Science of the Total Environment 890 (2023) 164281

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

# Active governance of agro-pastoral, forest and protected areas mitigates wildfire impacts in Italy

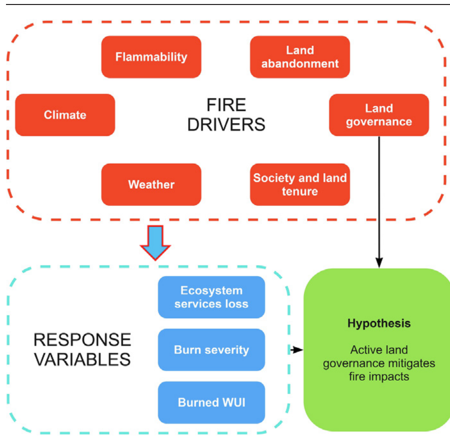
Gian Luca Spadoni [a,b,*], Jose V. Moris [a], Giorgio Vacchiano [c], Mario Elia [d], Matteo Garbarino [a], Emanuele Sibona [a], Antonio Tomao [e,f], Anna Barbati [e], Lorenzo Sallustio [g], Luca Salvati [h,i], Carlotta Ferrara [h], Saverio Francini [j,k,l], Enrico Bonis [m], Ilaria Dalla Vecchia [m], Andrea Strollo [n], Marco Di Leginio [n], Michele Munafò [n], Gherardo Chirici [j,k], Raoul Romano [h], Piermaria Corona [e,o], Marco Marchetti [g,l], Antonio Brunori [p], Renzo Motta [a], Davide Ascoli [a]

[a] *Department of Agricultural, Forest and Food Sciences (DISAFA), University of Torino, Largo Paolo Braccini 2, 10095 Grugliasco, Italy*
[b] *Department of Science, Technology and Society, University School for Advanced Studies IUSS Pavia, Palazzo del Broletto, Piazza della Vittoria 15, 27100 Pavia, Italy*
[c] *Department DISAA, University of Milan, via Celoria 2, 20133 Milan, Italy*
[d] *Department of Soil, Plant and Food Sciences, University of Bari Aldo Moro, Via Amendola 165/A, 70126 Bari, Italy*
[e] *Department for Innovation in Biological, Agro-food and Forest systems (DIBAF), University of Tuscia, Via San Camillo De Lellis, SNC, 01100 Viterbo, Italy*
[f] *Department of Agricultural, Food, Environmental and Animal Sciences, University of Udine, Via delle Scienze 206, 33100 Udine, Italy*
[g] *Department of Bioscience and Territory, University of Molise, c.da Fonte Lappone, 86090 Pesche, IS, Italy*
[h] *CREA Research Centre for Agricultural Policies and Bioeconomy, Forests Observatory, via Barberini 36, 00198 Rome, Italy*
[i] *Department of Methods and Models for Economics, Territory and Finance, Sapienza University of Rome, Via del Castro Laurenziano 9, 00161 Rome, Italy*
[j] *Department of Agriculture, Food, Environment and Forestry, Università degli Studi di Firenze, Via San Bonaventura, 13, 50145 Florence, Italy*
[k] *Fondazione per il Futuro delle Città, Florence, Italy*
[l] *National Biodiversity Future Center (NBFC), Palermo 90133, Italy*
[m] *Forest Stewardship Council, Italy*
[n] *Italian National Institute for Environmental Protection and Research (ISPRA), Via Vitaliano Brancati 48, 00144 Rome, Italy*
[o] *CREA Research Centre for Forestry and Wood, viale Santa Margherita 80, 52100 Arezzo, Italy*
[p] *PEFC Italia – Programme for the Endorsement of Forest Certification Schemes, Italy*

## HIGHLIGHTS

- The fire-regulatory effect of land governance has been rarely tested empirically.
- Random Forest models assessed the influence of major drivers on wildfire impacts.
- The analyses factored out primary drivers like climate and landscape flammability.
- Reduced wildfire impacts are associated with active land governance in Italy.

## GRAPHICAL ABSTRACT




* Corresponding author at: via Paolo Braccini 2, 10095 Grugliasco, TO, Italy.
*E-mail address:* gianluca.spadoni@unito.it (G.L. Spadoni).

http://dx.doi.org/10.1016/j.scitotenv.2023.164281
Received 2 February 2023; Received in revised form 15 May 2023; Accepted 15 May 2023
Available online 20 May 2023

A R T I C L E I N F O

Editor: Manuel Esteban Lucas-Borja

*Keywords:*
Fire drivers
Ecosystem services
Fire severity
Random Forest
Wildland-urban interface

A B S T R A C T

Wildfire regimes affected by global change have been the cause of major concern in recent years. Both direct prevention (e.g., fuel management planning) and land governance strategies (e.g., agroforestry development) can have an indirect regulatory effect on wildfires. Herein, we tested the hypothesis that active land planning and management in Italy have mitigated wildfire impacts in terms of loss of ecosystem services and forest cover, and burned wildland-urban interface, from 2007 to 2017. At the national scale, we assessed the effect size of major potential fire drivers such as climate, weather, flammability, socio-economic descriptors, land use changes, and proxies for land governance (e.g., European funds for rural development, investments in sustainable forest management, agro-pastoral activities), including potential interactions, on fire-related impacts via Random Forest modelling and Generalized Additive Mixed Model. Agro-forest districts (i.e., aggregations of neighbouring municipalities with homogeneous forest and agricultural characteristics) were used as spatial units of analysis. Our results confirm that territories with more active land governance show lower wildfire impacts, even under severe flammability and climatic conditions. This study supports current regional, national, and European strategies towards "fire resistant and resilient landscapes" by fostering agroforestry, rural development, and nature conservation integrated policies.

## 1. Introduction

Wildfires are a complex phenomenon guided by multiple biological, physical, and human drivers interacting through space and time (Moritz et al., 2005). In addition to regional climate and fire weather (Turco et al., 2019; Pereira et al., 2020), previous research highlights the influence of multiple anthropogenic factors on fire regimes, such as the flammability related to land uses and their changes (e.g., Moreira et al., 2011; Fernandes et al., 2016; Mantero et al., 2020), activities related to the rural economy (García-Ruiz et al., 2020), or fire management policies (Humphrey et al., 2021). In densely populated areas such as Southern Europe, the human impact on fire regimes has been particularly strong compared to other geographical regions (Fernandes et al., 2020).

In Southern Europe, there has been a scientific and political debate on whether land governance policies based on bio-economy principles (i.e., economies based on renewable natural resources for the production of goods, services and energy) and nature-based solutions, fostered by European funding programs (e.g., Rural Development Programme, LIFE+ program), can mitigate wildfire impacts under current climate change scenarios (European Commission, 2018, 2022; Moreira and Pe'er, 2018; Verkerk et al., 2018; Ascoli et al., 2023). Supported by those who promote such policies, a great variety of strategies to achieve fire resistant and resilient landscapes have been formulated (Fernandes, 2013; Tedim et al., 2016; Bacciu et al., 2022). These approaches involve both direct and indirect fire prevention (Colonico et al., 2022). Direct prevention is pursued by planning and implementing strategic fuel management actions (e.g., fuel breaks, prescribed burning) to support firefighting, protect the wildland-urban interface, and increase ecosystems resilience (Lachlan McCaw, 2013). Indirect prevention refers to the ensemble of land governance strategies supporting rural and natural land development, such as sustainable forest management (Corona et al., 2015; Verkerk et al., 2018; Varela et al., 2020), agro-pastoral activities (Moreira and Pe'er, 2018) and active nature conservation programs (Cánibe Iglesias et al., 2022), that have side-effects in reducing fire hazard by supporting ecosystems' fire regulation capacity at the landscape scale, i.e., "the ability of ecosystems and landscapes to regulate spatiotemporal attributes of fire regimes through the control of factors affecting fire behaviour resulting from the interaction between fire and biophysical structures such as vegetation types" (Depietri and Orenstein, 2019; Sil et al., 2022). Indirect prevention strategies can be framed within the broader concept of integrated fire management (Rego et al., 2010; Wolpert et al., 2022) that fosters cross-sectoral governance approaches, enhancing fire prevention targets (European Commission, 2018; Wunder et al., 2021).

Although several studies have assessed the local effect of direct fuel management (Ager et al., 2010; Espinosa et al., 2019; Cansler et al., 2021), the indirect influence of land governance policies in mitigating fire impacts at the landscape scale is challenging to quantify (Dale, 1997). Consequently, the few studies that attempted to test the leverage of such policies on fire disturbance in Southern Europe, have relied on simulations of landscape dynamics under alternative land governance approaches (Regos et al., 2016; Sil et al., 2019a; Aquilué et al., 2020; Pais et al., 2020; Campos et al., 2022; Lecina-Diaz et al., 2023).

In our research, we used Italy as a representative example of a Southern European region, characterized by strong climatic, topographic, and socio-economic gradients (Elia et al., 2022). Such heterogeneity is useful to test if active land governance has a quantifiable influence on fire impacts under a wide range of fire drivers. In Italy, many studies have assessed the effect of several drivers on wildfire metrics, e.g., fire occurrence, total burnt area (Barbati et al., 2015; Mancini et al., 2018b; Ferrara et al., 2019; Ascoli et al., 2021; Cilli et al., 2022; Malandra et al., 2022). However, previous research has focused on traditional fire metrics, and mainly on one or a few types of drivers, such as socio-economic (Michetti and Pinar, 2019; Mancini et al., 2018b), climate (Cilli et al., 2022), or land use change (Ascoli et al., 2021), without adopting a multivariate perspective. Furthermore, very few authors have attempted to test whether land governance measures influence wildfire patterns in Italy (Colonico et al., 2022).

To fill this gap, we employed a multivariate approach to explain the variability of wildfire impacts in Italy by considering different types of potential drivers simultaneously. We specifically tested the hypothesis that active land governance influences wildfires, contributing to the creation of more fire resistant and resilient landscapes. To do so, we considered and factored out the variability related to climate, fire behaviour (fire weather and flammability) and other socio-economic aspects (society and land tenure, land abandonment). In addition, following the approach outlined by Moreira et al. (2020), we focused on fire impacts rather than on descriptive fire metrics (e.g., burnt area, fire recurrence), looking at *what* burns rather than just *how much*. We specifically evaluated impacts on ecosystem services, forested areas, and wildland-urban interface, being these different socio-ecological dimensions on which fire damages have strong repercussions in ecological, economic, and public safety terms. Herein, we speculate that land governance mitigates such impacts, in different ways and with variable relevance.

## 2. Materials and methods

### 2.1. Study area and experimental design

We extracted from the Italian national wildfire information system (https://geoportale.incendiboschivi.it) and from autonomous regions databases (Aosta Valley, Trentino, South Tyrol, Friuli, Sardinia, Sicily) the wildfire perimeters and date of ignition of all the fire events larger than 1 ha which occurred from 2007 to 2017. The entire fire dataset was checked to fix possible errors related to spatial geometry and missing data. In total, we extracted data from 48,953 fire events throughout Italy (Fig. 1),

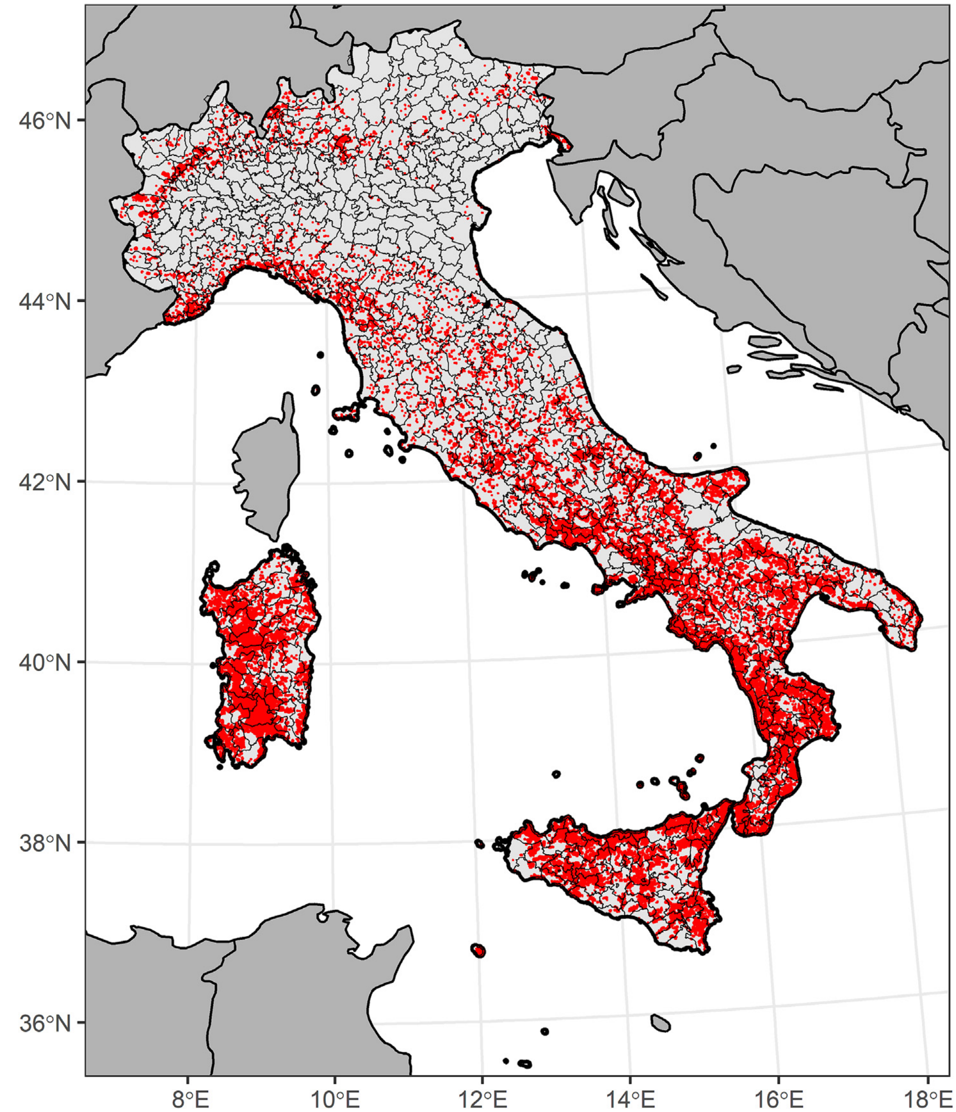



**Fig. 1.** Case study. The red areas represent all wildfire events larger than 1 ha which occurred in Italy between 2007 and 2017 in the 776 Agro-Forest Districts.

which were responsible for a burned area of 999,482 ha in the study period (i.e., 98.8 % of the total burned area in Italy; fires smaller than 1 ha accounted for the remaining 1.2 %).

