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## 202 years of changes in Mediterranean fire regime in *Pinus nigra* forest, Corsica

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**18 Abstract**

19 Wildfires are critical socio-ecological features in the Mediterranean basin. In a context of global  
20 changes (climate, land use), we questioned whether the wildfire regime was altered in the  
21 mountains of Corsica, France. Using tree-ring analysis of fire-scarred trees, we tested for  
22 changes in frequency, seasonality, area. We hypothesized that the fire regime changed during  
23 the middle-20<sup>th</sup> century due to human activities, as observed elsewhere in the Mediterranean.  
24 We sampled fire-scarred trees, geolocated for mapping fire areas, in a forest of black pine (*Pinus*  
25 *nigra laricio*). The oldest fire was in 1684 but the fire chronology with adequate sample depth  
26 for analysis covered 202 years [1820-1921]. Between 1820-2012, 15 fires were recorded, 8 of  
27 which scarred at least 25% of the sampled trees. The mean fire interval was 14 years,  
28 corresponding to a high fire frequency with 4 major fires per century. Most fires occurred  
29 between 1931-1970. On average, about 50% of trees were scarred by fires before 1931, but this  
30 percentage decreased thereafter. The exception was the 2000 fire that impacted 100% of living  
31 trees. Mapping showed spatially heterogenous fire areas. These results match other  
32 Mediterranean studies showing longer fire intervals since the late-20<sup>th</sup> century, and wildfires  
33 generally occurred during the period of late-earlywood or latewood formation, i.e., summer or  
34 early autumn, which is the season of contemporary fires. Although fires were recurrent for more  
35 than 200 years with no change in the fire season, the regime changed twice in frequency. These  
36 changes likely result from a combination of land use and warmer summer conditions. While  
37 pines survived most past fires of low intensity through the last large fire in the 1970's, the severe  
38 fire of 2000, following ca 30 years of fire suppression, killed large patches of mature trees. Such  
39 chronology provides rational arguments for black pine ecosystem management, notably to  
40 consider seeking to recover the sustainable fire regime of the 19<sup>th</sup> century, for instance by using  
41 prescribed fires to manage surface fuel.

42 Key words: climate; dendrochronology; fire frequency; fire season; fire area; fire scars; land  
43 use; management; mountain; *Pinus nigra laricio*; tree-ring

## 44 **1. Introduction**

45 Wildfire is a key component of ecosystem functioning at global scale (Bond and Keeley, 2005;  
46 Sayedi et al., 2023). The ecological roles of wildfire depend on fire regime parameters such as  
47 fire intervals, intensity, and seasonality, which are related to the frequency, extent, and severity  
48 of fires (Johnson, 1992; Keeley, 2009; Pausas and Ribeiro, 2013). Globally, fire regime shifts  
49 are driven by complex interplays between climate and land uses as reported in Mediterranean-  
50 climate areas of Australia, Europe and North America (Moritz et al., 2014) and at a global scale  
51 as well (Andela et al., 2017). Because fire regimes are under control of both climate and land  
52 uses over millennia, they are thus a *socio-ecosystems* component (*sensu* Liu et al., 2007),  
53 resulting from coupled natural and social drivers, including legacies of past conditions,  
54 producing multivariate responses of fire behaviour (e.g., Niklasson and Granström, 2000;  
55 Guiterman et al., 2019).

56 The Mediterranean Basin is fire prone due to dry and warm summers, as well as fire-adapted  
57 native species (Pausas et al., 2008). Climate models predict that the late-21<sup>st</sup> century will be  
58 warmer and drier, including in winter, leading to more fire years and a broader fire season in  
59 the region (Ozturk et al., 2015; Turco et al., 2018). Mediterranean ecosystems of southeastern  
60 France have already experienced changes in fire regimes since the 1970's through the mid-  
61 1990's, with more burned areas and higher yearly and seasonal fire occurrences (Fréjaville and  
62 Curt, 2015). However, since 1986 (Ruffault and Mouillot, 2015) or the mid-1990's (Fréjaville  
63 and Curt, 2017), the trend has changed suggesting a partial disconnection between fire regime  
64 and climate, or the effects of other drivers such as policies of land management. Similar trends  
65 have been recorded in other Mediterranean countries such as Spain (Pausas and Fernandez-  
66 Munoz, 2012), although not in north Africa (Chergui et al., 2018). Reconstructing and  
67 decomposing long-term fire regime characteristics (frequency, season, areas) remains helpful

68 for forest managers to constitute baselines for analyzing current trends in light of past recent  
69 regimes.

