller sized-fires near built-up areas. Fifty percent of fire events and more than two-thirds of recurrent fires occur within 200 m from built-up areas. On the other hand, the considerable amount of such fire events never reaches an incidence higher than 10% in flat areas and 30% in hilly and mountainous areas. More broadly, quantitative knowledge about where fires occur is essential to ensure appropriate fire management throughout large territories. With this in mind, our investigation intends to provide a solid base for further studies in landscapes with a high component of human-dominated land use.

Keywords: forest fire; fire recurrence; fire incidence; Mediterranean region; contour plot; Wildland Urban Interface

1. Introduction

Forest fire is an ecological factor in the Mediterranean region that often determines a wide range of impacts on ecosystem services [1]. The capability to understand and predict spatial patterns of forest fire occurrence and recurrence is crucial to improve the effectiveness of fire management resource allocation throughout large territories [2]. This is a remarkably complex research issue due to the multiple biophysical and socioeconomic drivers interacting over different spatial and temporal scales (e.g., [3–5]). Changes in wildfire driving forces (e.g., human pressure, climate change) can generate either slow or abrupt modifications in the spatial distribution of forest fires at the regional scale. Assessing and understanding the spatial patterns of wildfires may be a difficult task owing to limitations in fire recording protocols and the complexity of concurrent factors affecting wildfire ignition and spread. However, this knowledge is essential for designing and promoting

sustainable land management strategies that incorporate effective measures for fire prevention and suppression [6–8].

Earlier studies have investigated the factors affecting wildfire spatial distribution [9]. A high probability of fire occurrence was ascribed to weather (e.g., [10,11]), climate (e.g., [12–14]), landscape fuel conditions (e.g., [15,16]), soil moisture (e.g., [17]), ignition agents (e.g., [18,19]), and human pressure (e.g., [20,21]). Large-scale analyses investigating the role of each factor are often partial and not exhaustive. There is a need to develop more comprehensive approaches incorporating the stochastic dimension associated to wildfires and the importance of spatial variability in local environmental conditions and socioeconomic contexts.

Human-induced fires represent the vast majority of wildfires in many regions of the world [22–24], particularly in the countries of the Mediterranean region [25,26]. Currently, built-up areas and human pressure into the countryside have not only converted and altered farms and forests but have also produced a mixture of urbanized and rural lands. In addition, the expansion of human settlements into fire-prone landscapes has led to the creation of landscapes where built-up areas merge with wildland areas, namely Wildland-Urban Interfaces (WUIs) [27]. The interplay of biophysical and socioeconomic factors, such as fuel load accumulation, lack of management, proximity to main roads and built-up areas, and seasonal peaks of population density, creates conditions for potential fire ignition and spread. These landscapes, defined as potential forest fire environments, require specific fire protection strategies for defending people, infrastructures, and housing asset values but also to guarantee the provision of ecosystem services [28]. In this context, forest fires can cause remarkable damages to people living in these areas that may be on similar scales to the damages that have recently affected cities like Athens [29], Moscow [30], and Coimbra [31].

Based on these premises, understanding the role of distance from built-up areas in shaping wildfire spatial patterns is becoming a major concern. In the last decade, proximity to cities was considered and studied as an important factor increasing wildfire probability (e.g., [32,33]). Gralewicz et al. [34] identified human proximity and elevation as influential factors of fire susceptibility in Canada. Human impact on fire occurrence and recurrence is primarily a product of population density and road accessibility [34]. Darques [35] considered that the distance to populated places might play a crucial role in determining the growth pattern of wildfires. Based on this evidence, the use of proximity measures to built-up areas in assessing human influence on forest fires has been largely implemented in recent literature [36]. At the same time, elevation is expected to substantially influence fire ignition and spread through fuel moisture and altitudinal zonation of forest vegetation types [37]. All other factors being equal, fuel moisture tends to increase with elevation due to different precipitation levels and temperatures [10,38], while different forest types are characterized by intrinsically different flammability levels [37,39,40].

In the Mediterranean region, various studies have investigated the spatial patterns of wildfires [36,41–57], but none of them have used complete (i.e., all wildfires) spatial datasets (i.e., datasets of mapped wildfire polygons, see Mancini et al. [58]) on a national scale. Further, all these studies did not account for recurrent wildfires despite their key role in driving ecological processes and forest resilience [2,59,60].