We adopted the Italian Agro-Forest Districts (AFD) as sample unit for statistical analyses. AFD are groups of neighbouring municipalities (usually between 5 and 10) with homogenous agronomic, environmental, and socio-economic characteristics. Italy is divided into 766 AFD, with an average size of 394 $km^2$ each (Recanatesi et al., 2015; Sallustio et al., 2018). Previous studies have attempted to characterize wildfires in Italy by using the municipality as a sampling unit (e.g., Mancini et al., 2018b; Ferrara et al., 2019). However, these studies highlighted the need to expand the analysis to a larger scale to examine wildfire patterns, because large fire events generally extend beyond the territory of a single municipality. Indeed, Italian municipalities are highly variable in size, and large fires can affect several municipalities in one single event. We calculated that 96.6 % of the fire events in Italy between 2007 and 2017 occurred within one single AFD. We therefore considered that AFD are a suitable spatial unit for analysing landscape-scale attributes influencing wildfire impacts.

In this study, we modelled three types of response variables that characterize wildfire impacts: the amount of specific ecosystem services affected by fire, forest areas affected by high-severity fire, and burned areas in the wildland-urban interface (WUI; Table 1). Predictors were grouped into three classes: climate, fire behaviour, and socio-economic variables (Table 1). The fire behaviour potential driver was further divided into two subgroups: weather and flammability. Likewise, socio-economic potential driver was parted into three subgroups: society and land tenure, land abandonment and land governance. A short state-of-art of the literature on drivers of wildfire characteristics in Italy, that helped in defining main predictors, and a summary of the datasets used for this study are presented in the Supplementary material (Tables S1 and S2). All variables were computed at AFD scale.

### *2.2. Response variables*

#### *2.2.1. Loss of ecosystem services*

Landscape multi-functionality is an important aspect of territory planning. Goods and services provided by ecosystems are known as “ecosystem services” and may decline in various aspects (Fisher et al., 2009). Wildfire might have both positive and negative effects on the provision of ecosystem services, particularly under natural fire regimes or planned condition, e.g., prescribed burning (Pausas and Keeley, 2019). However, in Italy most of wildfires originates from unplanned anthropogenic ignitions determining unfavourable fire regimes under several attributes, i.e., seasonality, frequency, severity (e.g., Ascoli and Bovio, 2010; Valese et al., 2014), causing mostly disservices rather than services (Sil et al., 2019b; Roces-Díaz et al., 2021), and this is the assumption we considered for this study. To

**Table 1**
Response variables and potential drivers used in the study.

| Type | Subgroup | Variable | Unit | Reference year(s) | Expected relationship with fire impacts | Description |
|---|---|---|---|---|---|---|
| **Response variables** | | | | | | |
| Impact measures | | ES | – | 2012 | – | Measure of the proportions of burned ecosystem services |
| | | Burn severity | – | 2007–2017 | – | Total area burned at high severity normalized to biomass density |
| | | WUI | % | 2012 | – | Proportion of burned wildland-urban interface |
| **Potential drivers** | | | | | | |
| Climate | | tmax | °C | 1970–2000 | Increase | Maximum temperature |
| | | prec | mm | 1970–2000 | Decrease | Mean annual precipitations |
| | | bio9 | °C | 1970–2000 | Increase | Average temperature of the driest quarter of the year |
| | | fwi_p90 | – | 1979–2018 | Increase | 90th percentile of daily FWI[a] values |
| Fire behaviour | Weather | fwi_wstd | – | 1979–2018 | Increase | Mean FWI[a] associated to wildfire events |
| | Flammability | flammability | kW/m | 2006 | Increase | Mean potential fireline intensity |
| Socio-economic | Society and land tenure | pop_dens | inhab/km$^2$ | 2001 | Decrease | Population density |
| | | agr_state | % | 2000 | Increase | Agricultural land owned by the state on total agricultural land |
| | | farm_size | % | 2000 | Increase | Average farm size on total agricultural area |
| | | marginality | % | 2012 | Increase | Land suitable for agriculture but with low profitability |
| | | unsuitable | % | 2012 | Increase | Land unsuitable for agriculture |
| | | agr_value | €/ha | 2012 | Decrease | Value of agricultural land |
| | Land abandonment | aband_p | % | 1990–2006 | Increase | Land cover transitions towards a state of abandonment |
| | | pop_growth | % | 2001–2011 | Decrease | Population growth rate per year |
| | | built-up | % | 1991–2001 | Decrease | Dwellings built-up on total dwellings |
| | Land governance | managed_p | % | 1990–2006 | Decrease | Land cover transitions towards active management |
| | | pas | n°/ha | 2000 | Decrease | Grazing index: number of livestock units per ha of pasture |
| | | protected_p | % | 2012 | Decrease | Land within protected areas |
| | | life_bud | € | 1999–2012 | Decrease | Funds invested by the EU LIFE+ program in local projects |
| | | for_cert | % | 2003–2012 | Decrease | Forest surface certified by FSC[b] and by PEFC[c] on total forest surface |
| | | rdp_agr | – | 2007–2013 | Decrease | RDP[d] measures - agricultural sector enhancement |
| | | rdp_for | – | 2007–2013 | Decrease | RDP[d] measures - forest conservation efforts |
| | | rdp_marg | – | 2007–2013 | Decrease | RDP[d] measures - marginal areas support |
| | | for_harv | ha | 1997–2006 | Decrease | Harvested forest area |

[a] FWI = Fire Weather Index.
[b] FSC = Forest Stewardship Council.
[c] PEFC = Programme for the Endorsement of Forest Certification.
[d] RDP = Rural Development Programme.

assess the impact of wildfires on ecosystem services in each AFD, we used national maps of four different ecosystem services: i) habitat quality (dimensionless), which assesses the biodiversity conservation status (Terrado et al., 2016; Sallustio et al., 2017; Di Febbraro et al., 2018); ii) climate regulation service (ton/ha), estimated through carbon storage and sequestration (Munafò et al., 2016; FAO and ITPS, 2018; Assennato et al., 2022); iii) sediment retention service (ton/ha∗year), which indicates the capacity to retain sediment and it is measured in terms of avoided soil erosion (Panagos et al., 2015); iv) pollination potential (dimensionless), which measures pollinators availability (Munafò et al., 2016; Assennato et al., 2022). The four ecosystem services were estimated with the use of the InVEST model (Natural Capital Project, 2022).

The level of ecosystem services potentially affected by fire was calculated by dividing the amount of each ecosystem service within burned areas by the total amount of the given ecosystem service in the agro-forest district. Principal Component Analysis (PCA) was then applied to reduce the data on ecosystem services from four variables to one (Marsboom et al., 2018). The first Principal Component (PC) explained 89.9 % of the variance. Higher values of the first PC (i.e., "*ES*" in Table 1) indicate that larger amounts of ecosystem services were potentially affected by fire in relation to their total extent within the agro-forest district.

### 2.2.2. Burn severity

For this study, we defined high-severity fires as the events causing abrupt tree canopy cover loss. Due to the lack of data on burn severity covering the whole country and the study period, we used the tree cover loss layer from the Global Forest Change (GFC) product (Hansen et al., 2013) with a spatial resolution of 30 m (Elia et al., 2022). Because GFC does not provide information on the cause of tree cover loss, we assumed that the tree cover loss detected within a given fire perimeter in the year of fire occurrence and in the following year was due to immediate and delayed post-fire mortality, respectively. Salvage logging in Italy rarely occurs within two years after fire (Ascoli et al., 2013); consequently we assumed that the forest cover loss within fire perimeter is due to post-fire tree mortality and not by tree harvesting. We aggregated the tree cover loss within two years from the fire event in each fire perimeter, for every fire in AFD, to obtain the total forest cover loss due to fire in AFD from 2007 to 2017. Given the probability that high severity fire increases with live fuel load (i.e., in areas with dense live biomass; Parks et al., 2018a; García-Llamas et al., 2019), we rescaled burn severity by dividing total tree cover loss area by the total forest biomass (Avitabile et al., 2020) in each AFD to obtain the response variable "*Burn severity*".

### 2.2.3. Wildland-urban interface (WUI)

The wildland-urban interface (WUI) refers to areas or locations where wildfires can potentially ignite homes (Radeloff et al., 2018). In this study, we consider not only residential areas but also other artificial surfaces of high social and economic value. A WUI map for Italy was built following the approach of Modugno et al. (2016). First, we selected artificial areas and wildland fuels from the Italian CORINE Land Cover (CLC) map (2012 version; Feranec et al., 2016). Artificial surfaces correspond to urban, industrial and infrastructure areas, whereas wildland fuels correspond to forest, natural grassland, moorland, shrubland, other wooded lands, and recently burned areas. Second, a buffer zone was calculated for wildland fuels (400 m) and artificial surfaces (200 m; Mitsopoulos et al., 2020). Overlapping wildland fuel and artificial areas, with their respective buffers, were identified as WUI areas. For each AFD, we calculated: i) the total area of WUI; ii) the total area of burned WUI (i.e., the WUI area inside the fire perimeters); and iii) the ratio between burned WUI and total WUI. The latter, "*WUI*" in Table 1, was selected as a response variable and indicates the proportion of WUI affected by fire.

### 2.3. Potential drivers

#### 2.3.1. Climate

Climate data were obtained from the global dataset WorldClim, containing monthly records for the period 1970–2000 with a 1 $km^2$ spatial resolution (Fick and Hijmans, 2017). Climatic grids were averaged, temporally and spatially, to obtain mean values of climatic variables for each AFD. In particular, the selected climatic variables were: i) maximum temperature ("*tmax*"); ii) mean annual precipitation ("*prec*"); iii) mean temperature of driest quarter (i.e., the driest three months) of the year ("*bio9*"). Additionally, we calculated local (i.e., cell by cell) 90th percentiles of Fire Weather Index (FWI; Van Wagner, 1987) daily time series from global data (spatial resolution 0.25°) for the period from 1979 to 2018 (Vitolo et al., 2020) and averaged them spatially over each AFD. Percentiles of FWI are often applied to describe the climatology of fire danger (Vitolo et al., 2020; Abatzoglou et al., 2021).

#### 2.3.2. Fire behaviour

*2.3.2.1. Fire weather.* FWI data were also used to assess fire weather conditions during wildfire events (Vitolo et al., 2020). The FWI system is used to estimate fire danger worldwide (Field et al., 2015). For each fire >1 ha, we extracted the FWI value of the recorded starting day from the grid cell that contains the centroid of the final fire perimeter. The centroid was used because the FWI grid spatial resolution (0.25°) is much larger than individual burned areas and, therefore, fire perimeters stay mostly in one grid cell. Likewise, we used the start date because the fire duration was unknown. In fact, initial fire weather conditions and the related fire spread are commonly assumed to greatly affect the final burned area and the firefighting capacity in the region (Pezzatti et al., 2020).

FWI values can be interpreted better within the range of possible historical values in a particular area, especially when comparing different geographical zones (Vitolo et al., 2019). Therefore, the FWI value of each fire was standardized by dividing it by the maximum FWI value ever reported in the daily time series from 1979 to 2018 from the same grid cell. We then calculated the area-weighted average (i.e., the burned area of each fire was used as weight) of the standardized FWI values from all the fires that occurred in each AFD. This final value ("*fwi_wstd*" in Table 1) is assumed to characterize the average fire weather conditions during the fire events in each single AFD for the 2007–2017 period.

*2.3.2.2. Flammability.* We simulated potential fire activity with FlamMap (Finney et al., 2020) to characterize the gradient in landscape scale fire hazard among AFDs. Basic fire activity simulations in FlamMap require data on elevation, slope, aspect, canopy cover and fuel model (Finney, 2006). A national Digital Elevation Model (DEM) was used to derive data on elevation, slope and aspect, while a European tree cover density dataset was employed to extract canopy cover data (https://land.copernicus.eu/pan-european/high-resolution-layers/forests/tree-cover-density/status-maps/2015). The CLC map of 2006 (i.e., land cover before the start of the period of analysis in 2007; Feranec et al., 2016) was used to characterize the fuel models. Fuel data were generated by assigning a standard fuel model, according to Scott (2005), to each CORINE class (Kosztra et al., 2019) present in Italy (Table S3). All rasters were harmonized at a resolution of 60 × 60 m (the format used to compute elaborations on FlamMap) before the simulation in FlamMap.

The fire activity simulation was carried out under constant weather conditions for the whole national territory assuming a full alignment between wind and slope. In the simulation, wind was set to blow uphill at 16.1 km $h^{-1}$ in all the cells, and fuel moisture content was constant for all the standard fuel models (i.e., 5 %, 6 % and 7 % for the dead fuel 1-h, 10-h and 100-h classes, respectively, as well as 30 % and 60 % for the live herbaceous and woody classes, respectively). Fireline intensity was selected to characterize flammability in the study. Fireline intensity (kW/m) represents the rate of energy or heat release per unit time per unit length of fire front (Alexander and Cruz, 2019). Calculations of potential fireline intensity were performed independently for each cell. FlamMap generated a 60 × 60 m grid of fireline intensity, and the average value for each AFD was then calculated. This allows comparing the flammability across the country because the potential fire activity in each AFD will vary as a function of its topography and vegetation features. This fireline intensity variable was then renamed as "*flammability*" (Table 1).

#### 2.3.3. Socio-economic variables

*2.3.3.1. Society and land tenure.* Social and land tenure factors can have a strong influence on the fire regime of a territory (Vilar et al., 2016; Mancini et al., 2018b; Viedma et al., 2018). Accordingly, we included in our study the following variables: population density ("*pop_dens*"); agricultural land owned by the state ("*agr_state*"); average farm size ("*farm_size*"); land predisposition to agricultural activities ("*marginality*"); land unsuitable for agriculture ("*unsuitable*"); and value of agricultural land ("*agr_value*"). See Table 1 for a description of these variables. Population and agricultural production data were retrieved from Ferrara et al. (2019), while data on marginality, unsuitability and value of agricultural land were collected from Sallustio et al. (2018). Original data were available at municipal level but were aggregated to obtain values at AFD level.

*2.3.3.2. Land abandonment.* We examined land cover changes (LCCs) towards land abandonment, which is a predominant process in Southern Europe. Previous studies found a positive relationship between land abandonment and wildfire metrics (Pausas and Fernández-Muñoz, 2012; Sallustio et al., 2015; Viedma et al., 2015; Mantero et al., 2020; Ascoli et al., 2021). We assessed LCCs from 1990 to 2006 (i.e., changes before the start of the study period) based on the CLC Level 3 (Feranec et al., 2016) datasets. After merging the original CLC categories into six larger groups: forest (FO), shrubland (SH), grassland (GR), cropland (CR), urban (UR), and unvegetated (UV) (Table S4), we estimated the land cover changes of these major groups from 1990 to 2006. We then defined the proportion of abandoned areas ("*abandon_p*" in Table 1), which we calculated for each AFD, as the ratio between total hectares of transitions CR to FO, CR to SH, GR to FO, and GR to SH, and the AFD area.