70 In the Mediterranean basin, black pine (*Pinus nigra* Arnold) is common in many countries  
71 where it is a dominant tree, considering that its large biomass drives most ecosystem processes  
72 (the mass ratio hypothesis *sensu* Grime, 1998). Black pine has been also abundantly planted  
73 since late 19<sup>th</sup> century (hereafter c.) for timber production and soil protection, resulting globally  
74 in 3.5 million hectares of new forests (Isajev et al., 2004) sometimes for assisted migration  
75 (Michalet et al., 2023). Its management in the face of climate and fire changes would benefit  
76 from more precise baselines on historical fire regime of this region over time. Detailed baselines  
77 on historical fire regimes in *P. nigra* forests have started to emerge (Fulé et al., 2008;  
78 Christopoulou et al., 2013; Sahan et al., 2022), providing site- and time-specific reconstructions  
79 of past fires. All these studies showed that fire intervals were shorter during the late-19<sup>th</sup> or the  
80 early-20<sup>th</sup>c., and that the fire intervals became longer in the late-20<sup>th</sup>c. Generally, in Europe and  
81 the Mediterranean basin, the 19<sup>th</sup>c. was a period of intense rural and forest land uses for  
82 domestic herding and wood production (Grove and Rackham 2001). Such intense usages could  
83 explain the more frequent fires during the 19<sup>th</sup>c., despite a cooler climate (Büntgen et al., 2013;  
84 Luterbacher et al., 2016). However, the generalized land-use abandonment in the  
85 Mediterranean, varying somewhat among countries and regions (Chauchard et al., 2007; San  
86 Roman Sanz et al., 2013; Fortuny et al., 2014), altered risks of ignition. At the turn of the 21<sup>st</sup>c.,  
87 global warming enhanced a trend for more severe fires, indirectly fostered by land-use  
88 abandonment that triggers fuel build-up at stand scale and forest connectivity at landscape scale  
89 (Ganteaume and Jappiot, 2013, Mouillot et al., 2003).

90 A growing body of dendrochronological literature reported extensive surface fire in *P. nigra*  
91 massifs around the Mediterranean (Fulé et al., 2008; Christopoulou et al., 2013; Camarero et  
92 al., 2018; Sahan et al., 2022). However, Corsica is still an area of gap of knowledge on fire

93 regime, except for a multimillennial study based on sedimentary charcoal (Leys et al., 2014)  
94 reporting that fire was closely associated to black pine for more than 12,000 years. Szymczak  
95 et al. (2020) carried out a fire study based on tree-ring analysis of 10 fire-scarred cross-sections  
96 supplemented by increment cores and an administrative-based study in lowland forest of oaks  
97 and maquia was published by Mouillot et al. (2005). Therefore, the present study aims to test  
98 the hypothesis that the fire frequency has changed since the 19<sup>th</sup>c in forests of *Pinus n.* subsp.  
99 *laricio* (Poir.) Maire (hereafter *P. nigra*). The study is based on dendrochronological analysis  
100 of fire scars (Arno and Sneek, 1977; Zackrisson, 1977; Huffman et al., 2020).

101 On the 27<sup>th</sup> August 2000, a substantial area of lethal crown fire occurred near Vizzavona  
102 (central Corsica), reported to have burned a total of 3900 ha, i.e., 10% of black pine cover in  
103 Corsica. We selected this site to determine if fire regime has changed significantly during past  
104 centuries, and if there is evidence of drivers supporting the eventual change in fire regime in an  
105 area that experienced changes in its human demography. The main objective of the present  
106 study is to reconstruct the longest fire chronology, the temporal, seasonal and spatial variability  
107 in this central Corsican forest and, to a lesser extent, explore possible links between human  
108 demography and fire activity. We hypothesized that changes in fire regime were linked to local  
109 trends in human demography, and fire season was stable, occurring during the warm/dry  
110 summer season (climate driver). All these fire parameters will be helpful to establish the  
111 historical range of variability of fire regime useful to delineate baselines of Corsican black pine  
112 forest management.