In this research, we assessed wildfire distribution in Italy over a period of 8 years (2007–2014) to quantify fire occurrence and recurrence as a function of distance from built-up area in order to provide a solid base for further studies in landscapes with a high component of human-oriented land use.

2. Materials and Methods

2.1. Study Area

Italy is geographically located between 36° and 47°30′ north latitude and 5°30′ and 18°30′ east longitude, extending for 301,330 km^2, with 23% of the area classified as lowlands, 42% as uplands, and 35% as mountainous lands. Its complex orography is due to the presence of two main mountain

ranges: the Alps in the north and the Apennines in the center-south. In Italy, climate is highly variable following the latitudinal and altitudinal gradients and the distance from the sea, and ranges from Mediterranean warm to temperate cool.

The forested area is approximately 100,000 km^2. Overall, 32% of forest formations are included in the Alpine bio-geographical region, 16% in the Continental region, and 52% in the Mediterranean region (sensu the Habitat Directive of the European Commission 43/92). The most widespread forest formations are dominated by various oak species (*Quercus* spp.) and European beech (*Fagus sylvatica* L.). A large portion of the broadleaved forests area is managed as coppices [61]. Among conifers, the most widely represented forest types (sensu Barbati et al. [62]) are dominated by Norway spruce (*Picea abies* (L.) H. Karst.), followed by mountain pines (e.g., *Pinus sylvestris* L. and *P. nigra* J.F. Arnold) and Mediterranean pines (*P. halepensis* Mill., *P. pinaster* Aiton, and *P. pinea* L.). Mixed forests (sensu Bravo-Oviedo et al. [63]) are also widespread.

2.2. Forest Fires in Italy

Over the past 20 years, a total of 1,100,000 ha of forest land have been burnt in Italy. An average of 11,000 fires occur annually, burning more than 50,000 ha of forests. The largest wildfires are concentrated in southern Italy and the main islands [64]. In northern Italy, wildfires occur mostly over the first quarter of the year (from January to March), a period when herbaceous vegetation is arid and prone to ignition due to low rainfall and a flow of northern dry winds. Such a condition is especially common in the foothills of the Alps, up to 800 m, and at high elevations in the Apennines. By contrast, in southern Italy the highest probability of wildfire occurrence is essentially in the third quarter of the year (from June to August). Lack of rain and high air temperatures, possibly coupled with strong winds especially at an elevation up to 700 m a.s.l., result in dry fuel conditions that favor fire ignition and spread [40]. Moriondo et al. [65] found that future scenarios of climate change in Italy are expected to produce the highest increase in annual extreme events in all of Mediterranean Europe.

Mancini et al. [58] reported the distribution of fires per fuel types in Italy during the period 2007–2014, when nearly 150,000 hectares of forests were burned. Deciduous oak forests (6843 fires, 44,544 hectares) and broad-leaved evergreen forests (2868 fires, 22,880 hectares) are the most affected forest types both in terms of number of fires and sizes of burned areas, while Mediterranean pine forests are the most affected in relative terms.

2.3. Geospatial Datasets

Based on the perimeters of 33,504 forest fires recorded from 2007 to 2014, as provided by the Italian National Forest Service (Corpo Forestale dello Stato, CFS), we compiled an 8-year fire history of Italy (Figure 1). These datasets can have limitations and may contain errors. In different regions of Italy, often the methods of data collection are different, thus generating problems in obtaining reliable and verified data. In order to not fall into errors, we decided to use a time period that is neither too old (considering that we used the forest layer of 2012) nor too recent. For each event, data collection was based on defining the exact geographical position of the ignition point and a field GPS-based delimitation of the burnt area. The database contains all the fires recorded by the CFS, and we assumed the dataset to be complete and reliable, complete with the inclusion of even the smallest fires. The largest recorded size of burnt area was 10,550 ha, while the total burnt area during the study period was nearly 672,037 ha. The most critical situation was recorded in 2007 with over 170,000 hectares burned, while we have the lowest value in 2013 (43,770 hectares).