In addition, two variables, collected from Ferrara et al. (2019), were extracted for each AFD: population growth rate per year ("*pop_growth*") and dwellings built-up from 1991 to 2001, relative to total dwellings ("*built-up*"). These two variables offer information on processes opposed to land abandonment.

*2.3.3.3. Land governance.* Here, land governance refers to active land management initiatives, actions, policies, and strategies. Land governance, according to our main study hypothesis, may indirectly prevent and mitigate wildfire impacts having multiple side effects on ecosystems' fire regulatory capacity (Fernandes, 2013; Regos et al., 2016; Sil et al., 2019a; Campos et al., 2022). As land governance is the core feature of our study, we included a wide set of proxies to characterize its many facets (Table 1).

Two proxies of agro-pastoral land management were created. First, following the approach described in Section 2.3.3.2, we used the transition matrix of CLC 1990–2006 to calculate the proportion of changes towards managed land (i.e., transitions FO to CR, and SH to CR) in each AFD, forming the variable "*managed_p*" (Table 1). Second, given the effect of grazing on fuel reduction (Taylor Jr., 2006; Moreira and Russo, 2007; Siegel et al., 2022), we retrieved a grazing index (i.e., number of livestock units per ha of pasture) from Ferrara et al. (2019) named "*pas*" (Table 1).

Another proxy was used to characterize sustainable forest management. The variable "*for_cert*" (Table 1) quantifies the proportion of forest area certified according to the Forest Stewardship Council (FSC; https://fsc.org/en) and to the Programme for the Endorsement of Forest Certification schemes (PEFC; https://www.pefc.org/) in relation to the total forest area of the AFD. FSC and PEFC are the two major organizations providing worldwide forest certifications for forest owners and managers (public administrations, associations, and private companies; Clark and Kozar, 2011;

Mikulková et al., 2015). We obtained data on certified forest areas from the Italian FSC and PEFC offices.

As active forest management proxy, we estimated the amount of forest harvesting for each AFD in the period 1997–2006 (variable "*for_harv*"; Table 1). To do so, we exploited 3I3D, a forest disturbance detection algorithm specifically designed for Italy (Francini et al., 2021; Francini et al., 2022a) and recently implemented over Landsat imagery to detect natural and anthropogenic forest disturbances over the last four decades in Italy (Francini et al., 2022b). To filter out natural forest disturbances, for each AFD we calculated the median value of the annual forest disturbance areas over the entire period, which was assumed to be a good indicator of harvest because median values should limit the influence of random and sporadic natural forest disturbance events (e.g., wind, fire) and adequately represent the annual extent of planned and regular harvesting activities.

We included two proxies of active nature conservation. We assessed the amount of land within protected areas for each AFD, obtaining the variable "*protected_p*" (Table 1; Sallustio et al., 2018). Protected areas in Italy have competencies in wildfire prevention and must implement a fire management plan, which increases their resistance and resilience to wildfires, compared to other territories (Pereira et al., 2012; Rodrigues and de la Riva, 2014; Vilar et al., 2016). Additionally, we determined the total budget of all projects funded by the EU LIFE+ program, at the AFD level over the 1999–2012 period ("*life_bud*" in Table 1). LIFE+ projects promote actions for nature conservation and climate change adaptation, including fire prevention (https://cinea.ec.europa.eu/programmes/life_en). We assumed that LIFE+ projects reflect the attention of local communities, administrations, universities and other institutions towards nature conservation and adaptation to climate change through active land management and innovative solutions (D'Alfonso, 2015). In particular, we focused on LIFE+ projects gathered by the "GoProFor" database (https://www.lifegoprofor.eu/it/), which collects forestry-related LIFE+ projects developed in Italy since 1999.

Finally, we included the Rural Development Programme (RDP) funds spent at the municipal level in Italy (Colonico et al., 2022) as a proxy of rural activities, aggregating them at AFD level. RDP is a financing tool of the European Common Agricultural Policy (CAP) aimed to support rural areas development (European Commission, 2006) and is articulated in various measures. We selected 13 measures which, according to Colonico et al. (2022), are related to indirect fire prevention (Table S5). We then combined these measures with a PCA (Fig. S2) and extracted the first three principal components. Each component reflects a different cluster of RDP measures (Table 1). In particular, "*rdp_agr*" is connected to agricultural measures, "*rdp_for*" reflects forest conservation efforts, and "*rdp_marg*" reflects support to marginal areas (Table 1). The number of PCs to be extracted was limited to those that together explained >50 % of the total variance.

### 2.4. Data analyses

Fig. 2 provides a summary of the analysis carried out for this study. Once all the data were organized at AFD level, we followed some exploratory data analyses according to Zuur et al. (2010). We excluded AFD that did not reach a total burned area of 10 ha within the 11-year period because fire disturbance was of little relevance (e.g., AFD with strong urbanization and industrialization); consequently, these areas were considered as unsuitable to test the study hypothesis. From the initial 766 AFD, we excluded 164, mostly within the Po Valley, reducing our dataset to 602 AFD. Each of these AFD reported values associated with the 3 response variables and 24 independent variables grouped into 3 groups and 6 subgroups of potential drivers (Table 1).

We carried out a variable reduction of independent variables to concentrate the variability of our dataset on fewer components (McCune et al., 2002; Adler and Yazhemsky, 2010). We applied four Principal Component Analyses (PCAs) separately to climate, society and land tenure, land abandonment and land governance subgroups (Table 1). PCAs were computed with the R package Factominer (Lê et al., 2008). We did not apply PCA to the weather and flammability subgroups because both are represented by single variables that are computed using multivariate models (Table 1). For each PCA, we extracted PCs to reach 50 % or more of the variance explained. We carried out an additional PCA, in which we used the 10 independent variables that resulted from the variable reduction process (Table 2) to explore relationships within the dataset in a multivariate space (Fig. S4). Finally, we used Pearson's correlation coefficients to check collinearity among these 10 variables.

We applied Random Forest (RF; Breiman, 2001) to test the influence of the potential drivers on the three response variables (ES, Burn severity, WUI). RF modelling allows dealing with many different variables and produces outputs that are easy to interpret (Moris et al., 2017; Jain et al., 2020). Furthermore, RF has been previously used in similar studies (Cansler et al., 2021; Stritih et al., 2021; Cilli et al., 2022; Canadas et al., 2023). We ran a RF for each of the three response variables (Table 1). We set: i) the number of trees = 500 to find a balance between error rate (which decreases as the number of trees increases) and computational costs; ii) the number of variables tried at each split = 4 to be close to the square root of the total number of predictor variables; and iii) the resampling method used to grow trees = sampling without replacement, which is the most suitable method according to the literature (Boulesteix et al., 2012). Model performance was estimated in terms of R-squared values

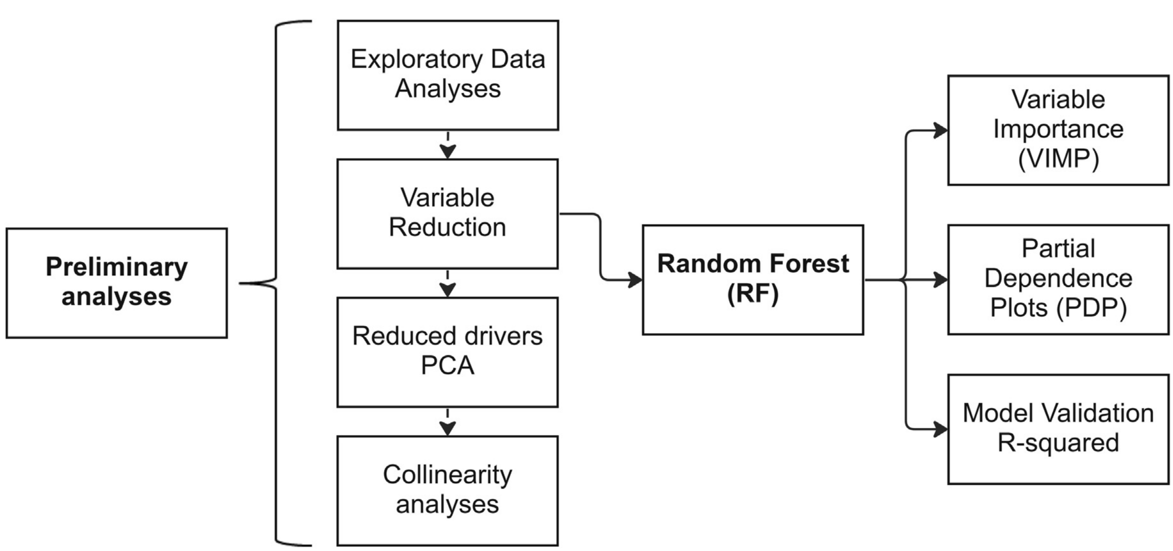



**Fig. 2.** Workflow of the main data analyses.

**Table 2**
Variables used in RF modelling.

| Type | Subgroup | Variable | Unit | Expected relationship with fire impacts | Description |
|---|---|---|---|---|---|
| **Potential drivers** | | | | | |
| Climate | | C1 | – | Increase | Warm and dry climate |
| Fire behaviour | Weather | fwi_wstd | – | Increase | Mean FWI[a] associated to wildfire events |
| | Flammability | flammability | kW/m | Increase | Mean potential fireline intensity |
| Socio-economic | Society and land tenure | S1 | – | Decrease | High profitability and densely populated areas |
| | | S2 | – | Increase | Marginal, hardly accessible and less developed areas |
| | Land abandonment | LA1 | – | Increase | Land abandonment |
| | Land governance | LG1 | – | Decrease | Forest and mountain areas governance |
| | | LG2 | – | Decrease | Rural and marginal areas governance |
| | | LG3 | – | Decrease | Intensive agriculture |
| | | LG4 | – | Decrease | Sustainable forest management |

[a] FWI = Fire Weather Index.

between observed and predicted values. We used the R package "randomForest" to carry out the RFs (Liaw and Wiener, 2002). For each RF model, we obtained two main outputs: Variable Importance (VIMP) and Partial Dependence Plots (PDP). VIMP shows the relative importance, in terms of percentage increase in mean squared error (%incMSE), of independent variables in predicting the response variable, while PDPs show the effect of each single predictor on the response variable after removing the effect of the remaining predictors. To check for potential interactions among drivers, we furtherly perform RF models, to test if the regulation capacity of land governance on the extent of wildfire affecting ecosystem services varied along different levels of predominant potential drivers, producing Partial Dependence Surfaces (PDS; i.e., three dimensional surfaces that, after removing the effect of the other drivers, display the combined influence of two predictors on a response variable). In addition, to further corroborate the relationships between interacting potential drivers and fire impacts on ecosystem services, we applied Generalized Additive Mixed Modelling (GAMM; Zuur et al., 2009). We categorized the agro-forest districts into three regions based on the clusters described in Ascoli et al. (2021) and illustrated in Fig. S5. These three regions are based on the main fire season (winter, mixed, summer) and a climate gradient (Alpine in the north, temperate in the centre, Mediterranean in the south and islands). We included these regions as a random factor in the GAMM, while the other potential drivers (excluding climatic variables) were considered as fixed factors. To model the affected ecosystem services (ES), we utilized the R package gamm4 (Wood and Sheipl, 2020) to implement a GAMM with a Gaussian distribution and an identity link function.

## 3. Results

The Principal Component Analyses (PCAs) reduced the number of predictor variables from 24 (Table 1) to 10 (Table 2). Land governance required four Principal Components (PCs) to achieve >50 % of the variance explained within the initial set of proxies, while society and land tenure variables required two, and climate and land abandonment only one PC (Table 2). We interpreted the new variables obtained from the PCA according to the set of original variables most correlated to each eigenvector (Table 2; Fig. S3 and Table S6). Additionally, we found that these 10 variables were not affected by strong collinearity, since absolute bivariate Pearson's correlation coefficients were all lower than 0.65, with an average value of 0.18 (Schober et al., 2018). Results from the descriptive PCA with the 10 eigenvectors are reported in the Supplementary results (Fig. S4). The reduced set of 10 variables (Table 2) was used as predictor variables in the subsequent RF.

Random Forest (RF) produced accurate models, returning high R-squared values for the three response variables: 0.85 for loss of ecosystem services, 0.73 for burn severity, and 0.83 for burned wildland-urban interface. Climate was the most important predictor in the *Burn severity* and *WUI* models, and the second most important in the *ES* model (Fig. 3). Concerning the fire behaviour variables, fire weather was a moderate predictor of *ES* and *WUI* though, surprisingly, a poor predictor of *Burn severity*. On the contrary, flammability was a strong predictor of *ES* and *WUI*, and to a lesser extent of *Burn severity*. Socio-economic factors have a lower weight, compared to climate and fire behaviour. Society and land tenure ranked third in the *ES* and *Burn severity* models and fourth for *WUI*, with a predominance of S1 for the *Burn severity* model and of S2 for the other two models. Land abandonment showed a low-to-moderate role in all the models. Predictors characterizing land governance obtained a lesser ranking, compared to other potential drivers, except for LG2 (i.e., proxy of governance of rural and marginal areas), which was the second most important variable in the *Burn severity* model (Fig. 3).

Fire impacts increased with warm and dry climate (C1), more severe fire weather (*fwi_wstd*) and higher flammability (*flammability*) (Figs. 4–6). C1 and *fwi_wstd* show similar relationships with the response variables in all three RF models (Figs. 4–6). *Flammability* also shows a positive relationship in all models, although, for *ES* and *WUI,* relationships are non-linear (Figs. 4–6), and linear for *Burn severity* (Fig. 5). Regarding the socio-economic predictors, S1 had positive and non-linear relationships with the response variables (Figs. 4–6), while for S2 the relationships were negative (Figs. 4 and 5), except for the *WUI* model (Fig. 6). Fire impacts also increased with land abandonment, even though the relationships are non-linear (Figs. 4–6). In general, fire impacts decreased with increasing values of the predictors characterizing active land governance. However, the relationships were not consistently negative, with strong non-linear patterns in some of them (Figs. 4–6). For instance, *Burn severity* decreased with LG2 up to the 50th percentile, and increased from that point on.