113

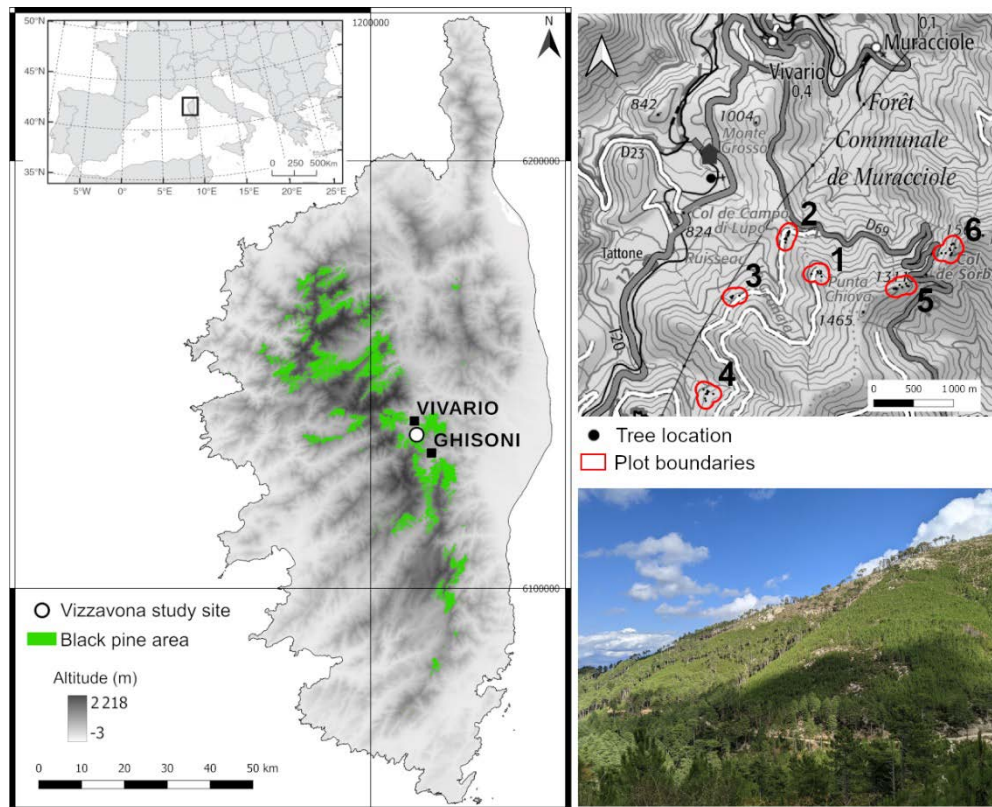
## 114 **2. Materials and methods**

### 115 **2.1 Study site**

116 Corsica is a French Mediterranean island, located west of the Italian peninsula and southeast  
117 of southeastern mainland France (Figure 1a). Corsica is mountainous with several summits  
118 above 2000 m above sea level (a.s.l.). The study site, hereafter the “Vizzavona forest”, is  
119 situated in central Corsica (42.14 N, 9.19°E). It corresponds to the state forest of Rospa-Sorba,  
120 and the two communal forests of Vivario and Muracciole, all mostly used for timber production,  
121 but not where the sampling was carried out. There are few semi-feral cattle extensively grazing  
122 in the study forest. One shepherd sometimes uses the forest for his goats. Vizzavona forest is  
123 also an emblematic site with high touristic and patrimonial value, located at the junction  
124 between north and south parts of the island. The bedrock is composed of igneous rocks or  
125 granites. Vizzavona forest soils are 35-65 cm deep brunisols, slightly acidic (pH: 5.5 to 6.5)  
126 sandy-silty, respectively 60% and 40% of sands and silts (IFN report 2004), resulting a low  
127 water storage.

128





129

130 **Figure 1.** (a) Map of Corsica displaying black pine distribution (green) according to the French  
 131 forest inventory (IFN data, 2017); the white dot represents the location of the study site or  
 132 Vizzavona forest; Vivario and Ghisoni are the two nearest villages of the study site, situated on  
 133 both Sorba pass sides; coordinates in meters are according to the Lambert 93 French grid. (b)  
 134 Local map of sampling area, and plots in red. (c) Scenery illustration. *(figure in color)*

135

136 At Vizzavona, the climate is Mediterranean with hot summers and cool winters, but the  
 137 orography results in cold seasonal conditions, notably in winter with 4 to 5 months of  
 138 intermittent snow cover. During the 1990-2020 period (nearest weather station at 772 m a.s.l.;  
 139 42.152608°N, 9.149188°E), mean annual precipitation was  $1265 \pm 291$  mm with a mean annual  
 140 temperature of  $9 \pm 0.6^\circ\text{C}$ . Mean monthly minimum precipitation and maximum temperatures  
 141 were both recorded in July ( $32 \pm 3.6$  mm;  $17.8 \pm 2.9^\circ\text{C}$ ) and August ( $33 \pm 3.2$  mm;  $17.7 \pm 2.8^\circ\text{C}$ ).

142 Mean monthly precipitation peaked in November ( $208 \pm 16.4$  mm), including snowfall, and  
143 monthly minimal average temperatures occurred in February ( $1.9 \pm 3.5^\circ\text{C}$ ).

144 Regarding wildfires in Corsica, the Prométhée fire database between 1973-2022  
145 (<https://bdiff.agriculture.gouv.fr/>) indicates that 55% of fires occurred between July and  
146 September, including 39% in July and August (Supplementary Information Figure S1); 95% of  
147 total area burned between July and September, especially between July and August (86%). In  
148 black pine forests, the main fuel is composed of shrubs, i.e., *Erica arborea* below 1400 m a.s.l.  
149 (max. 3-m tall) and *Juniperus sibirica* Lodd. Ex-Burgsd from 1400 to 1600 m a.s.l. (< 1-m),  
150 saplings of pines, a thick litter layer of pine needles, and woody debris (Figure S2).

## 151 **2.2 Material**

152 In Corsica, black pine covers 372 km<sup>2</sup> (Figure 1a) mostly above 1000 m up to 1800 m a.s.l.  
153 Its lifespan is potentially over 800 years (Szymczak et al. 2014). *P. nigra* needs a strong annual  
154 precipitation (800 to 1200 mm.yr<sup>-1</sup>) but supports dry summers and colonize soils with low water  
155 storage capacity. Trees can reach 40 m in height. They have a thick bark and a high crown base  
156 protecting adult trees from fires (Fréjaville et al., 2018b). Because it does not have serotinous  
157 cones, seedling regeneration is limited after severe fires (Pausas et al., 2008).

## 158 **2.3 Field sampling**

159 We selected six plots within the study area (Figure 1b) according to three main parameters:  
160 (i) presence of large black pines (assumed old trees) to sample multi-scarred trees and maximize  
161 the probability to obtain the longest fire chronology; (ii) areas characterized by a dense tree-  
162 cover of *Pinus pinaster* or *Fagus sylvatica* were excluded because they both present different  
163 flammability traits (Fréjaville et al., 2018b) and niche (Fréjaville et al., 2018a); (iii) due to  
164 severe relief, plots needed to be close to paths for transport of sampling equipment and wood  
165 samples. Mean plot slopes ranged from 45 to 80%, and aspect varied from north to west,

166 following an altitudinal gradient ranging from 1000 m to 1400 m. (Table 1). Plots were  
 167 relatively homogeneous with respect to topography and vegetation between and within them.  
 168 Depending on the plot, there could be regeneration of *P. nigra* only, or both *P. nigra* and *P.*  
 169 *pinaster* (VZ02); in more open areas, there was dense cover of tree heather (*Erica arborea* L.;  
 170 VZ03).