The forest High Resolution Layer (HRL) [66], including a 20-m resolution raster map of dominant leaf type (20 × 20 m) provided by the Copernicus Land Monitoring Service carried out by the European Earth monitoring program, was used to distinguish forest fires from fires involving other non-urban land-use classes. Forest land was typically characterized using the most updated geospatial dataset (2012) provided by the Corine Land Cover initiative 1:100,000 [67,68]; the 4th hierarchical level of CLC land-use nomenclature system assures a complete mapping of forest types in Italy [69].
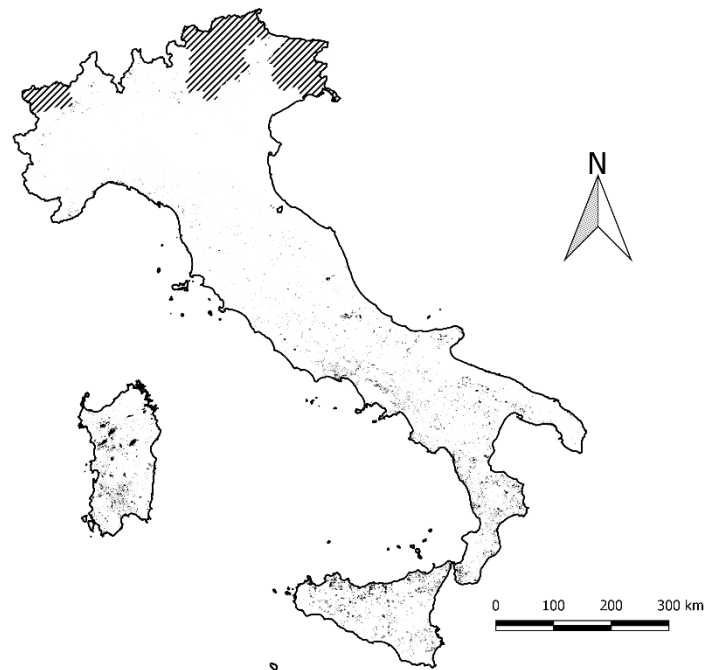
Figure 1. Map of the study area with fire perimeters of our dataset. Striped areas have missing values.

We used the Imperviousness Degree HRL [70], 20-m raster dataset, dated 2012 and provided by European Environment Agency, to identify built-up areas, referring to biophysical characteristics, and thus including roads, fabrics, and settlements. The IMD map illustrates the spatial distribution of artificially sealed areas, including the level of soil sealing per area unit [70].

2.4. Data Processing

In order to assess the frequency and incidence of forest fire occurrence and recurrence, we carried out the following analyses: (i) we created the distance raster from the built-up areas (i.e., pixels with imperviousness > 0%); for each fire polygon of the collected geodataset (see section above) we assessed the frequency distribution of fires according to 100-m distance class intervals from built-up areas; (ii) for each forest polygon of the CLC map (CLC class 31) affected by fire, we assessed: the total area of the polygon, the burnt area, and incidence as the ratio between burnt area and the total area of the polygon; we also assessed the mean incidence values for each distance class (100-m interval) from built-up areas; (iii) to assess forest fire recurrence, we selected polygons where fire events occurred at least twice between 2007 and 2014 and recorded the frequency and incidence of recurring fires according to distance class (100-m ramp) from built-up areas. We used a contour plot to investigate the spatial relationships between fire incidence and distance from built-up areas, and also included elevation as a relevant influential factor. As mentioned in the introduction, a contour plot diagram for a function of two variables is a curve connecting points where the function has the same value.

Lastly, we used Spearman's r nonparametric correlation analysis to assess relationships between fire incidence and the considered landscape variables (elevation and distance from built-up areas); significance was tested at $p < 0.05$ after Bonferroni's correction for multiple comparisons [71,72].

