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Assessing Climate Change Impacts on Wildfire Exposure in Mediterranean Areas

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- 1 Assessing climate change impacts on wildfire exposure in
- 2 Mediterranean areas
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#### 4 Abstract

5 We used simulation modeling to assess potential climate change impacts on wildfire exposure in Italy and Corsica (France). Weather data were obtained from a regional climate model for 6 7 the period 1981-2070 using the IPCC A1B emissions scenario. Wildfire simulations were 8 performed with the MTT fire spread algorithm using predicted fuel moisture, wind speed, and 9 wind direction to simulate expected changes in weather for three climatic periods (1981-2010, 2011-2040, and 2041-2070). Overall, the wildfire simulations showed very slight 10 11 changes in flame length, while other outputs such as burn probability and fire size increased significantly in the second future period (2041-2070), especially in southern portion of the 12 study area. The projected changes fuel moisture could result in a lengthening of the fire 13 14 season for the entire study area. This work represents the first application in Europe of a 15 methodology based on high resolution (250 m) landscape wildfire modeling to assess 16 potential impacts of climate changes on wildfire exposure at a national scale. The findings can provide information and support in wildfire management planning and risk mitigation 17 18 activities.

19

20 Keywords: fire exposure, climate change, MTT algorithm, Mediterranean areas, burn
21 probability

### 23 1. INTRODUCTION

Wildfires pose a growing threat to ecosystems<sup>(1,2)</sup> worldwide and are frequently responsible 24 for human casualties and substantial economic losses.<sup>(3)</sup> The occurrence of wildland fires in 25 the Mediterranean area is mainly related to human activities<sup>(4,5)</sup>, whereas area burned is 26 27 dependent on many factors such as climate and weather, topography, vegetation and land use, urban sprawl and fire policies.<sup>(6,7)</sup> A number of studies have highlighted that climate and 28 weather conditions are key factors to understand the fire spread and behavior, and directly 29 affect spatiotemporal patterns in wildfire exposure and risk.<sup>(8-11)</sup> It is widely recognized that 30 wildfire risk and exposure could be exacerbated by climate change. (12-20) According to the 31 most recent Intergovernmental Panel on Climate Change (IPCC) report,<sup>(21)</sup> temperatures in 32 33 southern Europe are expected to increase resulting in more frequent heat waves and droughts.<sup>(22-24)</sup> Fire activity is expected to increase in terms of both area burned and fire 34 occurrence, although climate change impacts will be variable around the region.<sup>(12,14–18,25)</sup> 35 36 However, most studies investigating climate change effects on wildfires are based on coarse 37 scale (> 1km grid data) and therefore did not capture the local drivers of fire behavior and 38 risk (e.g., fuels, weather, topography). For instance, previous studies on future fire risk and 39 danger in the Mediterranean basin used coarse scale fire danger indices such as the Canadian Forest Fire Weather Index (FWI)<sup>(26)</sup> or statistical models of climate and vegetation <sup>(16,18,27–31)</sup> 40 41 The fine scale patterns in fire behavior are important from a risk standpoint, and can be 42 assessed with a number of innovative approaches for estimating and mapping wildfire risk and exposure developed in the last decade. <sup>(5,32–36)</sup> These approaches use quantitative wildfire 43 risk assessment <sup>(34)</sup> and employ a number of relatively new large fire modelling systems. 44

Wildfire risk assessment includes two main factors: fire behavior probabilities and fire 45 46 effects. In this paper, we focused on the first component, also called exposure analysis, which is based on the estimation of the potential wildfire intensity and on the burn probability.<sup>(37)</sup> 47 Fire spread modeling is a necessary component for wildfire exposure assessment.<sup>(38)</sup> 48 Landscape fire spread and behavior models such as FSim,<sup>(39)</sup> FlamMap<sup>(40)</sup> and its command 49 50 line version Randig allow simulating thousands fires and generating burn probability and intensity maps based on the MTT algorithm.<sup>(41)</sup> The models have been tested and applied in a 51 number of fire systems in the United States, Canada, Portugal, and the Mediterranean 52 basin.<sup>(41–48)</sup> However, these models have not been fully leveraged 53

54 However, only few works in relatively small areas have been carried to analyze the potential future impacts of climate change on wildfire behavior and spread.<sup>(49–51)</sup> For instance, Arca *et* 55 al.<sup>(49)</sup> performed fire simulations for Sardinia, Italy (24,000 km<sup>2</sup>) to assess the impact of 56 57 future (2070-2100) climate changes on spatial variations of burn probability and intensity. Mitsopoulos et al.<sup>(50)</sup> analyzed climate change impacts (from 1991 to 2100) on fire intensity 58 and probability using the MTT algorithm, for an area of about 100 km<sup>2</sup> in Greece. More 59 recently, Kalabodikis et al.<sup>(51)</sup> combined future climate data and the MTT algorithm to assess 60 variations on burn probabilities, fire size and intensity in Messinia, Greece (3,000 km<sup>2</sup>). 61

In this study we apply fine scale simulation modeling to assess the impact of climate change on fire exposure at a national scale (covering a total area of about 310,000 km<sup>2</sup>) using a wildfire modeling approach based on the Minimum Travel Time algorithm. This work demonstrates the feasibility of the overall approach for assessing future climate change impacts on fire exposure (250 m) while considering fine scale risk factors (e.g., topography, 67 fuels) that influence landscape wildfire spread and behavior. The methodology and results 68 contribute to local mapping of climate induced changes in fire regimes that can help fire 69 managers respond to potential increased risk with improved management guidelines, risk 70 mitigation and prevention policies.

71

## 72 **2. METHODS**

### 73 **2.1. Study area**

The study area is located in the Euro-Mediterranean region, and consists of the entire country
of Italy as well as the French island of Corsica (Fig. 1). It is located between 35° 29' and 47°
05' N latitude and 8° 13' and 18° 31' E longitude, and covers about 310,000 km<sup>2</sup>.