171

172 **Table 1:** Plot characteristics (mean values) of the study site (Vizzavona). Plot areas were  
 173 calculated by creating a 100 m buffer around sampled tree points. Coordinates correspond to  
 174 the World Geodetic System 84. Understory vegetation: PN: *Pinus nigra*; PP: *Pinus pinaster*  
 175 (Aiton); PA: *Pteridium aquifolium* (L.) Kuhn; EA: *Erica arborea* L.; FS: *Fagus sylvatica* L.;  
 176 CS: *Castanea sativa* Mill. (cf. Figure S2).

| Plots<br>(VZ21) | Latitude<br>(°) | Longitude<br>(°) | Elevation<br>(m a.s.l.) | Slope<br>(%) | Aspect | Area<br>(ha) | Understory                          |
|-----------------|-----------------|------------------|-------------------------|--------------|--------|--------------|-------------------------------------|
| VZ2101          | 42.1453800      | 9.1744550        | 1250                    | 45           | N      | 6.6          | PN and PP saplings,<br>EA, PA       |
| VZ2102          | 42.1497071      | 9.1695536        | 1040                    | 43           | W      | 6.3          | Abundant saplings<br>of PP; EA      |
| VZ2103          | 42.1434320      | 9.1606060        | 1100                    | 43           | N      | 5.5          | Abundant saplings<br>of PP; EA      |
| VZ2104          | 42.1327850      | 9.1556100        | 1050                    | 46           | NW     | 7.8          | PP, PN, PA, EA,<br>Scattered FS, CS |
| VZ2105          | 42.1430427      | 9.1859809        | 1400                    | 54           | N-NW   | 7.6          | PN, EA                              |
| VZ2106          | 42.1468027      | 9.1941118        | 1370                    | 79           | NW     | 8.7          | Scattered EA                        |

177

178 We selected trees presenting the highest number of visible scars on living trees, stumps, logs  
 179 or snags to establish a thorough fire history (Farris et al., 2013). We used chainsaws to remove  
 180 small samples of wood from standing trees (living or dead), partial cross-sections that  
 181 represented <10% of a tree's cross-sectional area, a sampling approach that presents minimal  
 182 risks of tree breakage (Heyerdahl and McKay, 2008). Samples were labeled and wrapped with  
 183 plastic film for transport to the lab. For every sample, we measured diameter at breast height  
 184 (~1.3 m), latitude, longitude, elevation, slope, slope aspect, aspect of the scar, and the number  
 185 of suspected scars. Each sample was photographed.

186 Further, we sampled ten unscarred old trees in the VZ05 plot using increment borers to  
187 develop tree-ring chronologies on trees that were obviously not scarred, helpful for cross-dating  
188 and for comparison in addition to a reference chronology of *P. nigra*, extracted from the  
189 International Tree-Ring Data Bank ([www.ncei.noaa.gov/access/paleo-search/study/4389](http://www.ncei.noaa.gov/access/paleo-search/study/4389);  
190 author: Schweingruber, 2002). For this purpose, two cores were sampled per tree at 1.3 m  
191 height, one on the uphill side of the trunk and one at a 90° angle."

## 192 **2.4 Tree-ring crossdating and fire scar dating**

193 In the lab, wood samples were air-dried for at least one month, then sanded with progressively  
194 finer grits from P40 to P400, to obtain a smooth surface with cells visible under microscopes  
195 ( $\times 100$ ) (Stokes and Smiley, 1968). After surfacing, we digitized samples using an A3-format  
196 scanner EPSON expression 12000XL at 1200 dpi. We crossdated series with the reference  
197 chronology visually and with graphical assistance from CDendro© (Cybis.se) software  
198 (Maxwell and Larsson, 2021). Ring-widths were measured of scanned images in Coorecorder©  
199 software (Cybis.se) and we used Cofecha software (Holmes, 1983) to carry out quality control  
200 of crossdating.

201 The Schweingruber ring-width chronology (FRAN027) covered the period AD 1518 to 1980  
202 (Figure S3). We measured and crossdated cores from living unscarred pines then we added  
203 them to Schweingruber's reference chronology in order to update the chronology to 2021  
204 (Figure S3). The new chronology was used to crossdate scarred trees. The R package dplR  
205 (Bunn 2008) was used to calculate dendrochronological statistics of this chronology (master  
206 series length, series intercorrelation, mean sensitivityetc.).