Results related to Generalized Additive Mixed Modelling are shown in the Supplementary materials (Table S7 and Fig. S6). GAMM supported our initial hypothesis (Table 2) and concurred with the primary outcomes of the RF model related to impacts on ES (Figs. 3–4). Furthermore, findings from GAMM revealed a significant positive interaction between land governance variables (LG3, LG4) and *fwi_wstd*, indicating a decreased impact of the fire regulatory capacity of active land management as fire weather values increased. Similarly, results obtained with the Partial Dependence Surfaces (Fig. S7) showed a reducing effect of LG4 to increasing values of *fwi_wstd*, which indicates a limited mitigating effect of land governance as fire weather increases. Diversely, due to an increase of flammability and C1, the negative slope of LG4 appeared steeper (Fig. S7). Finally, no interaction seemed to affect land abandonment and LG4.

## 4. Discussion

The role of land governance in mitigating wildfire impacts is a controversial issue in Southern Europe (European Commission, 2018; Moreira and Pe'er, 2018; Verkerk et al., 2018), mainly addressed through position papers (Moreira et al., 2020; Bacciu et al., 2022) or landscape simulation analyses (Regos et al., 2016; Sil et al., 2019a; Pais et al., 2020; Campos et al., 2022; Lecina-Diaz et al., 2023). Following these earlier theoretical and modelling investigations, our study aimed to quantify the fire regulatory capacity of land governance by employing data related to real processes and landscapes. By using Italy as a case study, we collected various proxies of land governance aspects, such as rural development, agro-pastoral activities, sustainable forest management, and active nature

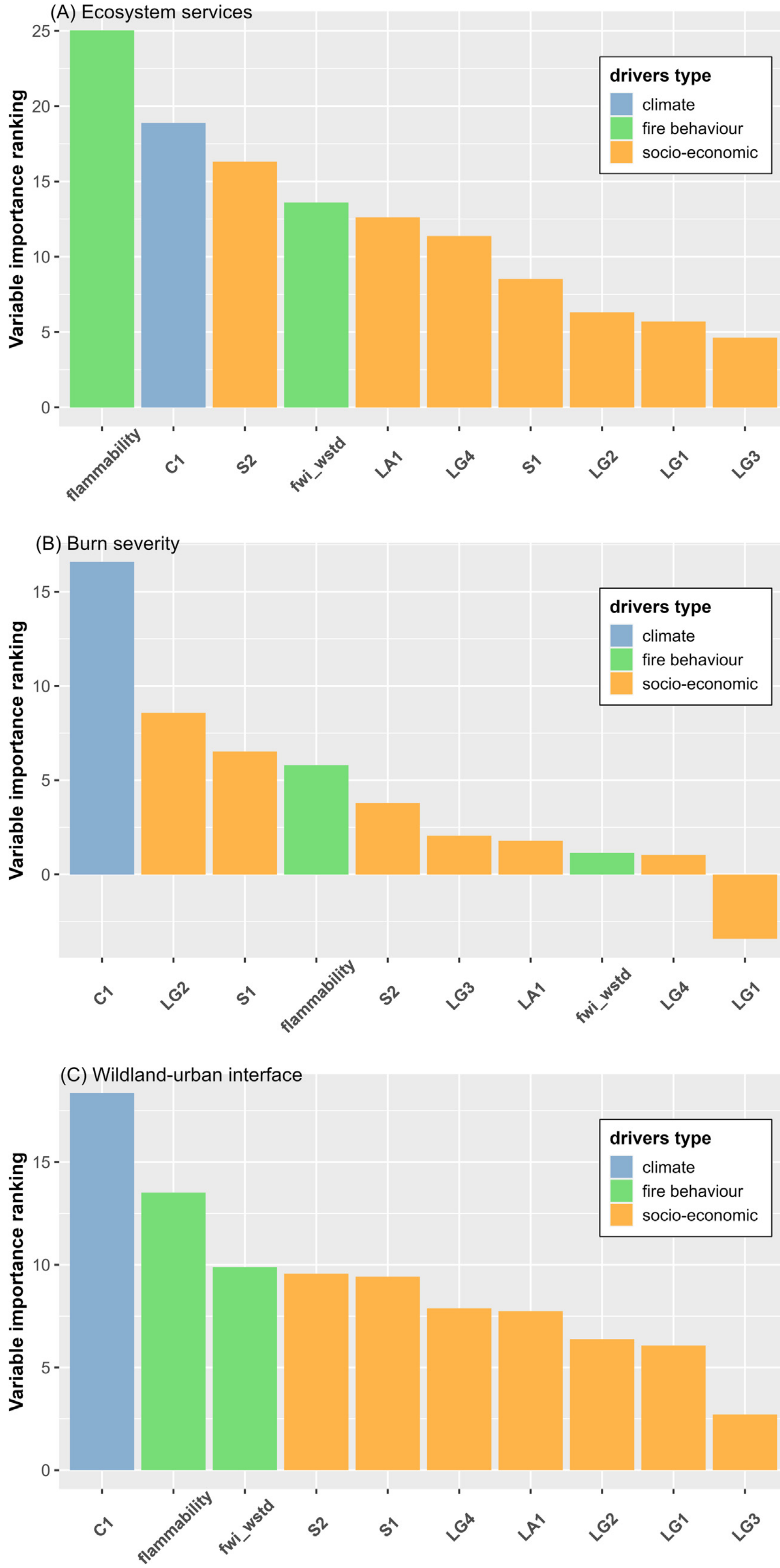



**Fig. 3.** Variable importance (VIMP) rankings from Random Forest models predicting burned ecosystem services (A), burn severity (B) and burned wildland-urban interface (C). C1 = warm and dry climate; S1 = high profitability and densely populated areas; S2 = marginal, hardly accessible and less developed areas; LA1 = land abandonment; LG1 = forest and mountain areas governance; LG2 = rural and marginal areas governance; LG3 = intensive agriculture; LG4 = sustainable forest management; flammability = mean potential fireline intensity; fwi_wstd = mean FWI (Fire Weather Index) associated to wildfire events.

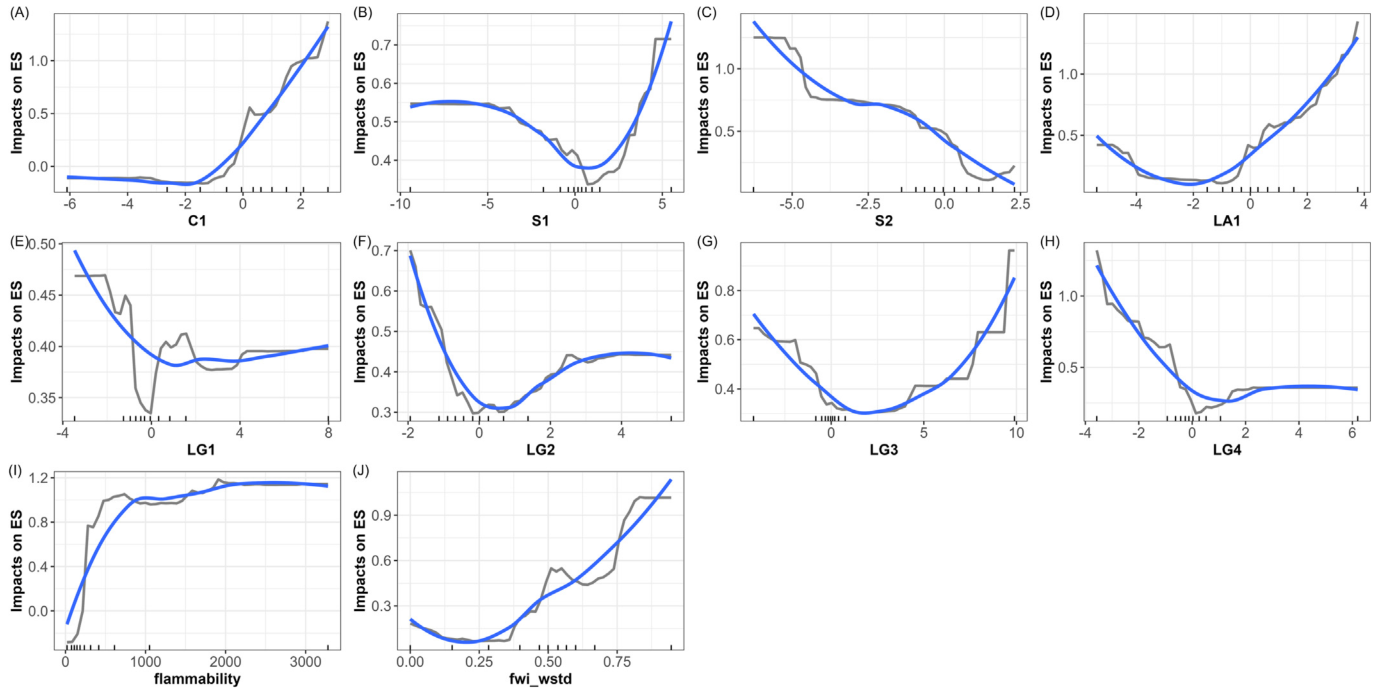



**Fig. 4.** Partial dependence plots for the response variable *ES*. Ticks on the x-axis represent the deciles of predictors distribution. The black lines represent the outputs from RF while the blue lines represent smooth curves obtained from LOESS (locally estimated scatterplot smoothing). C1 = warm and dry climate; S1 = high profitability and densely populated areas; S2 = marginal, hardly accessible and less developed areas; LA1 = land abandonment; LG1 = forest and mountain areas governance; LG2 = rural and marginal areas governance; LG3 = intensive agriculture; LG4 = sustainable forest management; flammability = mean potential fireline intensity; fwi_wstd = mean FWI (Fire Weather Index) associated to wildfire events.

conservation. We then examined how these proxies were related to wildfire impacts, such as burned ecosystem services, burned wildland-urban interface, and burn severity in forest ecosystems, while accounting for other major potential drivers of wildfire activity, such as climate, fire weather, and flammability. Our research showed that land governance, expressed as sustainable forest management, extensive farming practices, and active nature conservation practices tends to mitigate and reduce the impacts of wildfires.

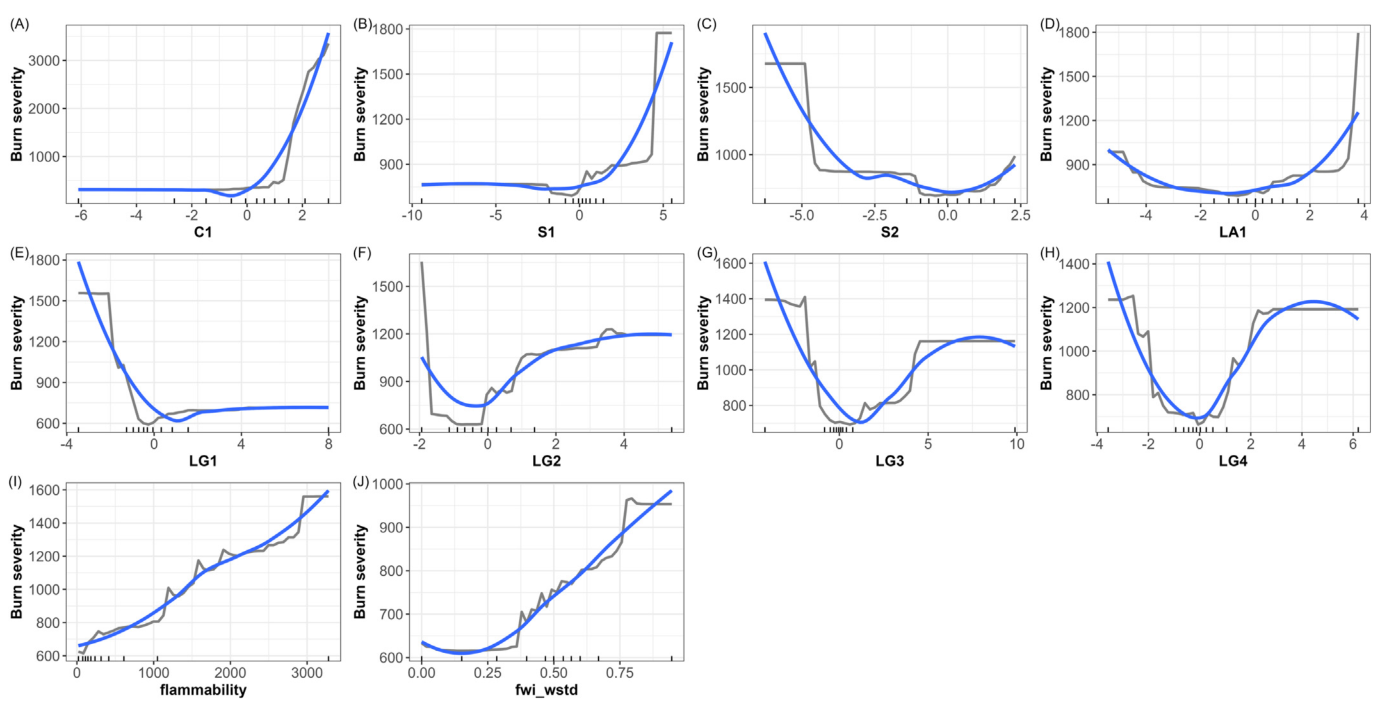



**Fig. 5.** Partial dependence plots for the response variable *Burn severity*. Ticks on the x-axis represent the deciles of predictors distribution. The black lines represent the outputs from RF while the blue lines represent smooth curves obtained from LOESS (locally estimated scatterplot smoothing). C1 = warm and dry climate; S1 = high profitability and densely populated areas; S2 = marginal, hardly accessible and less developed areas; LA1 = land abandonment; LG1 = forest and mountain areas governance; LG2 = rural and marginal areas governance; LG3 = intensive agriculture; LG4 = sustainable forest management; flammability = mean potential fireline intensity; fwi_wstd = mean FWI (Fire Weather Index) associated to wildfire events.