To ensure reasonable computational times for both climate change analysis and wildfire
modeling phases, the study area was divided into the following seven subareas (Fig. 1, Table
II): Northwest Italy (NW), Northeast Italy (NE), Central Italy (CI), South Italy (SI), Sicily
(SC), Sardinia (SA) and Corsica (CO). The general criteria for the division into subareas were
based on administrative limits (using provincial boundaries), climate and wildfire history.

The two main mountain ranges of the Italic peninsula are the Alps, as natural northern border, and the Apennine Mountains, which cross Italy from North to South (Fig. 2a). Flat areas are mainly concentrated in coastal zones and in the Po river area. According to the updated Köppen-Geiger climate classification (Fig. 2b)<sup>(52)</sup>, the most of the study area is characterized by a temperate climate (87.5% of the total area). The semi-arid climate can only be found in a small area on the southern coast. Cold climate types without dry season can be found in the Alps, whereas the highest zones are characterized by polar climate. The vegetation distribution within the study area is not uniform (Fig. 2c).<sup>(53)</sup> The most extended vegetation type is "grasslands" (Table I),<sup>(53)</sup> mostly situated in flat areas. Forests are mainly concentrated in hilly and mountain areas. Although shrublands (Mediterranean maquis and garrigue) represent less than 10% of the total study area, some regions like Sardinia and Corsica are mainly covered by this vegetation type. Vineyards and orchards are concentrated in some areas as the eastern areas of southern Italy and in Sicily, whereas herbaceous pastures are scattered along hills and mountains.

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### 97 **2.2. Input data for fire simulations**

### 98 2.2.1. Topography and fuels data

We obtained information on fuels and topography to produce a landscape file, as required by RANDIG, the command line version of FlamMap used for the wildfire simulations in the study. The landscape file is composed by eight layers: elevation, slope, aspect, fuel models and canopy cover, canopy bulk density, canopy base height, and stand height. All layers included in the landscape file were set at 250m resolution in UTM projection (WGS84 datum).

Input data for elevation, aspect and slope layers were obtained from digital elevation data (90 m resolution)<sup>(54)</sup> which was resampled by bilinear interpolation to 250 m resolution. To define fuel type and canopy cover layers, we reclassified the Corine land cover map of 2006 (250 m resolution)<sup>(53)</sup> following the methodology proposed by Salis *et al.*<sup>(45)</sup> From the original 44 Corine land cover categories present in the study area, 14 main fuel types were defined (Table I, Fig. 2c). Standard<sup>(55,56)</sup> or custom fuel models were attributed to each fuel type of the study area (Table I). The custom fuel models were developed as part of previous

wildfire researches<sup>(45,57)</sup> and were applied to shrubland vegetation (Mediterranean maquis and
garrigue). To each fuel model, a canopy cover class was also assigned: we used the class 4
(75-100% of canopy cover) for all pixels identified as "Forests" (coniferous, broadleaf and
mixed forests), while we used the class 1 (1-25% of canopy cover) for the cells classified as
"Mediterranean maquis". The canopy fuel layers (canopy bulk density, canopy base height
and stand height) were finally built using average values derived from the Italian Inventory of
Forests and Forest Carbon Sinks.<sup>(58)</sup>

119

### 120 2.2.2. Climate projections

The CMCC-CLM climate dataset associated to the A1B IPCC emissions scenario<sup>(59)</sup> was 121 used to obtain daily data on air temperature at 2 m, rainfall, relative humidity, wind speed and 122 direction at 12:00 UTC for the period 1981-2070. Although we used CMIP3 data, according 123 to the IPCC<sup>(60)</sup> the differences between CMIP3 and CMIP5 models in climate projections are 124 125 quite limited. The climate projections were produced by the Euro-Mediterranean Center on Climate Change (CMCC) within the FUME project (FP7/2007-2013, Grant Agreement 126 243888) using the CMCC-CLM regional climate model.<sup>(61)</sup> This regional model was 127 implemented over the Euro-Mediterranean area with boundary conditions from the CMCC-128 MED GCM model.<sup>(62,63)</sup> The CMCC-CLM model is a climate version of the regional 129 COSMO model,<sup>(64)</sup> an operational non-hydrostatic mesoscale weather forecast model 130 developed by the German Weather Service, which has been updated by the CLM-Community 131 132 to develop also climatic applications. The climate simulations have been performed for the period 1981-2070 following the IPCC 20C3M protocol for the 20th century part of the 133

integration and the A1B scenario for the 21<sup>st</sup> century. The climate dataset presents a spatial and temporal resolution of 14 km and 6 hours, respectively, thus providing a good representation of the topography for the entire Mediterranean region and contributing to accurately represent weather conditions. Climate data have been split in three 30-year periods: one used as baseline period (1981-2010), and two as future periods (2011-2040 and 2041-2070).

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# 141 2.2.3. Wind and fuel moisture for fire simulations

Daily conditions at noon of both wind direction and speed and fuel moisture content for the 142 period 1981-2070 were derived using the climate dataset described above. In detail, wind 143 144 variables were created from U (East-West) and V (North-South) wind components. The 145 frequency of each combination of wind speed and direction values (Annex 1) was calculated 146 for each subarea considering the three 30-year periods. Dead and live fuel moisture were estimated by using the Fine Fuel Moisture (FFMC) and Drought (DC) codes of the FWI as 147 indicators. Both codes have been shown to be good estimators of dead and live surface fuel 148 moisture in previous works.<sup>(28,65,66)</sup> To estimate fuel moisture conditions, for each subarea and 149 each 30-year period, we first calculated the 25<sup>th</sup>, 50<sup>th</sup>, 75<sup>th</sup>, 90<sup>th</sup>, 95<sup>th</sup> and 97<sup>th</sup> percentile of 150 FFMC and DC daily values for each pixel. As a result, 18 raster layers for each moisture code 151 152 were produced (6 percentiles x 3 periods), which summarized FFMC and DC values for each 153 pixel of the study area. Then, mean values of FFMC and DC of each percentile (raster layer) 154 were calculated within each subarea. Secondly, FFMC and DC values above the Sardinian 75<sup>th</sup> percentile, considering the baseline as reference, were labeled as 'moderate', 'dry', 'very 155

dry' or 'extreme' moisture categories, as reported in Table III. We associated to the abovementioned categories specific fuel moisture conditions (Table III) which were used to run the simulations. Finally, for each 30-year period and each subarea, we calculated the percentage of days corresponding to the four fuel moisture categories (moderate, dry, very dry and extreme).