207 We identified fire scars to the year and seasonal position within tree-rings using the  
208 designations of Baisan and Swetnam (1990): dormant season (D), earlywood (EE), mid-  
209 earlywood (ME), or late-earlywood (LE) and latewood (LW). The code U for undetermined  
210 was used to specify when we could not locate the scar position in the ring, usually in the case

211 of very narrow rings, decayed or fragmented samples (when scars are located at cracks). *Pinus*  
212 *nigra* growth starts in mid-April when temperatures are increasing coupled with available water  
213 (rain or melted snow). Growth slows in June and can be interrupted in early July when  
214 temperatures become too high and dryness too severe (Häusser et al., 2021). Thus, we defined  
215 the dormant season as the period between autumn and the following spring. Based on the  
216 overwhelming prevalence of summer to early-autumn fires reported in black pine forest since  
217 1973 when the French national fire database, Promethee, began ([www.promethee.com](http://www.promethee.com)), we  
218 assumed that dormant-season scars primarily formed in the late summer (August) or early  
219 autumn (September). However, we cannot rule out wildfires in spring or in winter prior to  
220 earlywood formation if conditions of ignition (lightning or people) and spread (dryness) were  
221 appropriate in winter; occurrences of winter fires have increased since the 1990's (Fréjaville et  
222 al., 2015).

223 We plotted composite fire chronologies for each plot beginning with the first fire event with  
224 a minimum of 2 recording samples. We also inventoried fire dates according to two different  
225 thresholds (25 and 50%) resulting in three classes of affected trees or severity: fire year affecting  
226 less than 25% of scarred samples, fire years affecting between 25 and 50% of scarred samples  
227 and fire years affecting 50% or more scarred samples.

## 228 **2.5 Mapping**

229 For mapping scarred trees, coordinates of each sample were measured with a Garmin GPS  
230 through the World Geodetic System 84 (WGS84) providing a positioning accuracy of 3-5 m.  
231 The plot areas were retrospectively estimated from GIS locations of sampled trees by defining  
232 a 100 m buffer zone around each geolocated tree. It is common to map locations of trees scarred  
233 by specific fires as an estimate of the spatial extent of fire (Farris et al., 2010). When samples  
234 have been collected over a systematic grid, maps based on Thiessen polygon tessellations have  
235 been shown to provide accurate reconstructions (Farris et al., 2010). In the case of irregularly

236 distributed samples, however, Thiessen polygons may create unusual shapes that are artifacts  
237 of the technique. Therefore, we estimated burned areas using a neutral kriging approach (Fulé  
238 et al., 2023), i.e., quadratic Kernel densities, called the “heatmap” tool in QGIS. We developed  
239 a map for each fire year. Densities of probabilities were calculated based on a spreadsheet  
240 containing binary values for each dated sample: 1 for fire year, and 0 without fire. Kriging  
241 parameters are explained in SI, section 4 and figure S4.

242 We merged all probability density functions for all fire years to provide a general probability  
243 of past fire occurrences corresponding to the reconstructed fire history. Probability densities  
244 were weighted by the total number of scars for each dated sample. This map makes it possible  
245 to estimate the wildfire pattern at the landscape level.

246 Note that the interpretations of burning probability are only accurate between plots and are  
247 contingent on the selection of plot locations. Thus, the kriged maps are useful for relative  
248 comparisons between fire years, but do not provide landscape-scale fire probability  
249 information.

## 250 **2.6 Human demography data**

251 We evaluated human demography as a proxy of land uses. Data were extracted from the INSEE  
252 (*Institut national de la statistique et des études économiques*) and EHESS (*Ecole des Hautes*  
253 *Études en Sciences Sociales*) databases that provided population census figures from 1800 to  
254 2019 (Figure S5). Censuses of human populations were made every 5 years between 1831 and  
255 2006 and each year since 2006. Before 1831, census intervals were not constant: 1800, 1806  
256 and 1820. For the present study, we extracted data for all of Corsica for the general trend, as  
257 well as the local trends reported for the village of Vivario (located on the northwest slope of  
258 Sorba pass), and for the village of Ghisoni (located on the southeast slope of Sorba pass). We  
259 also compared the dates of fires with historical events of World War 2 (WW2).

## 260 2.7 Data analysis

261 We used the R package burnr (Malevich et al., 2018) to calculate fire regime metrics for each  
 262 plot such as composite fire return intervals (FI), their arithmetic mean (MFI), median (median  
 263 FI), and the Weibull median probability interval.

264 Regarding FIs, we tested based on the two-samples Wilcoxon rank sum test whether they were  
 265 significant differences of mean burned areas and fire frequencies between periods characterized  
 266 by change point assumed tipping point. This method was used as fire intervals per period were  
 267 small ( $n < 10$ ) and non-parametric methods better suit this type of dataset than t-tests requiring  
 268 normal distribution and larger sample size.

269 The Weibull calculation (eq. 1) provides the  $c$  parameter, which characterizes the shape of the  
 270 curve characterizing the flammability risk trend (McCarthy et al., 2001). A  $c$  value  $< 0$  indicates  
 271 a decrease of the flammability over time ( $t$ ),  $c$  value  $> 0$  indicates that the flammability ( $h$ )  
 272 increases over time ( $t$ ), while  $c = 0$  indicates that the flammability is constant through time,  
 273 such as:

$$274 \quad h(t) = ht^c \quad \text{eqn. 1}$$

275

## 276 3. Results

277 On average, 11 trees were sampled per plot, ranging from 8 to 14 (Table 2). A total of 64 scarred  
 278 samples was collected in the Vizzavona forest, totaling 196 dated fire-scars, in a total survey  
 279 area of 43 ha (Table 1).