3. Results

On the whole, although weak, Spearman's r correlation showed a positive statistical association between distance from built-up areas and both fire incidence (rs = 0.12, $p < 0.05$), fire recurrence incidence (rs = 0.07, $p < 0.05$), and average burnt area per event (rs = 0.27, $p < 0.05$). A negative association between elevation and fire incidence (rs = −0.10, $p < 0.05$) and fire recurrence (rs = −0.11,

$p < 0.05$) can also be observed too. Fire size distribution in the 2007–2014 time interval was significantly explained by a power-law statistical function over many orders of magnitude, as shown for other case studies (e.g., by Malamud et al. [73] and by Ricotta et al. [74]). Of note, 24,347 events were less than 10 ha in size and only 996 fires extended to more than 100 ha; however, even if these last fires constituted less than 3% of the total fires recorded in Italy, they accounted for 47% of the total area burnt between 2007 and 2014 (Figure 2).
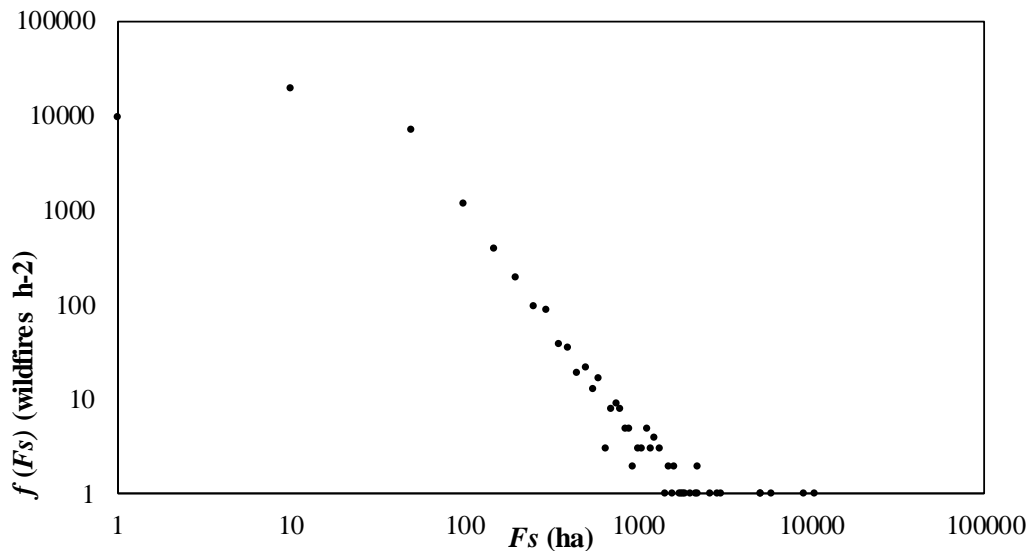
Figure 2. Normalized frequency-size statistics of forest fires in Italy within the 2007–2014 time interval. The *x*-axis *Fs* indicates burnt area and the *y*-axis $f(Fs)$ represents normalized frequency densities.

The distribution of forest fires by distance class from built-up areas (Figure 3) showed a similar trend for both occurrence and recurrence of forest fires. The frequency of fire occurrence decreases as the distance from built-up areas increases, for example, from 34% (100 m) to 13% (200 m). Fire recurrence decreased from 21% (100 m) to 15% (200 m). More than 70% of the fire events occurred within 500 m from built-up areas, while more than 70% of the recurring fires were within 600 m from built-up areas.
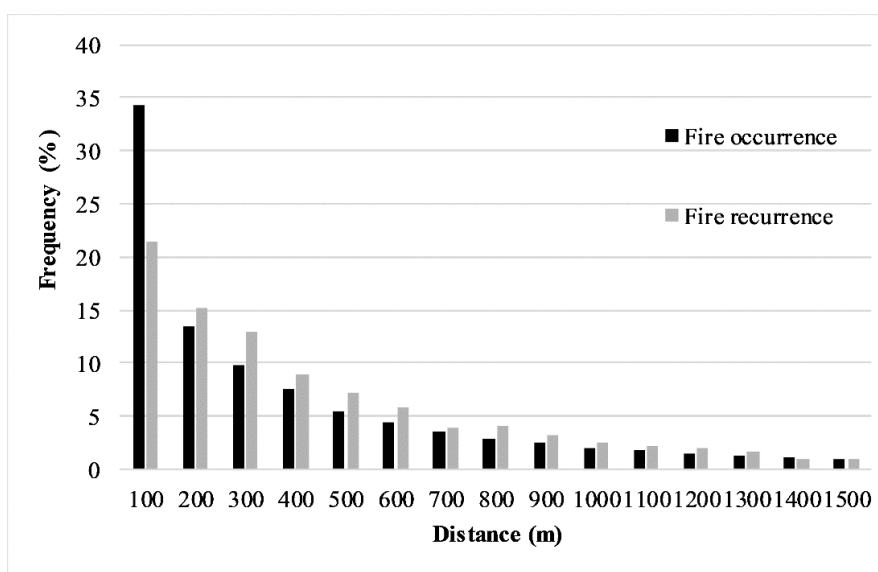
Figure 3. Relative frequency of forest fire events according to distance class from the built-up areas.