We used Sardinia as a reference for the entire study area since the relationships among weather conditions, FWI codes and fuel moisture content were reported in previous works in this area, based on large amounts of field data.<sup>(28,67–70)</sup> We focused our attention on data above the 75<sup>th</sup> percentile because this threshold characterizes the driest fuel moisture conditions, which correspond to the fire season periods.

In conclusion, these analyses allowed to create frequency distributions of wind speed and direction (4 wind speed values x 8 wind directions, Annex 1) and fuel moisture conditions (moderate, dry, very dry and extreme, Annex 2) for each subarea and 30-year period, which were used as input data for the fire spread simulations.

170

#### 171 *2.2.4. Fire occurrence database*

For the study area, we used the wildfire database from 1990 to 2008 provided by the JRC (Joint Research Center), which contains the total fire number and area burned per month at province level (European code NUTS3, Fig. 3). The spatial distribution of fire ignition points was produced by randomly assigning ignition coordinates within the province boundaries according to the mean annual number of fires at province level (Fig. 3a). This approach was performed in a GIS environment and allowed to locate random fire ignitions only in burnableareas, thus excluding unburnable fuels.

We then built an ignition probability grid by smoothing the fire ignition data using the inverse distance weighting algorithm (ArcMap Spatial Analyst toolbox, ESRI Inc.), with a search distance of 5000 m. This grid was used as input for the fire spread modeling exercise.

182

## 183 **2.3. Wildfire simulations**

Simulations were performed using the minimum travel time (MTT)<sup>(71)</sup> fire spread algorithm, 184 as implemented in RANDIG. This command line version of FlamMap allows simulating a 185 large amount of wildfires according to a given ignition density grid. Although each single 186 187 event is simulated under constant weather conditions, the fire simulations can be informed 188 considering given frequency distributions of wind speed, wind direction and fuel moisture. 189 This allowed us to compare the effects of the different climate conditions on the simulation 190 outputs, for each subarea and 30-year period. RANDIG is appropriate to model short-duration 191 single-day burn periods (e.g., 10 hours, as used in this study), such as the majority of fires in the Mediterranean Basin, while this approach could have more limitations in areas 192 characterized by multi-day large fire events, as for instance forests in northern United States 193 and Canada.<sup>(72)</sup> No suppression efforts were assumed for the simulations. Surface fire spread 194 is predicted by Rothermel's equation<sup>(73)</sup> and crown fire initiation is evaluated according to 195 Van Wagner model<sup>(74)</sup> as implemented by Scott and Reinhardt.<sup>(75)</sup> 196

As previously explained, the input data for the simulations were produced at 250 mresolution; the outputs were also produced at 250 m resolution.

Within each subarea, fuel moisture conditions and wind speed and direction for each event simulation were sampled from the distributions corresponding to each 30-years period, as described above. Wind fields at 250 m resolution were produced running the mass-consistent model WindNinja.<sup>(76,77)</sup> Furthermore, fire ignition locations were determined for each subarea from the ignition probability grid (as described in 'Input data'): this allowed for taking into account the historical spatial patterns of fire occurrence at provincial level. During a single fire event simulation, fuel moisture, and wind fields were hold constant.

206 Overall, we simulated 620,000 fire events in the entire study area for each 30-year period (a 207 total of 1,875,000), corresponding to an average of 2 fire ignitions per square kilometer. This 208 number of simulations resulted in more than 78% of pixels burned at least once and that the 209 total area burned was about 10 times the entire study area. All wildfires were simulated 210 considering a spread duration of 10 hours. We used a fixed fire spread duration of 10 hours 211 since: 1) previous methodologies for fire risk assessment based on fire spread models contemplated the use of fixed burn periods; (72) 2) a fixed fire spread duration for all study 212 213 areas and periods ensured that the differences in wildfire exposure (burn probability, fire size, 214 etc.) were only related to climate effects and not to differences in fire duration; and 3) 10 hours is a common duration of large fires in the Mediterranean basin.<sup>(46,68)</sup> 215

## 216 **2.4. Characterizing wildfire exposure**

The exposure analysis is a part of the risk analysis and quantifies the exposure to risk factors
(fire likelihood and intensity).<sup>(38)</sup>

To characterize wildfire exposure, we analyzed and processed RANDIG outputs, namely burn probability, conditional flame length and fire size, and we also calculated other specific indices such as fire potential index, high flame length burn probability and high flame length probability.

The burn probability (BP) is the probability that a pixel burns given a single fire occurrencein the study area:

$$225 \qquad BP = \frac{B}{n}$$

where B is the number of times a pixel burns and n is the total number of fires simulated.

Additionally, the FLP output file (Flame Length Probability) of RANDIG reports the conditional probability by twenty flame length categories of 0.5-m intervals, for each pixel of the study area. Fire intensity is calculated based on the fire spread rate predicted by the MTT algorithm and depends on the major direction of spread (i.e., heading, flanking or backing fire) in relation to the direction in which the fire encounters a pixel, slope and aspect. RANDIG converts fireline intensity (*FLI*, kW m<sup>-1</sup>) to flame length (*FL*, m) using the reformulation in SI units<sup>(78)</sup> of the Byram's equation:<sup>(79)</sup>

# 234 $FL = 0.0775 \cdot FLI^{0.46}$

The flame length distribution provided by the FLP output is used to calculate the conditional flame length (CFL), which is the weighted mean of the different FL generated from the multiple fires burning each pixel:

238 
$$CFL = \sum_{i=1}^{20} \frac{BP_i}{BP} \cdot FL_i$$

where  $FL_i$  is the flame length midpoint of the  $i^{\text{th}}$  category,  $BP_i$  is the probability that the pixel burns at a fire intensity *i* and BP is the burn probability for the pixel.