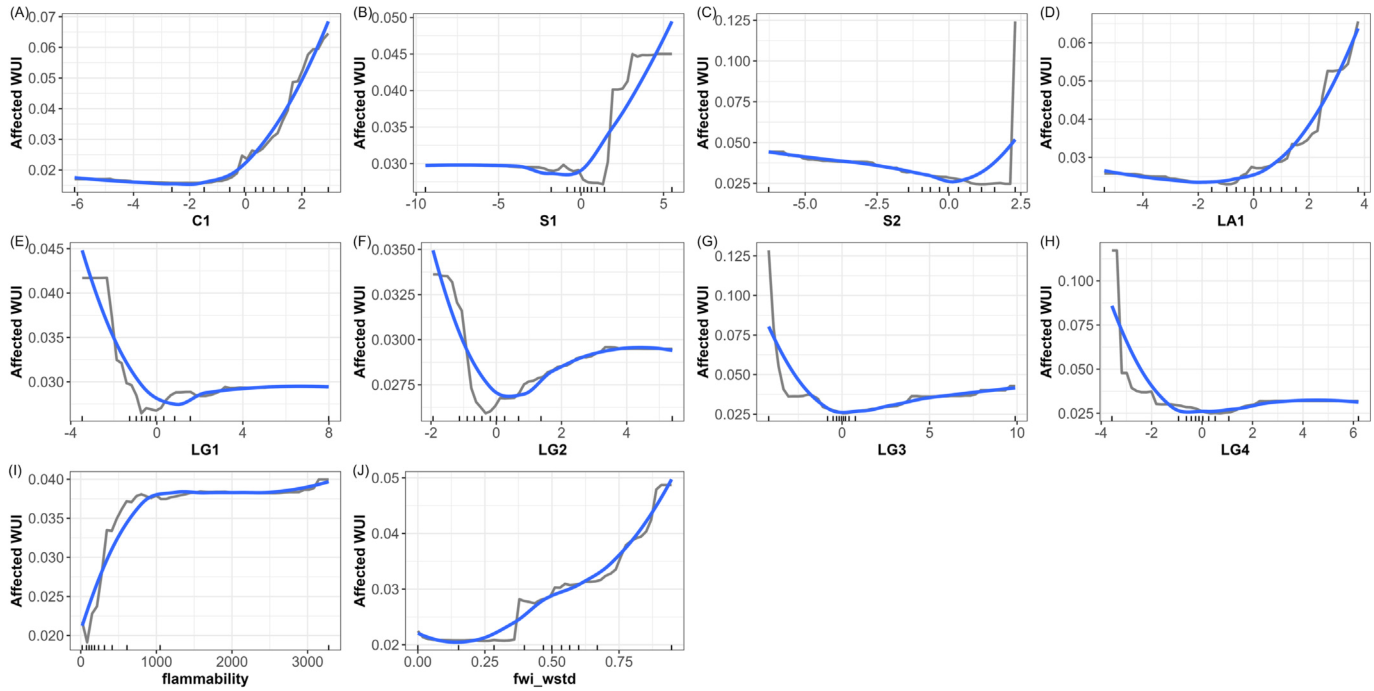



**Fig. 6.** Partial dependence plots for the response variable *WUI*. Ticks on the x-axis represent the deciles of predictors distribution. The black lines represent the outputs from RF while the blue lines represent smooth curves obtained from LOESS (locally estimated scatterplot smoothing). C1 = warm and dry climate; S1 = high profitability and densely populated areas; S2 = marginal, hardly accessible, and less developed areas; LA1 = land abandonment; LG1 = forest and mountain areas governance; LG2 = rural and marginal areas governance; LG3 = intensive agriculture; LG4 = sustainable forest management; flammability = mean potential fireline intensity; fwi_wstd = mean FWI (Fire Weather Index) associated to wildfire events.

### *4.1. Drivers of wildfire impacts*

The predominance of climate and fire behaviour drivers (i.e., fire weather and flammability) in explaining wildfire impacts (Fig. 3) confirmed that warm and dry climate, highly flammable land uses, and favourable weather conditions during wildfire events strongly influence wildfire activity and its impacts (Fernandes et al., 2016; Zald and Dunn, 2018). Italy displays a strong north-south gradient in both climate and landscape scale fire hazard (Ascoli et al., 2021; Elia et al., 2022), which might have a confusing effect. However, the significant positive slope of flammability on burned ecosystem services displayed in the GAMM model (Table S7), where climate regions (Alpine, temperate, and Mediterranean) were included as random factor, pointed out that flammable land uses are a major driver of fire impacts in most climate regions of Southern Europe (Moreira et al., 2020). Besides physical factors, our findings highlighted the key role of socio-economic factors in driving fire regimes in Southern Europe. The positive effect of land abandonment (LA1) on the three response variables is consistent with our hypothesis (Table 2) and with previous studies (Pausas and Fernández-Muñoz, 2012; Sallustio et al., 2015; Viedma et al., 2015; Mantero et al., 2020; Ascoli et al., 2021). Land abandonment (LA1) was, in fact, intended as a measure of lack of land governance. In this context, the absence of human activities may increase fire hazard at the landscape scale by reducing landscape heterogeneity and connecting fuel loads available to burn (Moreira et al., 2011; Sil et al., 2019a, 2019b; Kelly et al., 2020; Ascoli et al., 2021).

Although land governance displayed a limited effect, both the Random Forest and the GAMM models suggest that active land management played a key role in reducing wildfire impacts in Italy. In the ecosystem services (*ES*) and wildland-urban interface (*WUI*) models (Fig. 3), *sustainable forest management* (LG4) and *forest and mountain areas governance* (LG1) were important land governance predictors as ecosystem services and wildland-urban interfaces are strongly linked to forested areas. Given the negative relationships between these land governance proxies in the ecosystem service and WUI models (Figs. 4 and 6), we can assume that territories that invested in sustainable forest management, forest certifications, nature conservation, and in the agro-pastoral sector, displayed reduced wildfire impacts, despite other factors conducive to fire activity (e.g., flammability; Gan et al., 2015; Dini et al., 2019; Ascoli et al., 2023). Results are consistent with the drivers' PCA (Fig. S4), in which LG4 and LG1 show a negative correlation to fire predictors (C1, *flammability*, *fwi_wstd*, LA1).

*Rural and marginal areas governance* (LG2), mainly linked to forest harvesting and Rural Development Programme (RDP) funds (Fig. S3, Table S6), was an important predictor of *Burn severity*. However, the sign of this relationship was unexpected. *Burn severity* decreased initially with LG2, but, once it reached the mid LG2 value, *Burn severity* increased (Fig. 5F). A possible explanation might be related to the intensive forest harvesting that correlates with higher LG2 values (Lindenmayer et al., 2009; Santopuoli et al., 2015; Zald and Dunn, 2018). For instance, an excess in coppicing under Mediterranean conditions might favour coarse woody debris accumulation and the recolonization of open space by more flammable grass and shrub species (Cassagne et al., 2011; James et al., 2011). LG2 was also linked to the RDP measures supporting marginal areas (*rdp_marg*; Table S6). Significant investments may be directed to particularly disadvantaged regions which are often fire prone (Marcu, 2015; Viedma et al., 2015; Akter and Grafton, 2021) and in which RDP policy effects may not be detectable yet (Colonico et al., 2022). Indeed, in the drivers' PCA (Fig. S4) LG2 was positively correlated to flammability and land abandonment predictors. Similar conclusions can be assumed for the trends found in the models of ecosystem services and WUI (Figs. 4F and 6F). The less influence of *intensive agriculture* (LG3) on the three fire impacts suggested that intensive agricultural systems, when mediated over the entire country, do not have a primary role in driving the response variables analysed here. This result might also be explained by a bias towards a lower presence of wildfires in areas intensively cultivated (Marques et al., 2011; Moreira and Pe'er, 2018; Kganyago and Shikwambana, 2020).

*Marginal, hardly accessible and less developed areas* (S2) was an important predictor of impacts on ecosystem services, although the negative relationship was unexpected (Fig. 4C; Table 2). It's well proven that many ecosystem services are linked to forest cover. However, especially in southern

Italy, marginal areas are often characterized by transitional land uses towards wooded areas, such as secondary shrublands, as a consequence of abandonment or forest degradation processes, providing lower levels of ecosystem services (Gallego Fernández et al., 2004; Acácio et al., 2009; Quintas-Soriano et al., 2022). Likewise, positive relationships between *high profitability and densely populated areas* (S1) and fire impacts were also surprising (Figs. 4B, 5B, 6B; Table 2). Complex dynamics between human ignitions, land fragmentation and suppression capacity may regulate these relationships. Other studies on fire drivers in Italy highlighted this complexity, showing how human activities decrease fire spread but increase ignitions (Mancini et al., 2018a; Ferrara et al., 2019; Table S2).

Drivers' interactions tested by both Random Forest (Fig. S7) and GAMM models (Table S7) revealed that land governance had a stronger mitigation effect in more flammable landscapes or in environments with a warm and dry climate, while it appeared to be less effective when favourable weather conditions for fires are occurring (Finney, 2001; Schmidt et al., 2008; Espinosa et al., 2019). This might depend on the discrepancy between the adaptability of land governance models to long term and stable conditions, which, in some unfavourable cases, might amplify their effects (i.e., where land governance is more needed, it leads to higher benefits; Finney, 2001), and the inability to deal with short term meteorological extremes (Espinosa et al., 2018). These results highlighted how it is essential to promote land governance strategies in warm, dry, and flammable landscapes but, at the same time, how these actions might have limited effects under extreme fire weather conditions, which are becoming more and more frequent due to climate change (Fernandes et al., 2016; Moreira et al., 2020).

Our results are consistent with findings from modelling approaches simulating fire regimes in different land governance scenarios in other Southern European regions. Pais et al. (2020), Campos et al. (2022) and Lecina-Diaz et al. (2023), using a border area between Spain and Portugal as a case study, showed that high nature value farmlands (i.e., agricultural landscapes of high nature conservation value and dominated by low-intensity farming systems; Lomba et al., 2015; Moreira and Pe'er, 2018), fire smart management (i.e., vegetation cover mosaic conversions aimed at fostering a more fire resistant and resilient landscape; Fernandes, 2013) agro-silvo-pastoral sustainable systems and traditional farming activities can reduce fire hazard and support biodiversity conservation, climate regulation and the provision of other ecosystem services, while optimizing costs compared to suppression based approaches. Regos et al. (2016) and Aquilué et al. (2020) tested the positive influence of biomass extraction and natural and semi-natural areas conversion to agricultural land on fire suppression effectiveness in Catalonia (Spain), while Sil et al. (2019a) proved that a reduction of land management decreases ecosystems' fire regulation capacity in Portugal.

On the other hand, our findings are also in line with previous empirical results. Some related to direct fire prevention practices, such as the ones obtained by Ager et al. (2010), Espinosa et al. (2019), and Cansler et al. (2021), who demonstrated how silvicultural treatments can lower burn probability and reduce fire severity in different European and North American regions. Other studies mainly focused on socio-economic aspects associated with the governance. For instance, Rodrigues and de la Riva (2014) and Vilar et al. (2016) showed that the presence of protected areas reduced wildfire occurrence in Spain; while Taylor Jr. (2006), Moreira and Russo (2007) and Siegel et al. (2022) found that pasture, through fuel reduction, can have positive effects in terms of wildfire activity regulation, in different environments.

Our study presented elements of continuity and innovation compared to the state of the art of research on wildfire drivers in Italy (see Table S2). The positive relationship between land abandonment and wildfire impacts found in our study (Figs. 4D, 5D, 6D) strengthen previous findings (Ferrara et al., 2019; Ascoli et al., 2021). Similarly, some outcomes related to the fire regulatory capacity of the land governance were anticipated by Ascoli et al. (2021) and Colonico et al. (2022). Nonetheless, our experimental design, based on multivariate modelling and including different types of predominant drivers (i.e., biophysical and socio-economic), was able to address potential confounding factors, associated with the significant north-south climate, land use flammability, and socio-economic gradient, that affect fire activity, such as marginalization, rurality, or the use of fire in agriculture (Ascoli and Bovio, 2010; Mancini et al., 2018b; Sallustio et al., 2018; Michetti and Pinar, 2019), which have hindered to draw firm conclusions in past studies (Elia et al., 2022).

### 4.2. Management implications

Our findings are key for ongoing and future land planning within wildfire risk mitigation strategies in Southern Europe, and especially in Italy. Current wildfire prevention measures are mainly based on fuel reduction treatments in strategic areas, to support suppression capacity (Fernandes, 2013; Salis et al., 2018). However, fuel reduction programs often do not reach the necessary landscape scale to effectively mitigate wildfire risk, and lack of economic sustainability (Sil et al., 2019a, 2019b; Ascoli et al., 2023). Conversely, landowners and managers in the agro-silvo-pastoral and nature conservation sectors, by crossing their primary goals, might obtain an economic return (Pulido et al., 2023). This means that activities from these sectors which, as demonstrated in this study, have a scattered fire regulatory effect, can be renewed in space and time, representing a key element in terms of wildfire prevention and strategic fuel management. Our results emphasised the significance of promoting cross-sectoral policies at the local level, while integrating wildfire risk prevention and civil protection goals, especially in European funding strategies for rural development and nature conservation. Supported by various funding sources from different levels, wildfire management actions can achieve greater stability and continuity, thereby also stimulating, and encouraging private investments (Ascoli et al., 2023; Lecina-Diaz et al., 2023; Pulido et al., 2023).

### 4.3. Limitations

Limitations of this study are mostly due to the lack of availability of land governance data, namely concerning land planning and forest harvesting aspects. In consequence, we had to rely on several proxies, which limited our capacity to characterize and quantify the effect of land governance on fire impacts. For instance, in Italy country-wide databases covering forest harvesting operations are basically lacking; to overcome this aspect, we made use of the 3I3D algorithm to obtain a median disturbance value which may show some limitations. First, agro-forest districts (AFDs) with a consistent amount of annual burned area may represent a bias for the median forest disturbance value. Second, very small clear-cuts or low-intensity thinning areas may have remained undetected, given the 30-m spatial resolution of the Landsat imagery. Nevertheless, those low intensity harvested areas are not expected to significantly alter the relative ranking in total forest harvest among AFD (Chirici et al., 2020). Furthermore, 3I3D has been proven to be more accurate compared to other existing products (Francini et al., 2022a), and large detection performance was confirmed in several country-wide studies (Francini et al., 2021; Francini et al., 2022b).

Regarding burn severity, we used Global Forest Change (GFC) dataset as a proxy of high burn severity areas (associated with tree stand replacing fire events). We verified the reliability of this proxy by finding a high correlation with measures made with Normalized Burn Ratio (NBR) data (Parks et al., 2018b) and with a European Landsat-based map of forest disturbances (Senf and Seidl, 2020). Further details on these comparative analyses and the reasons for choosing GFC are reported in Section 2.2.2 of the Supplementary materials.

Another limitation concerns the assumption of wildfires having exclusively negative impacts on ecosystem services. Wildfires may have heterogeneous impacts on ecosystem services like habitat quality and pollination potential (Pausas and Keeley, 2019). For instance, the impact of wildfire on habitat quality might depend on fire severity and vary according to the individual relationship between species and their habitat (Flitcroft et al., 2016; Rockweit et al., 2017; Whitman et al., 2017). Similarly, pollination potential may increase following wildfires when they promote a more diverse understory vegetation community (Carbone et al., 2019). Nonetheless, for unplanned fires (i.e., as most wildfires occurred in Italy between 2007 and 2017), our assumption is well founded (Sil et al., 2019b; Roces-Díaz et al., 2021).