280 The ring-width chronology we constructed by updating Schweingruber's original FRAN027  
 281 chronology contained 30 series and covered the period 1518 to 1980. The overall correlation  
 282 ( $\bar{r}$ ) was 0.57, mean sensitivity 0.21, and EPS 0.96.

283 **Table 2:** Number of samples (tree, stump, snag, log), total of cross-dated samples and time  
 284 boundaries of chronologies

| Plot | Sample number ( <i>n</i> ) | Crossdated samples |     | Chronology (year AD) |           |
|------|----------------------------|--------------------|-----|----------------------|-----------|
|      |                            | ( <i>n</i> )       | (%) | Starting             | Finishing |
| 1    | 8                          | 7                  | 88  | 1819                 | 2021      |
| 2    | 14                         | 9                  | 64  | 1855                 | 2021      |
| 3    | 10                         | 8                  | 80  | 1824                 | 2021      |
| 4    | 10                         | 8                  | 80  | 1796                 | 2021      |
| 5    | 11                         | 9                  | 82  | 1663                 | 2021      |
| 6    | 11                         | 7                  | 64  | 1631                 | 2021      |

285

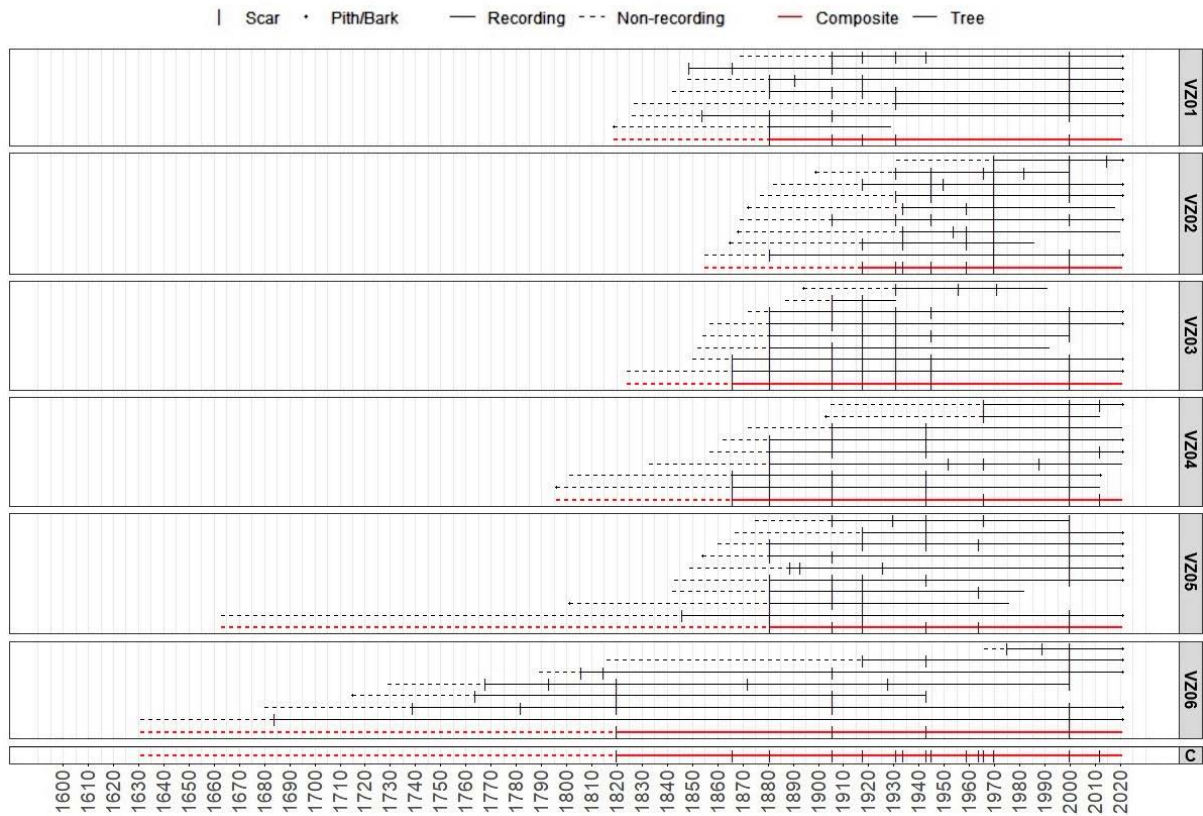
286

### 287 3.1 Fire records

288 Out of the 64 samples collected, 48 were successfully crossdated (75%), resulting in a mean  
 289 of 8 crossdated samples per plot (Table 2). The samples that could not be crossdated were  
 290 generally due to too much decayed wood (due to fungi or ants) or samples composed of too  
 291 many broken sections leading to unusable series containing not enough number of rings. Our  
 292 whole chronology covered a 390-year period, from 1631 to 2021. The oldest fire was dated to  
 293 1684 (VZ06) and the first fire present on more than one tree occurred in 1820. From 1820  
 294 onward, the 196 fire-scars recorded corresponded to 15 fire years (Figure 2). Fire interval  
 295 analyses were calculated beginning from the first fire year with a minimum of 2 samples  
 296 recording fire events. The common period for analysis was thus 1820–2021 (202 years).