Another output of RANDIG is the Fire Size (FS, ha) list, which indicates the size of the fire originated by each ignition point. The FS grid for the study areas was produced from the FS list and using the inverse distant weighting tool (ArcMap Spatial Analyst) with a search distance of 2500 m.

FS grid and historical ignition probability grid were then combined to calculate a specific index that we called fire potential index (FPI):<sup>(45)</sup>

 $247 \qquad FPI = FS \cdot IP$ 

where *FS* is the mean fire size for all fires that originated from a given pixel and *IP* is the historical ignition probability. High FPI values indicate elevated likelihood of having fire ignitions able to generate large fires.

Furthermore, we calculated the High Flame Length Burn Probability (HFLBP) index, which is the probability that a pixel burns with flame length greater than 2.5 m, given one ignition within the study area:

$$254 \qquad HFLBP = \sum_{i=6}^{20} FLP_i \cdot BP$$

Finally, the High Flame Length Probability (HFLP) index was calculated. This index represents the probability that a pixel burns with flame length greater than 2.5 m, without making reference to the BP value of the pixel:

$$258 \qquad HFLP = \sum_{i=6}^{20} FLP_i$$

In few words, HFLP is the probability a pixel will burn at high flame length, considering only the fires burning that pixel. This index, in addition to the HFLBP, provides quantitative information about the probability of high fire intensity when the pixel burns.

262

### 263 **2.5. Statistical analysis**

264 The differences between baseline and future periods in terms of wind, fuel moisture and fire 265 exposure indicators were evaluated by calculating the relative difference between mean 266 values; the analysis was replicated for each subarea (Fig. 4). To assess differences in fire exposure, a One-way analysis of variance (ANOVA), performed by the general linear models 267 268 method and followed by the post-hoc Student-Newman-Keuls test, was used to measure the 269 significance of differences between mean values of the fire exposure indicators (BP, CFL, FS, FPI, HFLP and HFLBP) for each period and subarea.<sup>(80)</sup> A *p*-value of 0.01 was used as 270 level of significance for comparisons among means. Statistical analyses were performed with 271 R software (R Development Core Team, 2013).<sup>(81)</sup> 272

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### **3. RESULTS**

## 275 **3.1. Overview of the projected changes in weather variables**

The climate projections highlighted an increase in temperatures for the entire study area, and a decrease in relative humidity and rainfall (data not shown). Moreover, wind speed is expected to decrease in terms of average values as well as in terms of frequency of days with strong winds, particularly in northern Italy (Fig. 4, Annex 1). No relevant variations were observed for wind direction. In the following sections, changes in wind speed and direction and fuel moisture are described in detail since these variables affect directly fire spreadmodeling.

### 283 3.1.1. Changes in wind speed and direction

284 Referring to the baseline period, the subareas with the highest incidence of the highest wind speed (21-30 and >30 km  $h^{-1}$ ) were Sardinia and Sicily, followed by South Italy, Corsica and, 285 to a lower extent, Central Italy (Annex 1). On the contrary, the subareas with high 286 frequencies of lower wind speed days (0-10 km h<sup>-1</sup>) were Northwest Italy and Northeast Italy. 287 With respect to the variation throughout the future periods (Fig. 4, Annex 1), the general 288 trend was an increase in the frequencies of the lowest wind speed class (0-10 km h<sup>-1</sup>) and a 289 decrease in the highest ones, especially for the class > 30 km  $h^{-1}$ . In the 2011-2040 period the 290 291 lowest wind speed frequencies mainly increased in Sicily, Sardinia and Corsica. The highest wind speed class frequencies decreased at a different scale for each subarea showing the 292 293 larger diminution in Northwest and Northeast Italy and the lower decrease in South and Central Italy. Similar changes were observed for the 2041-2070 period, but in this case 294 slightly higher differences were observed; regarding the 0-10 km h<sup>-1</sup> wind class, the 295 differences between the subareas were not particularly marked. 296

# 297 *3.1.2. Changes in fuel moisture*

As described in the Methods section, from the climate projections we derived FFMC and DC codes for the baseline period (1981-2010) and for the two future periods (2011-2040 and 2041-2070), and then we used these codes as indicators of fuel moisture. 301 The analysis of the baseline data (Annex 2) highlighted that the frequency of 'moderate' fuel 302 moisture days for both codes was always greater than 50% but with noticeable differences 303 among the subareas. For both codes, Sicily showed the highest values of 'dry', 'very dry' and especially 'extreme' moisture days (about 10% for dead fuels and 11-12% for live fuels), 304 305 followed by Sardinia and South Italy. On the contrary, the lowest frequencies of extreme fuel 306 moisture were shown by Northwest and Northeast Italy, being the frequency of 'moderate' 307 days more than 95% for both codes. Corsica and Central Italy showed similar fuel moisture 308 frequencies, particularly for fine fuels.

309 Regarding the variation between the baseline period (1981-2010) and the two future periods 310 (2011-2040 and 2041-2070), in the entire study area the frequency of 'moderate' fuel 311 moisture days is expected to decrease for both codes in the two future periods (Fig. 4, Annex 312 2). The frequencies of the driest categories for FFMC in the 2011-2040 period did not change 313 in Central and Northern areas, while in Sicily, Sardinia and to a lower extent in South Italy, 314 the frequencies of 'dry' and 'very dry' fuel moisture days slightly increased. However, in the 315 second period (2041-2070), the frequencies of the driest moisture categories increased, 316 except for Northeast and Northwest Italy. The highest increase in the driest categories of 317 FFMC was shown by Sicily followed by Corsica and Central Italy in this second future 318 period.