## 5. Conclusions

This study contributes to disentangle the complex relationships among wildfire drivers by quantifying the role of land governance in regulating wildfire impacts in Italy. Despite study limitations, mainly related to lack of harmonized data for the entire study area, results suggested that active land governance, classified into rural development policies (e.g., Rural Development Programme funds), forest certifications (e.g., FSC and PEFC) and biodiversity conservation programs (e.g., Life Program), contributed to build-up fire resistant and resilient landscapes in Italy along the last few decades. Accordingly, land governance seems to have a moderate but relevant effect in preventing and mitigating fire impacts on ecosystem services, forest fire severity, and the wildland-urban interface. Consequently, increasing actively managed areas appeared to be a viable strategy to decrease wildfire impacts in fire-prone landscapes.

Our findings support current European strategies under the Green Deal aimed at integrating agricultural, forestry, rural development, and nature conservation policies in structural wildfire risk mitigation strategies (Moreira and Pe'er, 2018; Ascoli et al., 2023; Lecina-Diaz et al., 2023). We encourage a step forward towards a wildfire governance system which recognizes the key role of land management in providing civil protection and ecosystem conservation under climate and land use changes.

## CRediT authorship contribution statement

**Gian Luca Spadoni:** Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing, Investigation, Software. **Jose V. Moris:** Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing, Software. **Giorgio Vacchiano:** Methodology, Supervision, Data curation. **Mario Elia:** Supervision, Investigation. **Matteo Garbarino:** Methodology, Data curation. **Emanuele Sibona:** Data curation. **Antonio Tomao:** Data curation, Investigation. **Anna Barbati:** Supervision. **Lorenzo Sallustio:** Data curation, Investigation. **Luca Salvati:** Supervision. **Carlotta Ferrara:** Data curation, Supervision. **Saverio Francini:** Data curation, Methodology. **Enrico Bonis:** Data curation. **Ilaria Dalla Vecchia:** Data curation. **Andrea Strollo:** Data curation. **Marco Di Leginio:** Data curation. **Michele Munafò:** Supervision. **Gherardo Chirici:** Supervision. **Raoul Romano:** Supervision. **Piermaria Corona:** Supervision. **Marco Marchetti:** Supervision. **Antonio Brunori:** Data curation. **Renzo Motta:** Project administration, Resources, Supervision. **Davide Ascoli:** Conceptualization, Funding acquisition, Project administration, Writing – review & editing, Supervision, Investigation.

## Data availability

Data will be made available on request.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgments

This paper and related research have been conducted during and with the support of the Italian inter-university PhD course in sustainable development and climate change (link: www.phd-sdc.it).

This study was carried out within the Agritech National Research Center and received funding from the European Union Next-Generation EU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.4 – D.D. 1032 17/06/2022, CN00000022). "Next change risks" and a baseline for the fulfilment of the milestones within the Task 4.3.3 titled: "Set-up of the ensemble of innovative models for productivity and vulnerability prediction under climate change scenarios. In particular, our study represents an original paper related to the Spoke 4 – "Risk management strategies and policies in the context of climate change". This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

The authors acknowledge the support of NBFC to University of Florence, funded by the Italian Ministry of University and Research, PNRR, Missione 4 Componente 2, "Dalla ricerca all'impresa", Investimento 1.4, Project CN00000033. J.V.M. acknowledges the support from a postdoctoral fellowship funded by the Government of Asturias (Spain) through FICYT (AYUD/2021/58534).

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

We wish to thank the two anonymous reviewers who significantly contributed to improve the quality of the manuscript.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.164281.

## References

Abatzoglou, J.T., Juang, C.S., Williams, A.P., Kolden, C.A., Westerling, A.L., 2021. Increasing synchronous fire danger in forests of the western United States. Geophys. Res. Lett. 48 (2). https://doi.org/10.1029/2020GL091377.

Acácio, V., Holmgren, M., Rego, F., Moreira, F., Mohren, G.M.J., 2009. Are drought and wildfires turning Mediterranean cork oak forests into persistent shrublands? Agrofor. Syst. 76, 389–400. https://doi.org/10.1007/s10457-008-9165-y.

Adler, N., Yazhemsky, E., 2010. Improving discrimination in data envelopment analysis: PCA–DEA or variable reduction. Eur. J. Oper. Res. 202 (1), 273–284. https://doi.org/10.1016/j.ejor.2009.03.050.

Ager, A.A., Vaillant, N.M., Finney, M.A., 2010. A comparison of landscape fuel treatment strategies to mitigate wildland fire risk in the urban interface and preserve old forest structure. For. Ecol. Manag. 259 (8), 1556–1570. https://doi.org/10.1016/j.foreco.2010.01.032.

Akter, S., Grafton, R.Q., 2021. Do fires discriminate? Socio-economic disadvantage, wildfire hazard exposure and the Australian 2019–20 'Black Summer' fires. Clim. Chang. 165, 53. https://doi.org/10.1007/s10584-021-03064-6.

Alexander, M.E., Cruz, M., 2019. Fireline intensity. In: Manzello, S. (Ed.), Encyclopedia of Wildfires And Wildland-urban Interface (WUI) Fires. Springer, Cham https://doi.org/10.1007/978-3-319-51727-8_52-1.

Aquilué, N., Fortin, M.J., Messier, C., Brotons, L., 2020. The potential of agricultural conversion to shape forest fire regimes in Mediterranean landscapes. Ecosystems 23 (1), 34–51. https://doi.org/10.1007/s10021-019-00385-7.

Ascoli, D., Bovio, G., 2010. Tree encroachment dynamics in heathlands of north-west Italy: the fire regime hypothesis. iForest 3 (5), 137. https://doi.org/10.3832/ifor0548-003.

Ascoli, D., Castagneri, D., Valsecchi, C., Conedera, M., Bovio, G., 2013. Post-fire restoration of beech stands in the Southern Alps by natural regeneration. Ecol. Eng. 54, 210–217. https://doi.org/10.1016/j.ecoleng.2013.01.032.

Ascoli, D., Moris, J.V., Marchetti, M., Sallustio, L., 2021. Land use change towards forests and wooded land correlates with large and frequent wildfires in Italy. Ann. Silvicult. Res. 46 (2), 177–188. https://doi.org/10.12899/asr-2264.

Ascoli, D., Plana, E., Oggioni, S.D., Tomao, A., Colonico, M., Corona, P., ... Barbati, A., 2023. Fire-smart solutions for sustainable wildfire risk prevention: Bottom-up initiatives meet top-down policies under EU green deal. Int. J. Disaster Risk Reduct. 103715. https://doi.org/10.1016/j.ijdrr.2023.103715.

Assennato, F., Smiraglia, D., Cavalli, A., Congedo, L., Giuliani, C., Riitano, N., Strollo, A., Munafò, M., 2022. The impact of urbanization on land: a biophysical-based assessment of ecosystem services loss supported by remote sensed indicators. Land 11 (2), 236. https://doi.org/10.3390/land11020236.

Avitabile, V., Pilli, R., Camia, A., 2020. The Biomass of European Forests: An Integrated Assessment of Forest Biomass Maps, Field Plots And National Statistics. Publications Office of the European Union, Luxembourg https://doi.org/10.2760/758855.

Bacciu, V., Sirca, C., Spano, D., 2022. Towards a systemic approach to fire risk management. Environ. Sci. Pol. 129, 37–44. https://doi.org/10.1016/j.envsci.2021.12.015.

Barbati, A., Corona, P., D'amato, E., Cartisano, R., 2015. Is landscape a driver of short-term wildfire recurrence? Landsc. Res. 40, 99–108. https://doi.org/10.1080/01426397.2012.761681.

Boulesteix, A.L., Janitza, S., Kruppa, J., König, I.R., 2012. Overview of random forest methodology and practical guidance with emphasis on computational biology and bioinformatics. Wires 2 (6), 493–507. https://doi.org/10.1002/widm.1072.

Breiman, L., 2001. Random forests. Mach. Learn. 45, 5–32. https://doi.org/10.1023/a:1010933404324.

Campos, J.C., Rodrigues, S., Sil, Â., Hermoso, V., Freitas, T.R., Santos, J.A., ... Regos, A., 2022. Climate regulation ecosystem services and biodiversity conservation are enhanced differently by climate-and fire-smart landscape management. Environ. Res. Lett. 17 (5), 054014. https://doi.org/10.1088/1748-9326/ac64b5.

Canadas, M.J., Leal, M., Soares, F., Novais, A., Ribeiro, P.F., Schmidt, L., Delicado, A., 2023. Wildfire mitigation and adaptation: two locally independent actions supported by different policy domains. Land Use Policy 124, 106444. https://doi.org/10.1016/j.landusepol.2022.106444.

Cánibe Iglesias, M., Hermoso, V., Campos, J.C., Carvalho-Santos, C., Fernandes, P.M., Freitas, T.R., Honrado, J., Santos, J.A., Sil, Â., Regos, A., Azevedo, J.C., 2022. Climate- And Fire-smart Landscape Scenarios Call for Redesigning Protection Regimes to Achieve Multiple Management Goals. SSRN Scholarly Paper, Rochester, NY https://doi.org/10.2139/ssrn.4141771.

Cansler, A.C., Kane, V.R., Hessburg, P.F., Kane, J.T., Jeronimo, S.M.A., Lutz, J.A., Povak, N.A., Churchill, D.J., Larson, A.J., 2021. Previous wildfires and management treatments moderate subsequent fire severity. For. Ecol. Manag. 504, 119764. https://doi.org/10.1016/j.foreco.2021.119764.

Carbone, L.M., Tavella, J., Pausas, J.G., Aguilar, R., 2019. A global synthesis of fire effects on pollinators. Glob. Ecol. Biogeogr. 28 (10), 1487–1498. https://doi.org/10.1111/geb.12939.

Cassagne, N., Pimont, F., Dupuy, J.L., Linn, R.R., Mårell, A., Oliveri, C., Rigolot, E., 2011. Using a fire propagation model to assess the efficiency of prescribed burning in reducing the fire hazard. Ecol. Model. 222 (8), 1502–1514. https://doi.org/10.1016/j.ecolmodel.2011.02.004.

Chirici, G., Giannetti, F., Mazza, E., Francini, S., Travaglini, D., Pegna, R., White, J.C., 2020. Monitoring clearcutting and subsequent rapid recovery in Mediterranean coppice forests with Landsat time series. Ann. For. Sci. 77, 40. https://doi.org/10.1007/s13595-020-00936-2.

Cilli, R., Elia, M., D'Este, M., Giannico, V., Amoroso, N., Lombardi, A., ... Lafortezza, R., 2022. Explainable artificial intelligence (XAI) detects wildfire occurrence in the Mediterranean countries of Southern Europe. Sci. Rep. 12 (1), 1–11. https://doi.org/10.1038/s41598-022-20347-9.

Clark, M.R., Kozar, J.S., 2011. Comparing sustainable forest management certifications standards: a meta-analysis. Ecol. Soc. 16, 3–27.. https://www.jstor.org/stable/26268869.

Colonico, M., Tomao, A., Ascoli, D., Corona, P., Giannino, F., Moris, J.V., Romano, R., Salvati, L., Barbati, A., 2022. Rural development funding and wildfire prevention: evidences of spatial mismatches with fire activity. Land Use Policy 117, 106079. https://doi.org/10.1016/j.landusepol.2022.106079.

Corona, P., Ascoli, D., Barbati, A., Bovio, G., Colangelo, G., Elia, M., Garfì, V., Iovino, F., Lafortezza, R., Leone, V., Lovreglio, R., Marchetti, M., Marchi, E., Menguzzato, G., Nocentini, S., Picchio, R., Portoghesi, L., Puletti, N., Sanesi, G., Chianucci, F., 2015. Integrated forest management to prevent wildfires under Mediterranean environments. Ann. Silvicult. Res. 39, 1–22. https://doi.org/10.12899/ASR-946.

Dale, V.H., 1997. The relationship between land-use change and climate change. Ecol. Appl. 7 (3), 753–769. https://doi.org/10.1890/1051-0761(1997)007[0753:TRBLUC]2.0.CO;2.

D'Alfonso, A., 2015. How the EU budget is spent: LIFE programme. Retrieved fromEPRS: European Parliamentary Research Service https://policycommons.net/artifacts/1336596/how-the-eu-budget-is-spent/1943894/ on 26 May 2022. CID: 20.500.12592/3c1060.

Depietri, Y., Orenstein, D.E., 2019. Fire-regulating services and disservices with an application to the Haifa-Carmel region in Israel. Front. Environ. Sci. 7, 107. https://doi.org/10.3389/fenvs.2019.00107.

Di Febbraro, M., Sallustio, L., Vizzarri, M., De Rosa, D., De Lisio, L., Loy, A., Eichelberger, B.A., Marchetti, M., 2018. Expert-based and correlative models to map habitat quality: which gives better support to conservation planning? Glob. Ecol. Conserv. 16, e00513. https://doi.org/10.1016/j.gecco.2018.e00513.

Dini, F., Brunori, A., Maetzke, F.G., 2019. Effetti della certificazione di gestione forestale sostenibile come strumento di prevenzione degli incendi forestali. XII Congresso Nazionale SISEF "La Scienza Utile per le Foreste: ricerca e trasferimento". Palermo, 12–15 novembre 2019. Abstract-book, Contributo 12.7.1 . https://congressi.sisef.org/?action=paper&id=2556.

Elia, M., Giannico, V., Ascoli, D., Argañaraz, J.P., D'Este, M., Spano, G., ... Sanesi, G., 2022. Uncovering current pyroregions in Italy using wildfire metrics. Ecol. Process. 11 (1), 1–17. https://doi.org/10.1186/s13717-022-00360-6.

Espinosa, J., Palheiro, P., Loureiro, C., Ascoli, D., Esposito, A., Fernandes, P.M., 2019. Fire-severity mitigation by prescribed burning assessed from fire-treatment encounters in maritime pine stands. Can. J. For. Res. 49 (2), 205–211. https://doi.org/10.1139/cjfr-2018-0263.

European Commission, 2006. Rural Development 2007–2013 - Handbook on Common Monitoring And Evaluation Framework. Guidance Document. Directorate General for Agriculture and Rural Development, Brussels, Belgium. https://ec.europa.eu/agriculture/sites/agriculture/files/rural-development-previous/2007-2013/docs/document_en.pdf.

European Commission, 2018. Forest fires: sparking firesmart policies in the EU. In: Vallejo Calzada, V., Faivre, N., Cardoso Castro Rego, F., Faivre, N., et al. (Eds.), Directorate General for Research and Innovation. Publications Office. https://data.europa.eu/doi/10.2777/181450.

European Commission, 2022. Directorate-General for Research and Innovation, European bioeconomy policy: stocktaking and future developments: report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Publications Office of the European Union https://data.europa.eu/doi/10.2777/997651.

FAO and ITPS, 2018. Global Soil Organic Carbon Map (GSOCmap). Technical Report. Rome162.