297 Our chronology and associated frequency changes partly matched administrative records  
 298 (Promethee, ONF, OEC databases, period 1950-2019). Two fire events were found in both fire  
 299 records and the fire scars (1970 and 2000) while others, such as the 2012 fire in VZ04, were  
 300 identified by dendrochronology only (Figure 2).





301

302 **Figure 2.** Facetted fire history chart per plot. Dashed horizontal lines indicate non-recording  
 303 periods (before first scar); solid horizontal lines are recording periods and filled vertical bars  
 304 are fire dates. The red lines represent the composite for each plot. The box labeled C is the  
 305 composite for the whole sampling site. *(figure in color)*

### 306 3.2 Fire interval analysis

307 Between 1820–2021, a total of 15 fires was reported among the different plots covering 43 ha  
 308 in total (Figure 2). The minimum fire interval per plot was 3 years (VZ02) and the maximum  
 309 was 86 years (VZ06; Table 3). At the scale of the study site (43 ha), the minimum interval  
 310 between two occurrences was 2 years, and the maximum was 46 years (Table 3). The mean fire  
 311 interval (MFI) of 14 ( $\pm 13$ ) years is close to the median interval of 12.0 years and the Weibull  
 312 median probability interval of 10.7 years as well. Eight fires affected at least 25% of sampled  
 313 trees in 1820, 1866, 1881, 1906, 1918, 1931, 1943 and 2000. Considering this filter, minimum  
 314 and maximum FI were 12 and 57 years respectively, MFI of  $26 \pm 19$  years and Weibull median

315 probability interval of 23.2 years (Table 2). Five fires affected at least 50% of recorded samples  
 316 (1820, 1881, 1906, 1918, 2000) with a minimal FI of 12 years, a maximum of 82 years, a mean  
 317 ( $\pm$ sd) of  $45 \pm 32$  years and a Weibull median probability interval of 40 years. Regarding the 8  
 318 major fires (>25% of samples with fire-scars), all occurred before 1943, except the one of 2000.

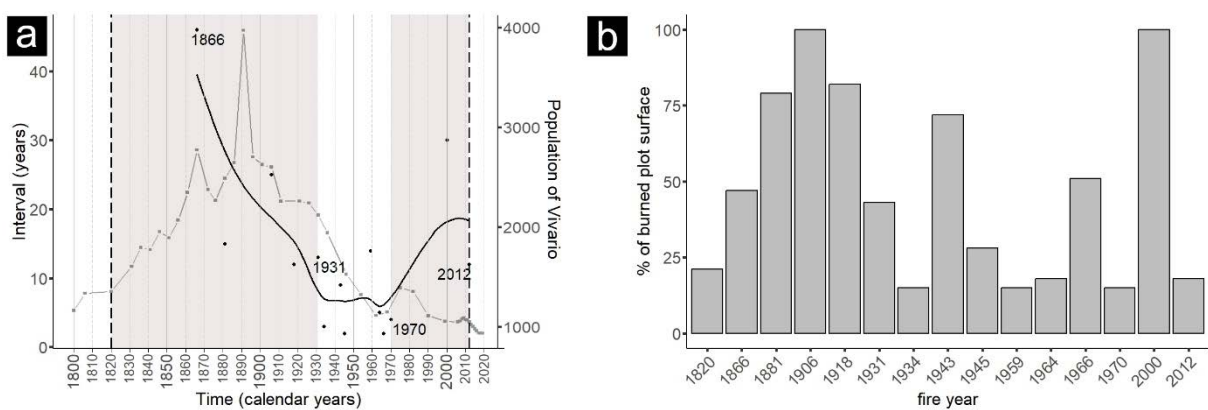
319

320 **Table 3.** Fire return intervals (FI) per plot and for the whole study site (Vizzavona): total  
 321 number of fire intervals, MFI, median FI and Weibull median, minimum and maximum values  
 322 per plot and for the whole study area. The calculation of FI is bounded at 2012 (last fire date  
 323 inventoried) because the period between 2012 and the sampling date (2021) is not a fire interval.  
 324 “Major fires” refer to fire events scarring at least 25% of samples. Rule for brackets: ]1931-  
 325 1970], means 1931 is not included in the period, and 1970 is included.

| Plots and site                     | Fire-return interval (FI, years) |                 |        |         |          |          |
|------------------------------------|----------------------------------|-----------------|--------|---------|----------|----------|
|                                    | Intervals                        | Mean            | Median | Weibull | Min      | Max      |
|                                    | no ( <i>n</i> )                  | ( $\pm$ sd)     |        | median  | interval | interval |
| VZ01                               | 4                                | 29.8 $\pm$ 26.8 | 19.0   | 25.4    | 12       | 69       |
| VZ02                               | 6                                | 13.7 $\pm$ 8.9  | 12.0   | 12.5    | 3        | 30       |
| VZ03                               | 6                                | 22.3 $\pm$ 16.7 | 14.5   | 20.2    | 12       | 55       |
| VZ04                               | 6                                | 24.3 $\pm$ 10.0 | 24.0   | 24.2    | 12       | 37       |
| VZ05                               | 5                                | 23.8 $\pm$ 8.6  | 25.0   | 23.8    | 12       | 36       |
| VZ06                               | 3                                | 60.0 $\pm$ 24.6 | 57.0   | 60.2    | 37       | 86       |
| Vizzavona (whole site, all fires)  | 14                               | 13.7 $\pm$ 12.5 | 12.0   | 10.7    | 2        | 46       |
| [1820-1931] (112 yrs) $c=1.89$     | 5                                | 22.2 $\pm$ 14.3 | 15.0   | 20.8    | 12       | 46       |
| ]1931-1970] (39 yrs) $c=1.48$      | 7                                | 5.6 $\pm$ 4.4   | 4.0    | 4.9     | 2        | 14       |
| ]1970-2012] (32 yrs) $c=n/a$       | 2                                | n/a             | n/a    | n/a     | 12       | 30       |
| [1820-2012] (major fires) $c=1.64$ | 7                                | 25.7 $\pm$ 18.5 | 15.0   | 23.2    | 12       | 57       |