The changes in DC categories frequencies were in general higher than those in FFMC (Fig. 4, Annex 2). In the 2011-2040 period, the frequency of the days with the highest DC values increased in Corsica and Sardinia and, to a much lower extent, the frequency of 'very dry' days in Sicily; the frequency of 'extreme' days in Sicily decreased slightly as well as the frequencies of the driest categories in South Italy. The frequencies of the other subareas did not change in this period. In the 2041-2070 period the changes in DC are more evident. The frequencies of the driest categories increased for all subareas except for Northwest and Northeast Italy, where only the 'very dry' live fuel moisture frequency increased. In this case, Corsica showed the highest increase followed by Central Italy, Sicily and Sardinia.

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### 329 **3.2. Changes in wildfire exposure**

From the outputs of RANDIG simulations, a set of fire exposure indicator maps (BP, CFL, FS, Figs. 5-7) was derived for the different study periods and subareas. The highest values of BP, CFL and FS were observed in Sardinia, Corsica and Sicily, while the lowest values were observed in northern areas and Central Italy (Figs. 5-7 and 10, Table IV). Overall, BP and FS changed in a similar way in both future periods and for all subareas (mostly decreasing in the 2011-2040 period and increasing in the 2041-2070 period), whereas the CFL barely varied among periods and subareas (Table IV, Fig. 10).

In particular, in the 2011-2040 period the values of BP and FS with respect to the baseline 337 decreased to a slightly higher extent in Sicily, Central and Northwest Italy, whereas in 338 339 Sardinia and South Italy the variation was minor. CFL values decreased slightly in this first 340 future period in all subareas. In the 2041-2070 period, Sicily showed the highest increase for BP and FS followed by Central Italy and South Italy; to a much lower extent, BP and FS 341 342 increased also in Sardinia. On the contrary, BP and average FS decreased in Northwest Italy 343 and Northeast Italy and slightly also in Corsica. The CFL increased slightly in Corsica in this 344 second future period whereas in Northwest Italy, Northeast Italy and Sardinia decreased.

345 As presented in the Material and Methods section, from the primary fire exposure indicators 346 we derived an extended set of indicators (FPI, HFLP, HFLBP) with the aim to summarize the 347 information on fire probability and severity for the entire study area (Figs. 8 and 9). The 348 evolution of FPI throughout the three studied periods is similar to the evolution of BP or FS 349 (Fig. 10). Regarding the HFLP and HFLBP indicators, results showed limited differences 350 between the three studied periods (Fig. 9, Table IV), except for NE in case of HFLBP and 351 NW in both cases where differences are higher in proportion to their values. The highest mean values of FPI, HFLP, HFLBP were observed in Corsica and Sardinia (Table IV). 352

In the 2011-2040 period, FPI decreased in all subareas: in Northwest Italy and Sicily the reduction is higher; in Sardinia the decrease is minor; and in the other subareas it ranges from -1.78 to -1.23%. The changes of this index in the 2041-2070 period are different for each subarea. In this period the value of FPI increases for Sicily, Central Italy, South Italy and Sardinia and decreases for Northwest Italy, Northeast Italy and Corsica.

358 Results provided by ANOVA on all fire exposure indicators (BP, CFL, FS, FPI, HFLP and 359 HFLBP) have shown that the temporal variations between baseline and future periods were 360 significant for p = 0.01 in all subareas. Regarding the variations among subareas, the results 361 provided by the post-hoc Student-Newman-Keuls test showed (Table IV) significant 362 differences (p = 0.01) for all exposure indices except for NW and NE, where FSs predicted for the two future time periods are similar; some significant similarities were observed 363 between NW and CI, regarding HFLP and FPI; likewise, significant similarities were 364 365 observed between NW and NE, affecting the HFLP.

#### 367 4. DICUSSION AND CONCLUSIONS

368 In this work, we extend our understanding of the potential impact of future climate change on 369 wildfire exposure specifically for the Mediterranean region using a wildfire spread modeling 370 approach. We incorporated projected climate change into a mechanistic wildfire spread 371 modelling system to better represent the effects of fine scale drivers of wildfire propagation 372 on the assessment of climate change impacts. This work is one of the first applications in 373 Europe of a methodology to assess the impacts of climate change on wildfire exposure through a wildfire modeling approach, using both fine resolutions (250 m) and a large 374 375 assessment scale. Although we used a single climate model rather than an ensemble, the 376 present work contributes methods that can be applied in other areas to analyze different time 377 frames, scenarios, and climate models. The climate projections we used in this study are 378 overall in line with previous works and highlighted an increase in future temperatures and a reduction in precipitation and relative humidity for the entire study area.<sup>(22–24)</sup> This result is 379 380 also compatible with the conclusions of the fifth IPCC report that forecasted strong warming 381 trends and precipitation decrease in Southern Europe, with marked increase in number of warm days, heat waves and droughts.<sup>(21)</sup> We also observed a decrease in average wind speed 382 values and in the frequency of days with strong winds in the future periods for the entire 383 study areas. Although according to the fifth IPCC report<sup>(21)</sup> there are uncertainties regarding 384 the projections of future wind speed trends, especially during Summer season.<sup>(82)</sup> However, 385 there is agreement in the decrease of average annual mean wind speed in the study area.<sup>(82)</sup> 386

387 The analysis of the FWI codes (FFMC and DC) highlighted that the frequencies of the 388 'extreme' fuel moisture categories strongly vary among subareas. In particular, there is a

gradient of the 'extreme' fuel moisture frequency from South to North, being the southern 389 390 subareas characterized by the highest values. The most relevant variations in FFMC and DC 391 were observed in the 2041-2070 period, and the increase in the frequency of the driest days 392 suggests that the fire seasons will be longer than the baseline. A similar finding for Italy was reported by Bedia et al.<sup>(83,84)</sup>, who analyzed the future trends in FWI using a multi-model 393 394 approach considering the SRES-A1B scenario, and observed also a more marked FWI 395 increase in the 2041-2070 period than in the 2011-2040. The lengthening in future fire 396 seasons related to the increased frequency of drier days was also highlighted by other studies.<sup>(16,27–29,49,83)</sup> 397

To assess the potential impacts of climate change on wildfire exposure, and to remove possible uncertainties related to future land use changes and therefore variation in fuel types and characteristics (e.g., load, depth, etc), the fuel layer was held constant input for the wildfire simulations of the three periods. For the same reason, we also assumed constant fire ignitions number and location, and we used the historic ignition grids of the period 1990-2008 as a reference for the three study periods.