Feranec, J., Soukup, T., Hazeu, G., Jaffrain, G., 2016. European Landscape Dynamics: CORINE Land Cover Data. CRC Press, Boca Ranton.

Fernandes, P.M., 2013. Fire-smart management of forest landscapes in the Mediterranean basin under global change. Landsc. Urban Plan. 110, 175–182. https://doi.org/10.1016/j.landurbplan.2012.10.014.

Fernandes, P.M., Monteiro-Henriques, T., Guiomar, N., Loureiro, C., Barros, A.M.G., 2016. Bottom-up variables govern large-fire size in Portugal. Ecosystems 19, 1362–1375. https://doi.org/10.1007/s10021-016-0010-2.

Fernandes, P.M., Delogu, G.M., Leone, V., Ascoli, D., 2020. Wildfire policies contribution to foster extreme wildfires. Extreme Wildfire Events and Disasters. Elsevier, pp. 187–200 https://doi.org/10.1016/B978-0-12-815721-3.00010-2.

Ferrara, C., Salvati, L., Corona, P., Romano, R., Marchi, M., 2019. The background context matters: local-scale socioeconomic conditions and the spatial distribution of wildfires in Italy. Sci. Total Environ. 654, 43–52. https://doi.org/10.1016/j.scitotenv.2018.11.049.

Fick, S.E., Hijmans, R.J., 2017. WorldClim 2: new 1km spatial resolution climate surfaces for global land areas. Int. J. Climatol. 37, 4302–4315. https://doi.org/10.1002/joc.5086.

Field, R.D., Spessa, A.C., Aziz, N.A., Camia, A., Cantin, A., Carr, R., de Groot, W.J., Dowdy, A.J., Flannigan, M.D., Manomaiphiboon, K., Pappenberger, F., Tanpipat, V., Wang, X., 2015. Development of a Global Fire Weather Database. Nat. Hazards Earth Syst. Sci. 15, 1407–1423. https://doi.org/10.5194/nhess-15-1407-2015.

Finney, M.A., 2001. Design of regular landscape fuel treatment patterns for modifying fire growth and behavior. For. Sci. 47 (2), 219–228. https://doi.org/10.1093/forestscience/47.2.219.

Finney, M.A., 2006. An overview of FlamMap fire modeling capabilities. Andrews, P.L., Butler, B.W., (Comps)Fuels Management—How to Measure Success: Conference Proceedings. Proceedings RMRS-P-41. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, pp. 213–220.

Finney, M.A., Brittain, S., Seli, R.C., McHugh, C.W., Gangi, L., 2020. FlamMap: fire mapping and analysis system (version 6.1) [software]. Available from http://www.firelab.org/document/flammap-softwar.

Fisher, B., Kerry Turner, R., Morling, P., 2009. Defining and classifying ecosystem services for decision making. Ecol. Econ. 68, 643–653. https://doi.org/10.1016/j.ecolecon.2008.09.014.

Flitcroft, R.L., Falke, J.A., Reeves, G.H., Hessburg, P.F., McNyset, K.M., Benda, L.E., 2016. Wildfire may increase habitat quality for spring Chinook salmon in the Wenatchee River subbasin, WA, USA. For. Ecol. Manag. 359, 126–140. https://doi.org/10.1016/j.foreco.2015.09.049.

Francini, S., McRoberts, R.E., Giannetti, F., Marchetti, M., Scarascia Mugnozza, G., Chirici, G., 2021. The Three Indices Three Dimensions (3I3D) algorithm: a new method for forest disturbance mapping and area estimation based on optical remotely sensed imagery. Int. J. Remote Sens. 42 (12), 4693–4711. https://doi.org/10.1080/01431161.2021.1899334.

Francini, S., McRoberts, R.E., D'Amico, G., Coops, N.C., Hermosilla, T., White, J.C., Wulder, M.A., Marchetti, M., Scarascia Mugnozza, G., Chirici, G., 2022a. An open science and open data approach for the statistically robust estimation of forest disturbance areas. Int. J. Appl. Earth Obs. Geoinf. 106, 108297. https://doi.org/10.1016/j.jag.2021.102663.

Francini, S., D'Amico, G., Vangi, E., Borghi, C., Chirici, G., 2022b. Integrating GEDI and Landsat: spaceborne Lidar and four decades of optical imagery for the analysis of forest disturbances and biomass changes in Italy. Sensors 22 (5), 2015. https://doi.org/10.3390/s22052015.

Gallego Fernández, J.B., Rosario García Mora, M., García Novo, F., 2004. Vegetation dynamics of Mediterranean shrublands in former cultural landscape at Grazalema Mountains, South Spain. Plant Ecol. 172, 83–94. https://doi.org/10.1023/B:VEGE.0000026039.00969.7a.

Gan, J., Jarrett, A., Johnson Gaither, C., 2015. Landowner response to wildfire risk: adaptation, mitigation or doing nothing. J. Environ. Manag. 159, 186–191. https://doi.org/10.1016/j.jenvman.2015.06.014.

García-Llamas, P., Suárez-Seoane, S., Taboada, A., Fernández-Manso, A., Quintano, C., Fernández-García, V., Fernández-Guisuraga, J.M., Marcos, E., Calvo, L., 2019. Environmental drivers of fire severity in extreme fire events that affect Mediterranean pine Forest ecosystems. For. Ecol. Manag. 433, 24–32. https://doi.org/10.1016/j.foreco.2018.10.051.

García-Ruiz, J.M., Lasanta, T., Nadal-Romero, E., Lana-Renault, N., Álvarez-Farizo, B., 2020. Rewilding and restoring cultural landscapes in Mediterranean mountains: opportunities and challenges. Land Use Policy 99, 104850. https://doi.org/10.1016/j.landusepol.2020.104850.

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O., Townshend, J.R.G., 2013. High-resolution global maps of 21st-century forest cover change. Science 342, 850–853. https://doi.org/10.1126/science.1244693.

Humphrey, J.G., Gillson, L., Ziervogel, G., 2021. How changing fire management policies affect fire seasonality and livelihoods. Ambio 50 (2), 475–491. https://doi.org/10.1007/s13280-020-01351-7.

Jain, P., Coogan, S.C.P., Ganapathi Subramanian, S., Crowley, M., Taylor, S., Flannigan, M.D., 2020. A review of machine learning applications in wildfire science and management. Environ. Rev. 28 (4), 478–505. https://doi.org/10.1139/er-2020-0019.

James, P.M.A., Fortin, M.J., Sturtevant, B.R., et al., 2011. Modelling spatial interactions among fire, spruce budworm, and logging in the boreal forest. Ecosystems 14, 60–75. https://doi.org/10.1007/s10021-010-9395-5.

Kelly, L.T., Giljohann, K.M., Duane, A., Aquilué, N., Archibald, S., Batllori, E., Bennett, A.F., Buckland, S.T., Canelles, Q., Clarke, M.F., Fortin, M.J., Hermoso, V., Herrando, S., Keane, R.E., Lake, F.K., McCarthy, M.A., Morán-Ordóñez, A., Parr, C.L., Pausas, J.G., ... Brotons, L., 2020. Fire and biodiversity in the Anthropocene. Science 370 (6519), eabb0355. https://doi.org/10.1126/science.abb0355.

Kganyago, M., Shikwambana, L., 2020. Assessment of the characteristics of recent major wildfires in the USA, Australia and Brazil in 2018–2019 using multi-source satellite products. Remote Sens. 12 (11), 1803. https://doi.org/10.3390/rs12111803.

Kosztra, B., Büttner, G., Hazeu, G., Arnold, S., 2019. European Topic Centre on Urban, Land And Soil Systems: Updated CLC Illustrated Nomenclature Guidelines. European Environment Agency, Copenhagen.