Figure 4 shows the spatial variations in fire frequency by elevation. Fire frequency decreased as elevation increased. Fire occurrence and recurrence were extremely high at elevations up to 400 m a.s.l., and overall, 74% of forest fires and 77% of the recurring fires occurred at elevations below 600 m a.s.l.
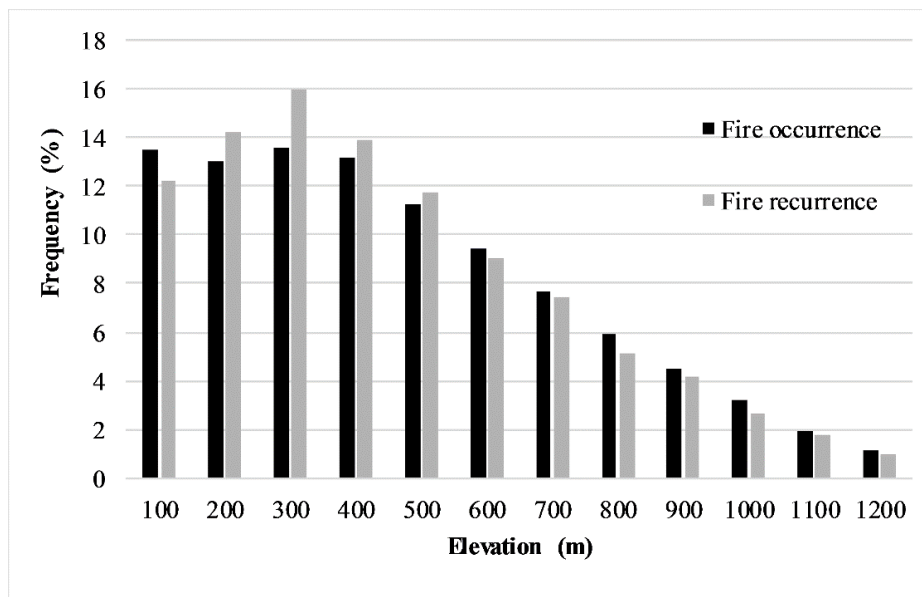

Figure 4. Relative frequency of forest fire events by elevation class.