We observed slight changes in CFL for all periods and for all subareas, primarily because fire intensity is strongly dependent on fuel type, which was held constant. However, climate variations did influence other fire exposure indicators. We found a slight decrease of most of the fire exposure indicators for the first future period and for the entire study area. This was probably related to the decrease in frequency of higher wind speeds. By contrast, in the second future period the values of the fire exposure indicators noticeably increased, probably due to the increase in the frequency of FFMC and DC values associated with extreme 411 conditions. The different trend in the two periods suggests that probably the fuel moisture 412 content is the most important factor for the fire spread in the study area since a decrease in 413 wind speed in the first future period was able to reduce the exposure indices when the dry 414 fuel conditions increase slightly, whereas a decrease of wind speed from the first to second 415 future periods was not able to counteract the increase of extremely dry fuel conditions. 416 However, there was a high variability among responses in subareas, and for instance the slight increase in the exposure indices in Sardinia in the second future period (2041-2070) 417 418 and the decreasing trend in Corsica, Northwest Italy and Northeast Italy, confirm that in these regions wind does play a key role. Similar results were provided by Arca et al.<sup>(49)</sup> who 419 studied the fire danger variations in Sardinia using the MTT algorithm and climate data 420 421 provided by the regional climate model EBU-POM for the IPPC A1B emission scenario. This 422 study showed for the 2071-2100 period an increase in the burn probability associated with an overall increase of the frequency of potential days with extreme fires as measured by the 423 number of days with high values of FWI. Likewise, Kalabokidis et al.<sup>(51)</sup> combined 424 425 simulations with climate projections from the SRES A1B scenario, in this case derived from 426 simulations of the KNMI regional climate model RACMO2 in Messinia (Greece). They also observed an increase in burn probability at the end of the 21st century. 427

The differences among subareas are significant for most of the fire exposure indicators. In fact, southern areas and islands showed the highest values for fire exposure variables while northern areas showed the lowest in both present and future periods. These differences were notable even if we used a fixed burn period for all subareas and the number of ignitions was proportional to the size of the study area. Therefore, differences in the fire exposure 433 indicators among subareas are exclusively due to differences in fuel types, fuel moisture and434 wind, which are strongly determined by climate conditions.

435 In conclusion, fire modeling outputs projected an increase in wildfire incidence due to 436 climate change that may lead to several threats in the future. For instance, an increase in greenhouse gas emissions is expected, which in turn favors climate warming.<sup>(85–87)</sup> Moreover, 437 438 increasing wildfires might cause substantial changes in the existing vegetation composition and distribution or even desertification of some areas and probably a subsequent erosion.<sup>(88-</sup> 439 <sup>90)</sup> Many Mediterranean plants are adapted to cope with fire, but some Mediterranean 440 ecosystems may be strongly affected by wildfires.<sup>(86)</sup> However, damages in highly valued 441 442 resources and assets, and human casualties are the most relevant concern.

443 The main strategy to prevent or minimize future wildfire damages in the Mediterranean basin 444 will be the fuel load reduction and forest management by traditional silvicultural techniques or by alternative solutions.<sup>(87,91–95)</sup> This approach requires the identification of major concern 445 446 areas to prioritize interventions. For this purpose, the outputs from our work can be used as a 447 baseline to support the decision making process, aiming at fire management planning and risk 448 mitigation activities. Furthermore, the outputs we obtained can be useful to prioritize specific 449 areas of interest taking into account the affected values, the potential fire behavior or the burn 450 probability, or the landscape physical constraints. This may be done combining GIS analysis 451 and fire exposure maps as key information to plan and evaluate the fuel and fire management 452 activities. Innovative tools, modules and software developed in recent years might also be coupled to fire exposure maps in supporting fire and land managers.<sup>(96,72)</sup> Further research is 453 454 now needed to assess how future changes in land cover and ignition patterns will also

- 455 contribute to increased fire exposure and risk, and how risk governance systems will adapt to
- 456 the projected future fire regimes.

## 458 FIGURES AND TABLES



460 Fig. 1. Location of the study area in the Euro-Mediterranean context (left), and of the seven subareas used in the461 present study (right).



464 Fig. 2. Digital Elevation Model (a), Koeppen-Geiger climate classification (b), and main vegetation types derived from the Corine land cover map of 2006 (c) of the study
 465 area.



467 Fig. 3. Average annual fire ignitions at province level (a) and annual area burned relative to the area covered by468 each province (ha/ha) (b) from historical data (fires occurred from 1990 to 2008, source: JRC).



- 471 Fig. 4. Variation in FFMC (a), DC (b) and wind speed frequencies (c) from the baseline (1981-2010) to the
- 472 second (2011-2040) and third (2041-2070) study periods.



475 Fig. 5. Maps of Burn Probability (BP): for the baseline period (1981-2010) (a); difference between first future period (2011-2040) and baseline (b); and difference between
476 second future period (2041-2070) and baseline.



479

480 Fig. 6. Maps of Conditional Flame Length (CFL): for the baseline period (1981-2010) (a); difference between first future period (2011-2040) and baseline (b); and difference

481 between second future period (2041-2070) and baseline.



484 Fig. 7. Maps of Fire Size (FS): for the baseline period (1981-2010) (a); difference between first future period (2011-2040) and baseline (b); and difference between second
485 future period (2041-2070) and baseline.



488 Fig. 8. Maps of Fire Potential Index (FPI) calculated as the product of Fire Size and historical Ignition Probability: for the baseline period (1981-2010) (a); difference
489 between first future period (2011-2040) and baseline (b); and difference between second future period (2041-2070) and baseline.



493 Fig. 9. Maps of High Flame Length Probability (HFLP), which is the probability of high flame length (> 2.5 m) given a fire burning the cell: for the baseline period (1981494 2010) (a); difference between first future period (2011-2040) and baseline (b); and difference between second future period (2041-2070) and baseline.