Lachlan McCaw, W., 2013. Managing forest fuels using prescribed fire – a perspective from Southern Australia. For. Ecol. Manag. 294, 217–224. https://doi.org/10.1016/j.foreco.2012.09.012.
Lê, S., Josse, J., Husson, F., 2008. FactoMineR: a package for multivariate analysis. J. Stat. Softw. 25 (1), 1–18. https://doi.org/10.18637/jss.v025.i01.
Lecina-Diaz, J., Chas-Amil, M.L., Aquilué, N., Sil, Â., Brotons, L., Regos, A., Touza, J., 2023. Incorporating fire-smartness into agricultural policies reduces suppression costs and ecosystem services damages from wildfires. J. Environ. Manag. 337, 117707. https://doi.org/10.1016/j.jenvman.2023.117707.
Liaw, A., Wiener, M., 2002. Classification and regression by randomForest. R News 2 (3), 18–22.
Lindenmayer, D.B., Hunter, M.L., Burton, P.J., Gibbons, P., 2009. Effects of logging on fire regimes in moist forests. Conserv. Lett. 2 (6), 271–277. https://doi.org/10.1111/j.1755-263X.2009.00080.x.
Lomba, A., Alves, P., Jongman, R.H.G., McCracken, D.I., 2015. Reconciling nature conservation and traditional farming practices: a spatially explicit framework to assess the extent of High Nature Value farmlands in the European countryside. Ecol. Evol. 5 (5), 1031–1044. https://doi.org/10.1002/ece3.1415.
Malandra, F., Vitali, A., Morresi, D., Garbarino, M., Foster, D.E., Stephens, S.L., Urbinati, C., 2022. Burn severity drivers in Italian large wildfires. Fire 5 (6), 180. https://doi.org/10.3390/fire5060180.
Mancini, L.D., Elia, M., Barbati, A., Salvati, L., Corona, P., Lafortezza, R., Sanesi, G., 2018a. Are wildfires knocking on the built-up areas door? Forests 9 (5), 234. https://doi.org/10.3390/f9050234.
Mancini, L.D., Corona, P., Salvati, L., 2018b. Ranking the importance of wildfires' human drivers through a multi-model regression approach. Environ. Impact Assess. Rev. 72, 177–186. https://doi.org/10.1016/j.eiar.2018.06.003.
Mantero, G., et al., 2020. The influence of land abandonment on forest disturbance regimes: a global review. Landsc. Ecol. 35, 2723–2744. https://doi.org/10.1007/s10980-020-01147-w.
Marcu, A.M., 2015. Supporting of disadvantaged areas from Romania through agri-environment measures of the RDP 2007–2013. Georeview 25, 117–123. https://doi.org/10.4316/GEOREVIEW.2015.25.1.279.
Marques, S., Borges, J.G., Garcia-Gonzalo, J., et al., 2011. Characterization of wildfires in Portugal. Eur. J. For. Res. 130, 775–784. https://doi.org/10.1007/s10342-010-0470-4.
Marsboom, C., Vrebos, D., Staes, J., Meire, P., 2018. Using dimension reduction PCA to identify ecosystem service bundles. Ecol. Indic. 87, 209–260. https://doi.org/10.1016/j.ecolind.2017.10.049.
McCune, B., Grace, J.B., Urban, D.L., 2002. Analysis of Ecological Communities. 28. MjM software design, Gleneden Beach, OR.
Michetti, M., Pinar, M., 2019. Forest fires across Italian regions and implications for climate change: a panel data analysis. Environ. Resour. Econ. 72 (1), 207–246. https://doi.org/10.1007/s10640-018-0279-z.
Mikulková, A., Hájek, M., Štěpánková, M., Ševčík, M., 2015. Forest certification as a tool to support sustainable development in forest management. J. For. Sci. 61 (8), 359–368. https://doi.org/10.17221/16/2015-JFS.
Mitsopoulos, I., Mallinis, G., Dimitrakopoulos, A., Xanthopoulos, G., Eftychidis, G., Goldammer, J.G., 2020. Vulnerability of peri-urban and residential areas to landscape fires in Greece: evidence by wildland-urban interface data. Data Brief 31, 106025. https://doi.org/10.1016/j.dib.2020.106025.
Modugno, S., Balzter, H., Cole, B., Borrelli, P., 2016. Mapping regional patterns of large forest fires in Wildland-Urban Interface areas in Europe. J. Environ. Manag. 172, 112–126. https://doi.org/10.1016/j.jenvman.2016.02.013.
Moreira, F., Pe'er, G., 2018. Agricultural policy can reduce wildfires. Science 359 (6379), 1001–1002. https://doi.org/10.1126/science.aat1359.
Moreira, F., Russo, D., 2007. Modelling the impact of agricultural abandonment and wildfires on vertebrate diversity in Mediterranean Europe. Landsc. Ecol. 22, 1461–1476. https://doi.org/10.1007/s10980-007-9125-3.
Moreira, F., Viedma, O., Arianoutsou, M., Curt, T., Koutsias, N., Rigolot, E., Barbati, A., Corona, P., Vaz, P., Xanthopoulos, G., Mouillot, F., Bilgili, E., 2011. Landscape e wildfire interactions in Southern Europe: implications for landscape management. J. Environ. Manag. 92, 2389–2402. https://doi.org/10.1016/j.jenvman.2011.06.028.
Moreira, F., Ascoli, D., Safford, H., Adams, M.A., Moreno, J.M., Pereira, J.M.C., Catry, F.X., Armesto, J., Bond, W., González, M.E., Curt, T., Koutsias, N., McCaw, L., Price, O., Pausas, J.G., Rigolot, E., Stephens, S., Tavsanoglu, C., Vallejo, V.R., Van Wilgen, B.V., Xanthopoulos, G., Fernandes, P.M., 2020. Wildfire management in Mediterranean-type regions: paradigm change needed. Environ. Res. Lett. 15, 011001. https://doi.org/10.1088/1748-9326/ab541e.
Moris, J.V., Vacchiano, G., Ravetto Enri, S., Lonati, M., Motta, R., Ascoli, D., 2017. Resilience of European Larch (Larix decidua Mill.) Forests to Wildfires in the Western Alps. New For. 48 (5), 663–683. https://doi.org/10.1007/s11056-017-9591-7.
Moritz, M.A., Morais, M.E., Summerell, L.A., Carlson, J.M., Doyle, J., 2005. Wildfires, complexity, and highly optimized tolerance. Proc. Natl. Acad. Sci. 102 (50), 17912–17917. https://doi.org/10.1073/pnas.0508985102.
Munafò, M., et al., 2016. Consumo di suolo, dinamiche territoriali e servizi ecosistemici. Istituto Superiore per la Protezione e la ricerca Ambientale (ISPRA), Sistema Nazionale per la Protezione dell'Ambiente (SNPA). Report 248/2016.
Natural Capital Project, 2022. InVEST 3.13.0.post5 + ug.gce76c6e User's Guide. Stanford University, University of Minnesota, Chinese Academy of Sciences, The Nature Conservancy, World Wildlife Fund, and Stockholm Resilience Centre.
Pais, S., Aquilué, N., Campos, J., Sil, Â., Marcos, B., Martínez-Freiría, F., Domínguez, J., Brotons, L., Honrado, J.P., Regos, A., 2020. Mountain farmland protection and fire-smart management jointly reduce fire hazard and enhance biodiversity and carbon sequestration. Ecosyst. Serv. 44, 101143. https://doi.org/10.1016/j.ecoser.2020.101143.
Panagos, P., Borrelli, P., Meusburger, K., Alewell, C., Lugato, E., Montanarella, L., 2015. Estimating the soil erosion cover-management factor at the European scale. Land Use Policy 48, 38–50. https://doi.org/10.1016/j.landusepol.2015.05.021.
Parks, S.A., Holsinger, L.M., Panunto, M.H., Jolly, W.M., Dobrowski, S.Z., Dillon, G.K., 2018a. High-severity fire: evaluating its key drivers and mapping its probability across western US forests. Environ. Res. Lett. 13 (4), 044037. https://doi.org/10.1088/1748-9326/aab791.
Parks, S.A., Holsinger, L.M., Voss, M.A., Loehman, R.A., Robinson, N.P., 2018b. Mean composite fire severity metrics computed with Google Earth Engine offer improved accuracy and expanded mapping potential. Remote Sens. 10 (6), 879. https://doi.org/10.3390/rs10060879.
Pausas, J.G., Fernández-Muñoz, S., 2012. Fire regime changes in the Western Mediterranean Basin: from fuel-limited to drought-driven fire regime. Clim. Chang. 110, 215–226. https://doi.org/10.1007/s10584-011-0060-6.
Pausas, J.G., Keeley, J.E., 2019. Wildfires as an ecosystem service. Front. Ecol. Environ. 17, 289–295. https://doi.org/10.1002/fee.2044.
Pereira, M.G., Parente, J., Amraoui, M., Oliveira, A., Fernandes, P.M., 2020. The role of weather and climate conditions on extreme wildfires. Extreme Wildfire Events And Disasters. 3, pp. 55–72. https://doi.org/10.1016/B978-0-12-815721-3.00003-5.
Pereira, P., et al., 2012. Fire in protected areas - the effect of protection and importance of fire management. Environ. Res. Eng. Manag. 59 (1), 52–62. https://doi.org/10.5755/j01.erem.59.1.856.
Pezzatti, G.B., De Angelis, A., Bekar, İ., Ricotta, C., Bajocco, S., Conedera, M., 2020. Complementing daily fire-danger assessment using a novel metric based on burnt area ranking. Agric. For. Meteorol. 295, 108172. https://doi.org/10.1016/j.agrformet.2020.108172.
Pulido, F., Corbacho, J., Bertomeu, M., Gómez, Á., Guiomar, N., Juárez, E., ... Palomo, G., 2023. Fire-Smart Territories: a proof of concept based on Mosaico approach. Landsc. Ecol. 38, 1–18. https://doi.org/10.1007/s10980-023-01618-w.
Quintas-Soriano, C., Buerkert, A., Plieninger, T., 2022. Effects of land abandonment on nature contributions to people and good quality of life components in the Mediterranean region: a review. Land Use Policy 116, 106053. https://doi.org/10.1016/j.landusepol.2022.106053.
Radeloff, V.C., Helmer, D.P., Kramer, H.A., Mockrin, M.H., Alexandre, P.M., Bar-Massada, A., Butsic, V., Hawbaker, T.J., Martinuzzi, S., Syphard, A.D., Stewart, S.I., 2018. Rapid growth of the US wildland-urban interface raises wildfire risk. Proc. Natl. Acad. Sci. U. S. A. 115 (13), 3314–3319. https://doi.org/10.1073/pnas.1718850115.
Recanatesi, F., Clemente, M., Grigoriadis, E., Ranalli, F., Zitti, M., Salvati, L., 2015. A fifty-year sustainability assessment of Italian agro-forest districts. Sustainability 8, 32. https://doi.org/10.3390/su8010032.
Rego, F., Rigolot, E., Fernandes, P., Montiel, C., Sande, Silva J., 2010. Towards integrated fire management. 16 pp.European Forest Institute https://hal.inrae.fr/hal-02823739.
Regos, A., Aquilué, N., López, I., Codina, M., Retana, J., Brotons, L., 2016. Synergies between forest biomass extraction for bioenergy and fire suppression in Mediterranean ecosystems: insights from a storyline-and-simulation approach. Ecosystems 19 (5), 786–802. https://doi.org/10.1007/s10021-016-9968-z.
Roces-Díaz, J.V., Santín, C., Martinez-Vilalta, J., Doerr, S.H., 2021. A global synthesis of fire effects on ecosystem services of forests and woodlands. Front. Ecol. Environ. https://doi.org/10.1002/fee.2349.
Rockweit, J.T., Franklin, A.B., Carlson, P.C., 2017. Differential impacts of wildfire on the population dynamics of an old-forest species. Ecology 98 (6), 1574–1582. https://doi.org/10.1002/ecy.1805.
Rodrigues, M., de la Riva, J., 2014. An insight into machine-learning algorithms to model human-caused wildfire occurrence. Environ. Model. Softw. 57, 192–201. https://doi.org/10.1016/j.envsoft.2014.03.003.
Salis, M., Del Giudice, L., Arca, B., Ager, A.A., Alcasena-Urdiroz, F., Lozano, O., ... Duce, P., 2018. Modeling the effects of different fuel treatment mosaics on wildfire spread and behavior in a Mediterranean agro-pastoral area. J. Environ. Manag. 212, 490–505. https://doi.org/10.1016/j.jenvman.2018.02.020.
Sallustio, L., Simpatico, A., Munafò, M., Giancola, C., Tognetti, R., Vizzarri, M., Marchetti, M., 2015. Recent trends in forest cover changes: only positive implications? L'Italia Forestale e Montana 70 (4), 273–294. https://doi.org/10.4129/ifm.2015.40.03.
Sallustio, L., De Toni, A., Strollo, A., et al., 2017. Assessing habitat quality in relation to the spatial distribution of protected areas in Italy. J. Environ. Manag. 201, 129–137. https://doi.org/10.1016/j.jenvman.2017.06.031.
Sallustio, L., Pettenella, D., Merlini, P., Romano, R., Salvati, L., Marchetti, M., Corona, P., 2018. Assessing the economic marginality of agricultural lands in Italy to support land use planning. Land Use Policy 76, 526–534. https://doi.org/10.1016/j.landusepol.2018.02.033.
Santopuoli, G., Ferranti, F., Marchetti, M., 2015. Implementing criteria and indicators for sustainable forest management in a decentralized setting: Italy as a case study. J. Environ. Policy Plan. 18 (2), 177–196. https://doi.org/10.1080/1523908X.2015.1065718.
Schmidt, D.A., Taylor, A.H., Skinner, C.N., 2008. The influence of fuels treatment and landscape arrangement on simulated fire behavior, Southern Cascade range, California. For. Ecol. Manag. 255 (8–9), 3170–3184. https://doi.org/10.1016/j.foreco.2008.01.023.
Schober, P., Boer, C., Schwarte, L.A., 2018. Correlation coefficients: appropriate use and interpretation. Anesth. Analg. 126 (5), 1763–1768. https://doi.org/10.1213/ANE.0000000000002864.
Scott, J.H., 2005. Standard Fire Behavior Fuel Models: A Comprehensive Set for Use With Rothermel's Surface Fire Spread Model. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.
Senf, C., Seidl, R., 2020. Mapping the forest disturbance regimes of Europe. Nat. Sustain. 4, 63–70. https://doi.org/10.1038/s41893-020-00609-y.
Siegel, K.J., Macaulay, L., Shapero, M., Becchetti, T., Larson, S., Mashiri, F.E., Waks, L., Larsen, L., Butsic, V., 2022. Impacts of livestock grazing on the probability of burning in wildfires vary by region and vegetation type in California. J. Environ. Manag. 322, 116092. https://doi.org/10.1016/j.jenvman.2022.116092.
Sil, Â., Fernandes, P.M., Rodrigues, A.P., Alonso, J.M., Honrado, J.P., Perera, A., Azevedo, J.C., 2019a. Farmland abandonment decreases the fire regulation capacity and the fire

protection ecosystem service in mountain landscapes. Ecosyst. Serv. 36, 100908. https://doi.org/10.1016/j.ecoser.2019.100908.
Sil, A., Azevedo, J., Fernandes, P.M., Regos, A., Vaz, A.S., Honrado, J.P., 2019b. (Wild) fire is not an ecosystem service. Front. Ecol. Environ. 17 (8), 429–430. http://hdl.handle.net/10198/20675.
Sil, Â., Azevedo, J.C., Fernandes, P.M., Alonso, J., Honrado, J.P., 2022. Fine-tuning the BFOLDS Fire Regime Module to support the assessment of fire-related functions and services in a changing Mediterranean mountain landscape. Environ. Model. Softw. 155, 105464. https://doi.org/10.1016/j.envsoft.2022.105464.
Stritih, A., Senf, C., Seidl, R., Grêt-Regamey, A., Bebi, P., 2021. The impact of land-use legacies and recent management on natural disturbance susceptibility in mountain forests. For. Ecol. Manag. 484, 118950. https://doi.org/10.1016/j.foreco.2021.118950.
Taylor Jr., C.A., 2006. Targeted grazing to manage fire risk. Targeted Grazing: A Natural Approach to Vegetation Management And Landscape Enhancement, pp. 107–112.
Tedim, F., Leone, V., Xanthopoulos, G., 2016. A wildfire risk management concept based on a social-ecological approach in the European Union: Fire Smart Territory. Int. J. Disaster Risk Reduct. 18, 138–153. https://doi.org/10.1016/j.ijdrr.2016.06.005.
Terrado, M., Sabater, S., Chaplin-Kramer, B., Mandle, L., Ziv, G., Acuña, V., 2016. Model development for the assessment of terrestrial and aquatic habitat quality in conservation planning. Sci. Total Environ. 540, 63–70. https://doi.org/10.1016/j.scitotenv.2015.03.064.
Turco, M., Jerez, S., Augusto, S., et al., 2019. Climate drivers of the 2017 devastating fires in Portugal. Sci. Rep. 9, 13886. https://doi.org/10.1038/s41598-019-50281-2.
Valese, E., Conedera, M., Held, A.C., Ascoli, D., 2014. Fire, humans and landscape in the European Alpine region during the Holocene. Anthropocene 6, 63–74. https://doi.org/10.1016/j.ancene.2014.06.006.
Van Wagner, C.E., 1987. Development And Structure of the Canadian Forest Fire Weather Index System. Forestry Technical Report. 35. Canadian Forest Service, Ottawa.
Varela, E., Pulido, F., Moreno, G., Zavala, M.Á., 2020. Targeted policy proposals for managing spontaneous forest expansion in the Mediterranean. J. Appl. Ecol. 57, 2373–2380. https://doi.org/10.1111/1365-2664.13779.
Verkerk, P.J., Martinez de Arano, I., Palahí, M., 2018. The bio-economy as an opportunity to tackle wildfires in Mediterranean forest ecosystems. Forest Policy Econ. 86, 1–3. https://doi.org/10.1016/j.forpol.2017.10.016.
Viedma, O., Moity, N., Moreno, J.M., 2015. Changes in landscape fire-hazard during the second half of the 20th century: agriculture abandonment and the changing role of driving factors. Agric. Ecosyst. Environ. 207, 126–140. https://doi.org/10.1016/j.agee.2015.04.011.
Viedma, O., Urbieta, I.R., Moreno, J.M., 2018. Wildfires and the role of their drivers are changing over time in a large rural area of west-central Spain. Sci. Rep. 8, 17797–17810. https://doi.org/10.1038/s41598-018-36134-4.
Vilar, L., Gómez, I., Martínez-Vega, J., Echavarría, P., Riaño, D., Martín, M.P., 2016. Multitemporal modelling of socio-economic wildfire drivers in central Spain between the 1980s and the 2000s: comparing generalized linear models to machine learning algorithms. PLoS ONE 11, 1–17. https://doi.org/10.1371/journal.pone.0161344.
Vitolo, C., Di Giuseppe, F., Krzeminski, B., San-Miguel-Ayanz, J., 2019. A 1980–2018 global fire danger re-analysis dataset for the Canadian Fire Weather Indices. Sci. Data 6, 190032. https://doi.org/10.1038/sdata.2019.32.
Vitolo, C., Di Giuseppe, F., Barnard, C., Coughlan, R., San-Miguel-Ayanz, J., Libertá, G., Krzeminski, B., 2020. ERA5-based global meteorological wildfire danger maps. Sci. Data 7, 216. https://doi.org/10.1038/s41597-020-0554-z.
Whitman, E., Parisien, M.A., Price, D.T., St-Laurent, M.H., Johnson, C.J., DeLancey, E.R., Arseneault, D., Flannigan, M.D., 2017. A framework for modeling habitat quality in disturbance-prone areas demonstrated with woodland caribou and wildfire. Ecosphere 8 (4), e01787. https://doi.org/10.1002/ecs2.1787.
Wolpert, F., Quintas-Soriano, C., Pulido, F., Huntsinger, L., Plieninger, T., 2022. Collaborative agroforestry to mitigate wildfires in Extremadura, Spain: land manager motivations and perceptions of outcomes, benefits, and policy needs. Agrofor. Syst. 96, 1135–1149. https://doi.org/10.1007/s10457-022-00771-6.
Wood, S., Sheipl, F., 2020. gamm4: Generalized Additive Mixed Models using 'mgcv' and 'lme4'. R package version 0.2-6. https://CRAN.R-project.org/package=gamm4.
Wunder, S., Calkin, D.E., Charlton, V., Feder, S., Martínez de Arano, I., Moore, P., Rodríguez y Silva, F., Tacconi, L., Vega-García, C., 2021. Resilient landscapes to prevent catastrophic forest fires: socioeconomic insights towards a new paradigm. Forest Policy Econ. 128, 102458. https://doi.org/10.1016/j.forpol.2021.102458.
Zald, H.S.J., Dunn, C.J., 2018. Severe fire weather and intensive forest management increase fire severity in a multi-ownership landscape. Ecol. Appl. 28 (4), 1068–1080. https://doi.org/10.1002/eap.1710.
Zuur, A.F., Ieno, E.N., Walker, N.J., Saveliev, A.A., Smith, G.M., 2009. GLMM and GAMM. Mixed Effects Models And Extensions in Ecology With R. Statistics for Biology and Health. Springer, New York, NY https://doi.org/10.1007/978-0-387-87458-6_13.
Zuur, A.F., Ieno, E.N., Elphick, C.S., 2010. A protocol for data exploration to avoid common statistical problems: data exploration. Methods Ecol. Evol. 1 (1), 3–14. https://doi.org/10.1111/j.2041-210X.2009.00001.x.