Forest fire incidence showed a more dispersed pattern at increasing distances from built-up areas (Figure 5). However, the highest values of fire incidence (i.e., 15–20% for fire occurrence and 12–14% for fire recurrence) were observed at distances >1000 m; by contrast, the lowest values (i.e., <10% for fire occurrence and <3% for fire recurrence) were found within 200 m from built-up areas. This trend was also reflected by the distribution of average burnt area per event with respect to distance from built-up areas (Figure 6).
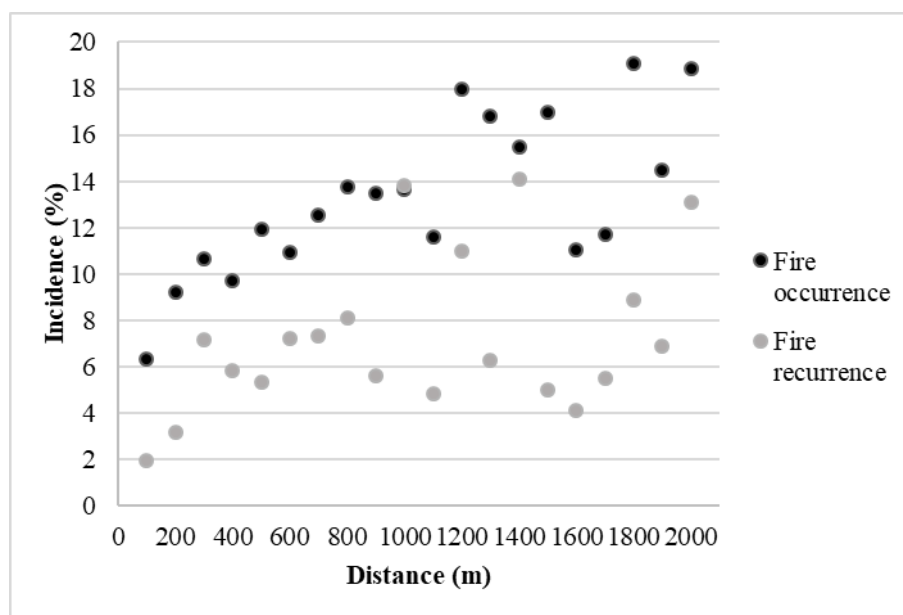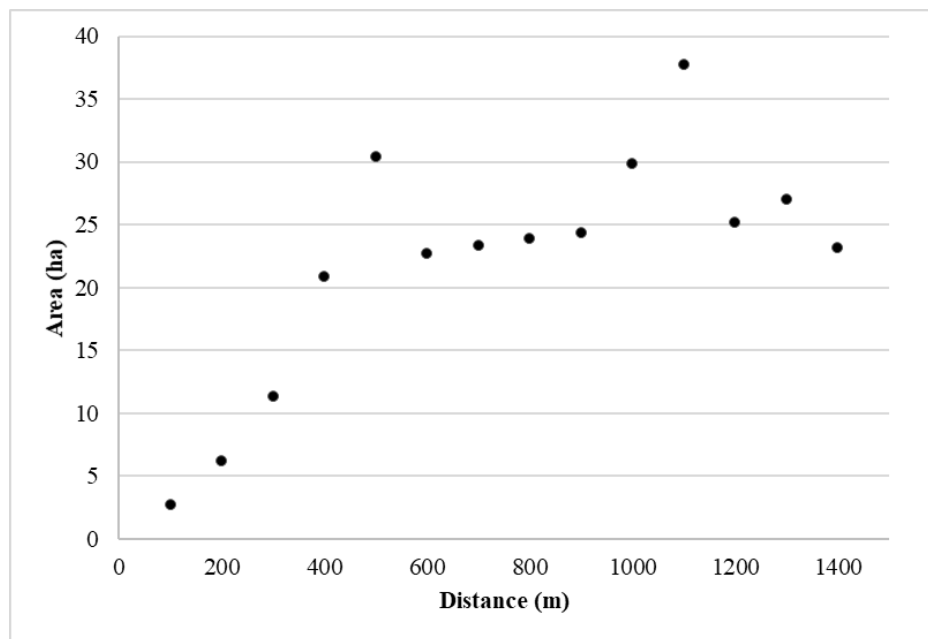

Figure 5. Mean values of fire incidence according to distance class from the built-up areas.

**Figure 6.** Mean values of burnt area per event according to distance class from the built-up areas.

The share of forest lands affected by single or repeated burning decreases as elevation increases. Fire incidence ranged between 12% and 15% up to an elevation of <700 m, being systematically lower than 10% at an elevation of >1200 m a.s.l.; fire recurrence reached the highest values in correspondence of the 100, 200, and 300 m a.s.l. elevation classes (13.7%, 9.1%, and 8.5%, respectively) and the lowest values (<2%) above 1200 m a.s.l.