- 498 Fig. 10. Variation in Burn Probability (BP), Conditional Flame Length (CFL), Fire Size (FS) and Fire Potential Index (FPI) from the baseline (1981-2010) to the second
- 499 (2011-2040) and third (2041-2070) study periods respectively. The differences were calculated from the outputs of the fire simulations for each subarea and the entire studied
- 500 area (ST) as follows:

501  $Change(\%) = \frac{Value_{future_peiod} - Value_{baseline}}{Value_{baseline}} *100$ 

502 Table I. Main fuel types and relative incidence. The fuel types were derived from the 2006 Corine Land Cover

503 (CLC) map. To each fuel type, a specific standard or custom fuel model was associated.	(45)
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Fuel types	CLC codes	Reference Fuel Models used	Area (km <sup>2</sup> )	Incidence (%)
Urban and anthropic area	1	NB1 <sup>(56)</sup>	14,861	4.80
Water	4; 5	NB8 <sup>(56)</sup>	4,007	1.29
Rocks	332	Mod 1 (reduced load $50\%$ ) <sup>(55)</sup>	4,722	1.53
Sands	331	Mod 1 <sup>(55)</sup>	758	0.24
Grasslands	211; 212; 213; 231	Mod 1 <sup>(55)</sup>	88,579	28.62
Mixed agricultural	241; 242; 243; 244	Mod 1 <sup>(55)</sup>	48,211	15.58
Vineyard and orchard	221; 222; 223	Mod 2 <sup>(55)</sup>	21,610	6.98
Pastures	321	CM 27 <sup>(57)</sup>	15,521	5.02
Garrigue	333; 334	CM 29 <sup>(57)</sup>	4,840	1.56
Mediterranean maquis	322; 323; 324	CM 28 <sup>(57)</sup>	24,880	8.04
Conifer forests	312	TL6 <sup>(56)</sup>	13,259	4.28
Broadleaf forests	311	TL3 <sup>(56)</sup>	56,693	18.32
Mixed forests	313	TU1 <sup>(56)</sup>	11,107	3.59
Glaciers	335	NB8 <sup>(56)</sup>	405	0.13

506 Table II. Geographic data of the seven subareas identified. The data include administrative region, total area and

507	inhabitants (year of reference	2013), <sup>(97,98)</sup> and wild	dfire history from 1990 to	2008. <sup>(99)</sup>
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	Code	<b>Regions</b> included	Total area (km <sup>2</sup> )	Inhabitants (million)	Average annual number of fires	Average annual area burned (ha)	Average annual area burned/Total area (%)
Corsica	СО	Corsica	8,716	0.32	302	6,053	0.69
Sardinia	SA	Sardegna	23,909	1.66	1,019	9,898	0.41
Sicily	SC	Sicilia	25,552	5.09	639	14,990	0.64
South Italy	SI	Basilicata, Calabria, Campania, Puglia	58,435	12.52	3,154	32,043	0.55
Central Italy	CI	Abruzzo, Lazio, Marche, Molise, Toscana, Umbria	73,395	13.72	1,628	14,561	0.20
Northwest Italy	NW	Emilia- Romagna (West part), Liguria, Lombardia, Piemonte, Valle d'Aosta	68,926	18.10	1,434	15,203	0.26
Northeast Italy	NE	Emilia- Romagna (East part), Friuli- Venezia, Giulia, Trentino- Alto Adige, Veneto	50,992	9.69	420	2,479	0.05
Entire study area	ST		309,925	61.10	8,597	95,226	0.30

- 508 Table III. Ranges of dead and live fuel moisture values (in % of dry weight) used as simulation input data for
- 509 the different vegetation types. The data where derived from the analysis of different FFMC and DC percentile
- 510 thresholds (75, 90, 95, 97), using Sardinia as reference.

Moisture category label		MODERATE	DRY	VERY DRY	EXTREME
Percentile threshold		$75^{th}-90^{th}$	$90^{th}-95^{th}$	$95^{th}-97^{th}$	$> 97^{th}$
	1 h	11 - 14	9 - 11	7 - 9	5 - 7
DEAD FUEL	10h	13 - 16	11 - 13	9 - 11	7 - 9
	100h	15 - 18	13 - 15	11 - 13	9 - 11
	SHRUBS	110 - 90	90 - 80	80 - 75	75 - 65
	FORESTS	130 - 105	105 - 100	100 - 95	95 - 85

Table IV. Mean values of the different fire exposure indicators calculated for each subarea, for the entire study area (ST), and for each study period (1st timeframe 1981-2010; 2nd timeframe 2011-2040, 3rd timeframe 2041-2070). Values followed by the same letter along the row mean that subareas are not significantly different from each other according to the Student-Newman-Keuls test (for p = 0.01); all differences between the baseline and the future time steps are significantly different according to the Student-Newman-Keuls test (p = 0.01).

		СО	SA	SC	SI	CI	NW	NE	ST
BP	1 <sup>st</sup>	5.1720·10 <sup>-5</sup> <b>a</b>	9.0739·10 <sup>-5</sup> <b>b</b>	3.9580·10 <sup>-5</sup> <b>c</b>	4.4730·10 <sup>-5</sup> <b>d</b>	$5.0956 \cdot 10^{-6}  \mathbf{e}$	$3.0600 \cdot 10^{-6}  \mathbf{f}$	$1.0800 \cdot 10^{-6}  \mathbf{g}$	2.2243·10 <sup>-5</sup>
	$2^{nd}$	5.0930·10 <sup>-5</sup> <b>a</b>	9.0740·10 <sup>-5</sup> <b>b</b>	3.8640 · 10 <sup>-5</sup> <b>c</b>	$4.4240 \cdot 10^{-5}  \mathbf{d}$	4.9781 · 10 <sup>-6</sup> <b>e</b>	2.9800·10 <sup>-6</sup> <b>f</b>	$1.0700 \cdot 10^{-6}  \mathbf{g}$	$2.2001 \cdot 10^{-5}$
	3 <sup>rd</sup>	5.1200·10 <sup>-5</sup> <b>a</b>	9.3057·10⁻⁵ <b>b</b>	4.4190 · 10 <sup>-5</sup> <b>c</b>	$4.7240 \cdot 10^{-5}  \mathbf{d}$	5.4492 · 10 <sup>−6</sup> e	2.9300·10 <sup>-6</sup> <b>f</b>	$1.0500 \cdot 10^{-6}  \mathbf{g}$	2.3312·10 <sup>-5</sup>
CFL	1 <sup>st</sup>	1.7158 <b>a</b>	1.5493 <b>b</b>	1.1304 <b>c</b>	0.9499 <b>d</b>	0.6164 <b>e</b>	0.3102 <b>f</b>	0.2527 <b>g</b>	0.6973
	$2^{nd}$	1.7150 <b>a</b>	1.5440 <b>b</b>	1.1279 <b>c</b>	0.9444 <b>d</b>	0.6157 <b>e</b>	0.3031 <b>f</b>	0.2506 <b>g</b>	0.6934
	3 <sup>rd</sup>	1.7413 <b>a</b>	1.5334 <b>b</b>	1.1332 <b>c</b>	0.9482 <b>d</b>	0.6195 <b>e</b>	0.3038 <b>f</b>	0.2480 <b>g</b>	0.6948
FS	1 <sup>st</sup>	444.7256 <b>a</b>	743.3677 <b>b</b>	540.4703 <b>c</b>	284.2069 <b>d</b>	78.8086 <b>e</b>	50.5048 <b>f</b>	43.2407 <b>g</b>	205.2689
	$2^{nd}$	439.1410 <b>a</b>	740.7777 <b>b</b>	525.6507 <b>c</b>	282.6651 <b>d</b>	76.9429 <b>e</b>	48.8820 <b>f</b>	42.8441 <b>f</b>	202.5211
	3 <sup>rd</sup>	442.3663 <b>a</b>	759.1505 <b>b</b>	603.0428 <b>c</b>	299.8642 <b>d</b>	84.0047 <b>e</b>	48.2669 <b>f</b>	41.8648 <b>f</b>	215.0340
FPI	$1^{st}$	38.4007 <b>a</b>	30.9625 <b>b</b>	13.0511 <b>c</b>	13.8969 <b>d</b>	1.7928 <b>e</b>	1.4609 <b>e</b>	0.4047 <b>f</b>	7.9804
	$2^{nd}$	37.7167 <b>a</b>	30.8614 <b>b</b>	12.5008 <b>c</b>	13.7108 <b>d</b>	1.7644 <b>e</b>	1.3962 <b>e</b>	0.4006 <b>f</b>	7.8509
	3 <sup>rd</sup>	38.0890 <b>a</b>	31.8974 <b>b</b>	14.5849 <b>c</b>	14.6820 <b>c</b>	1.9384 <b>d</b>	1.3800 <b>e</b>	0.3885 <b>f</b>	8.3325
4	$1^{st}$	$2.0180 \cdot 10^{-1} \mathbf{a}$	$1.5031 \cdot 10^{-1} \mathbf{b}$	$5.7811 \cdot 10^{-2} c$	$2.8831 \cdot 10^{-2} \mathrm{d}$	9.5917·10 <sup>-3</sup> <b>e</b>	$7.3840 \cdot 10^{-4}  \mathbf{f}$	$6.2250 \cdot 10^{-4}  \mathbf{f}$	2.9893·10 <sup>-2</sup>
HFL	$2^{nd}$	$2.0305 \cdot 10^{-1} \mathbf{a}$	$1.5128 \cdot 10^{-1}  \mathbf{b}$	$5.7589 \cdot 10^{-2} c$	$2.8489 \cdot 10^{-2} \mathrm{d}$	9.6256 ⋅ 10 <sup>-3</sup> e	$3.5930 \cdot 10^{-4}  \mathbf{f}$	$6.2960 \cdot 10^{-4}  \mathbf{f}$	3.0493·10 <sup>-2</sup>
	3 <sup>rd</sup>	$2.0536 \cdot 10^{-1}  \mathbf{a}$	1.4992·10 <sup>-1</sup> <b>b</b>	5.9475 · 10 <sup>-2</sup> <b>c</b>	$2.9232 \cdot 10^{-2}  \mathbf{d}$	9.7861 · 10 <sup>-3</sup> <b>e</b>	$5.0400 \cdot 10^{-4}  \mathbf{f}$	$6.1130 \cdot 10^{-4}  \mathbf{f}$	3.0632.10-2
Р	$1^{st}$	$3.7389 \cdot 10^4  \mathbf{a}$	$1.9050 \cdot 10^{-4}  \mathbf{b}$	5.4760·10 <sup>-5</sup> c	$7.0500 \cdot 10^{-6}  \mathbf{d}$	4.9239 · 10 <sup>-7</sup> <b>e</b>	$4.0000 \cdot 10^{-8} e$	$4.0000 \cdot 10^{-8}  \mathbf{e}$	3.1049.10-5
FLB	$2^{nd}$	$3.6356 \cdot 10^4  \mathbf{a}$	$1.8900 \cdot 10^{-4}  \mathbf{b}$	5.3070·10 <sup>-5</sup> <b>c</b>	6.9600 · 10 <sup>-6</sup> <b>d</b>	4.8936 ⋅ 10 <sup>-7</sup> e	$2.0000 \cdot 10^{-8} e$	5.0000 · 10 <sup>-8</sup> <b>e</b>	3.2161·10 <sup>-5</sup>
H	3 <sup>rd</sup>	$3.6356 \cdot 10^4  \mathbf{a}$	$1.8900 \cdot 10^{-4}  \mathbf{b}$	5.3070·10 <sup>-5</sup> <b>c</b>	6.9600 · 10 <sup>−6</sup> <b>d</b>	$4.8936 \cdot 10^{-7} e$	$2.0000 \cdot 10^{-8} e$	$5.0000 \cdot 10^{-8} e$	3.2164·10 <sup>-5</sup>

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