Figure 7 illustrates the values of fire incidence considering both distance from built-up areas and elevation. The contour plot shows areas where forest fire incidence reached maximum values, i.e., at an elevation of approximately 800 m and a distance of 1800 m from built-up areas. We found other critical values for elevations less than 550 m and distances from built-up areas greater than 1800 m.
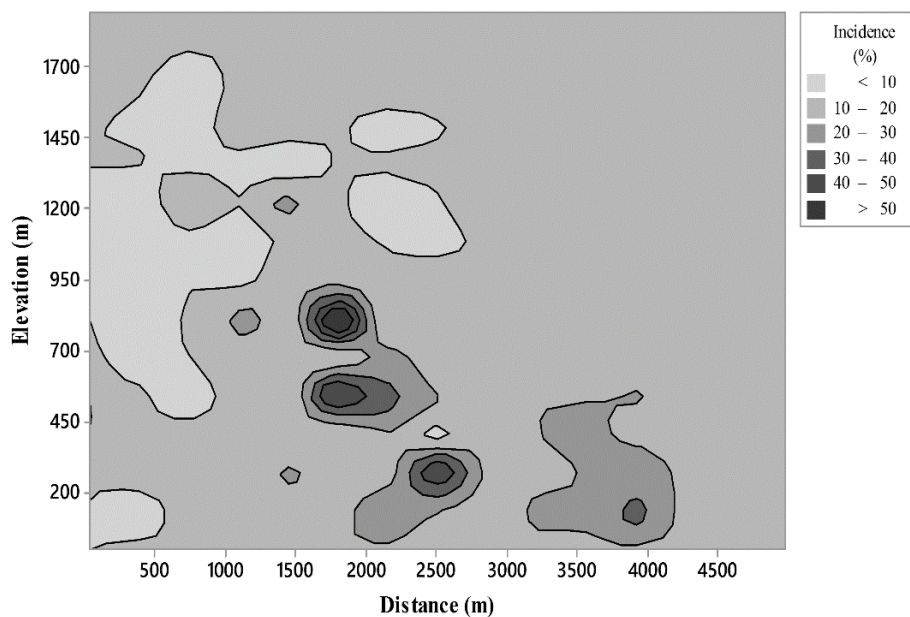
Figure 7. Contour plot diagram where fire incidence is shown as a function of elevation and distance from built-up areas.

In the case of fire recurrence incidence (Figure 8), the highest values were recorded at an elevation of about 600 m and a distance of 2700 m from built-up areas.
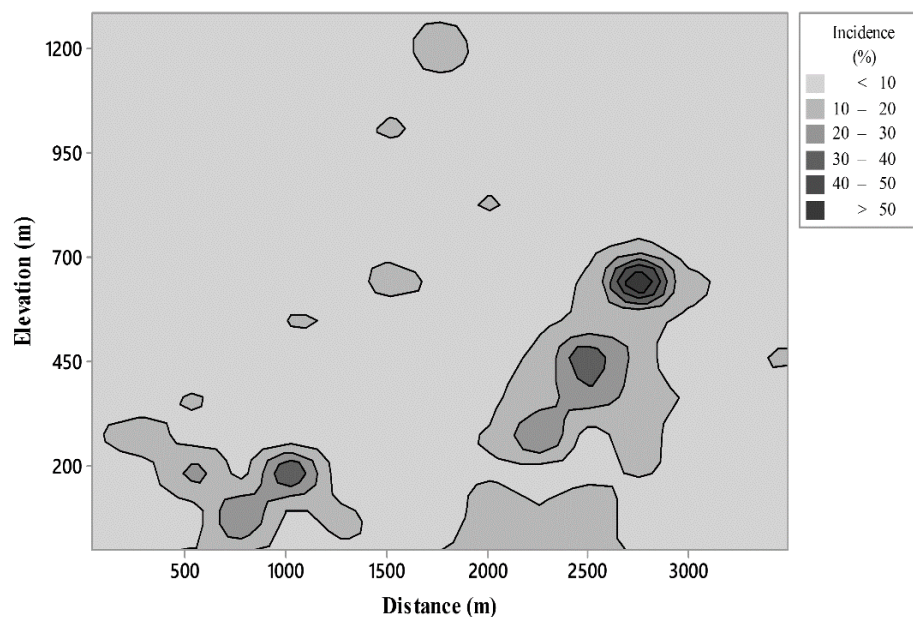
Figure 8. Contour plot diagram where fire recurrence incidence is shown as a function of elevation and distance from built-up areas.

4. Discussion

We analyzed the spatial distribution of forest fires in the Italian peninsula during the 2007–2014 time period. In particular, we investigated two pivotal issues of fire regime: frequency and incidence of forest fires according to relevant territorial predictors such as distance from built-up area and elevation. Notably, distance from built-up areas proved to be one of the most important predictors of wildfire occurrence in landscapes affected by widespread urbanization; this was expected, as in the Mediterranean region the large majority of wildland fires are caused by humans [36,75]. On the other hand, our results indicate that there is a negative relation between distance from built-up areas and fire frequency and recurrence but also a positive relation between the distance from built-up areas and fire incidence: thus, there are more fires, and more recurring events, in closer proximity to built-up areas, but the burnt areas that are closer to built-up areas are usually smaller than what is typically observed in more distant areas.

Our findings, documented on a large (national) scale, are in line with previous local studies affirming that as the distance to roads, urban settlements, and built-up areas increases, fire occurrence decreases (e.g., [36,41,42,45–48,50–53,55,56,76]), and fire incidence increases (e.g., [54,77]). In the examined case, nearly 50% of fire occurrence and 36% of recurrent fires occurred within 200 m from built-up areas. Interestingly, a 200-m buffer has been considered to be particularly suitable in the definition of WUIs in Europe [78]: this buffer area should play a key role in the management of prevention activities. Nevertheless, in Italy, such a considerable amount of fires never reached an incidence higher than 10% in flat areas (<200 m) and higher than 30% in hilly and mountainous areas in the considered period.

Territorial zones closer to man-made settlements are thus more likely to burn due to direct human activities and road accessibility (Figure 3). On the other hand, in our national-scale study we found the lowest values of burnt area per event in those zones. This is most likely a result of higher efficiency of fire management in areas where fires may pose significant direct risks to people, infrastructures, and asset values. Proximity to roads may make suppression operations more feasible, and such a

proximity is even usually considered a priority zone when managing emergency calls and interventions (e.g., [79–82]).

Elevation also significantly influences both fire frequency and incidence. Contour plots suggest that elevation and distance from built-up areas represent the most critical combination in terms of fire incidence of single or recurrent fires; these hotspots of fire incidence are located in hilly and low mountain rural areas (1800 to 2700 m from built-up areas, at an elevation between 600 and 800 m).

Quantitative knowledge about where wildfires ignite and spread is essential to ensure appropriate fire management throughout large territories: any rational decision needs to be the outcome of evidence-based considerations [83]. The ability to assess and understand how patterns of wildfires are distributed across large territories helps decision makers to improve the effectiveness of fire prevention, detection, and the allocation of firefighting resources. This issue is particularly crucial for managing fires under the increasing growth of "WUI-scapes". The use of such a strategy helps in the effective protection of overall ecosystem services [84,85].

5. Conclusions

This study investigated forest fires on a large-scale, covering the entire territory of Italy from both "horizontal" (distance from built-up areas) and "vertical" (elevation) points of view. Once spatial patterns of forest fire occurrence and recurrence across landscapes are identified and analyzed following this approach, fire managers can use this information to answer questions related to fire risk management, especially under extreme weather and fuel conditions. Such questions can range from what type of areas are likely to be treated (and where interventions should occur) to which fuel treatments are most effective for safeguarding people and urban settlements (e.g., [16,86,87]).

The spatial analysis presented here reveals two faces of the same coin: a disproportionately high wildfire occurrence close to built-up areas along with high fire incidence hotspots in quite distant rural areas. The results of this study suggest a greater need for fire management to tackle the complex issue of fire protection in WUIs, for example, the need to optimize the spatial allocation of fire suppression resources to defend people, infrastructures, or asset values. On the other hand, fire protection in rural areas requires the spatial allocation of fire prevention measures, such as prescribed burning and silvicultural tending (e.g., [40]) in order to reduce the size of burned forest areas.

Our findings result from an analysis of wildfires under a dynamic landscape framework and are consequently subject to change as new knowledge is obtained. Nevertheless, this explorative study may be of great practical significance because it not only corroborates prior research, but it also considers a large-scale perspective that will likely impact future analyses in this field. More broadly, the proposed analysis of large-scale spatial patterns of wildfires may apply to other countries (or regions) where time series of geospatial information on forest fire perimeters are available: ultimately, this would allow researchers and policymakers alike to quantitatively address the issue of whether wildfires are knocking on the doors of built-up-areas, and if so, to determine how best to respond.

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