326 The FI trend shows that three significant fire periods occurred over the past 202 years (figure  
 327 3a): [1820-1931], [1931-1970] and [1970-2012]. Two of these periods: [1820-1931] ( $n = 5$   
 328 intervals), [1931-1970] ( $n = 7$ ) were statistically different (Wilcoxon test,  $p = 0.015$ ). The MFI  
 329 for the period [1820-1931] was  $22 \pm 14$  years (Weibull median = 21 years, min = 12, max = 46  
 330 years), MFI for the period 1931-1970 was  $6 \pm 4$  years (Weibull median of 5 years, min interval  
 331 = 2 years, max interval = 14 years). For the last period 1970-2012, FI values could not be  
 332 calculated as it did not contain enough fire intervals ( $n = 2$ ). The  $c$  parameter inferred from  
 333 Weibull calculus indicates that it was  $1.89 \pm 0.63$  (unitless) for [1820-1931], and  $1.48 \pm 0.42$  for  
 334 1931-1970. Like the MFI for [1970-2021], the  $c$  parameter could not be calculated. Over the  
 335 whole period, [1820-2021], the  $c$  parameter was  $1.18 \pm 0.24$ . Both  $c$  values for first and second  
 336 period indicated that the flammability increased over time, but this increase was more important  
 337 for the first period (1820-1931) characterized by longer FI (Table 3). We also tested if the end  
 338 of the second world war in 1945 could be a tipping point. We found that fire frequencies were  
 339 not different before and after this year in the Vizzavona forest, i.e., MFI  $16 \pm 14$  yrs versus  $11$   
 340  $\pm 10$  yrs (Wilcoxon test:  $p = 0.65$ ).

341



342

343 **Figure 3.** (a) Fire interval duration plotted against fire years. Red line is the local regression  
 344 (also known as Loess method), averaging interval duration variability. It is a non-parametric  
 345 regression approach performing least squares regression based on a span of 0.75. Background

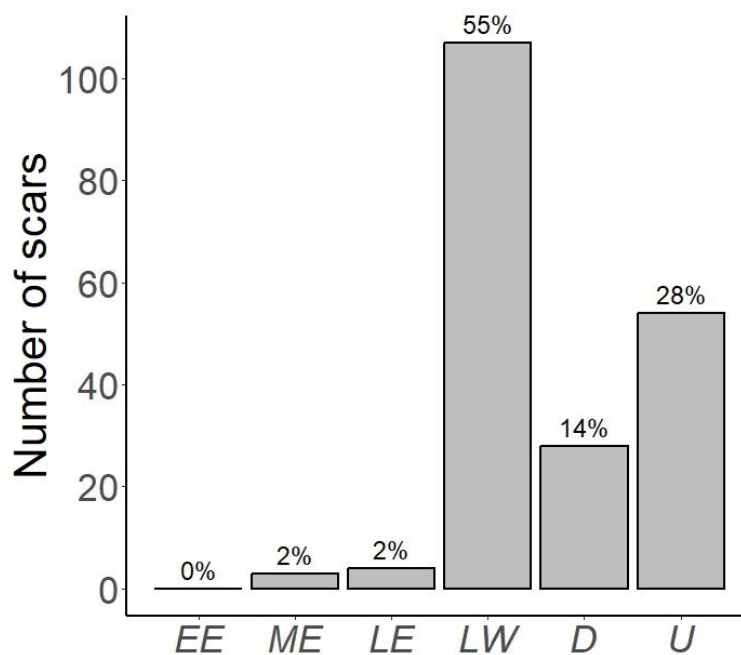
346 shading distinguishes the period defined by a type of duration interval variation (Wilcoxon test,  
 347  $p = 0.015$ ): tipping points of FI are 1931 and 1970. Vertical black dashed lines represent the  
 348 study temporal boundaries [1820-2012]. **(b)** Percentage of burned areas per fire year. *(figure in*  
 349 *grey scale)*

350

### 351 3.3 Fire season

352 Fire season could be identified on 72% of the fire scars, i.e., 142 out of 196. We found that  
 353 71% of scars were formed during latewood (55%), late earlywood (2%) or the dormant season  
 354 (14%), i.e., during the summer to autumn seasons (Figure 4). We identified 2% of scars in mid-  
 355 earlywood and no scars in earlywood (dataset available in Table S1).

356



357

358 **Figure 4.** Fire seasonality summary showing the positions of scars in the tree-rings. EE: early  
 359 earlywood; ME: middle earlywood; LE: late earlywood; LW: latewood; D: dormant period; U:  
 360 undetermined. *(figure in grey scale)*

361

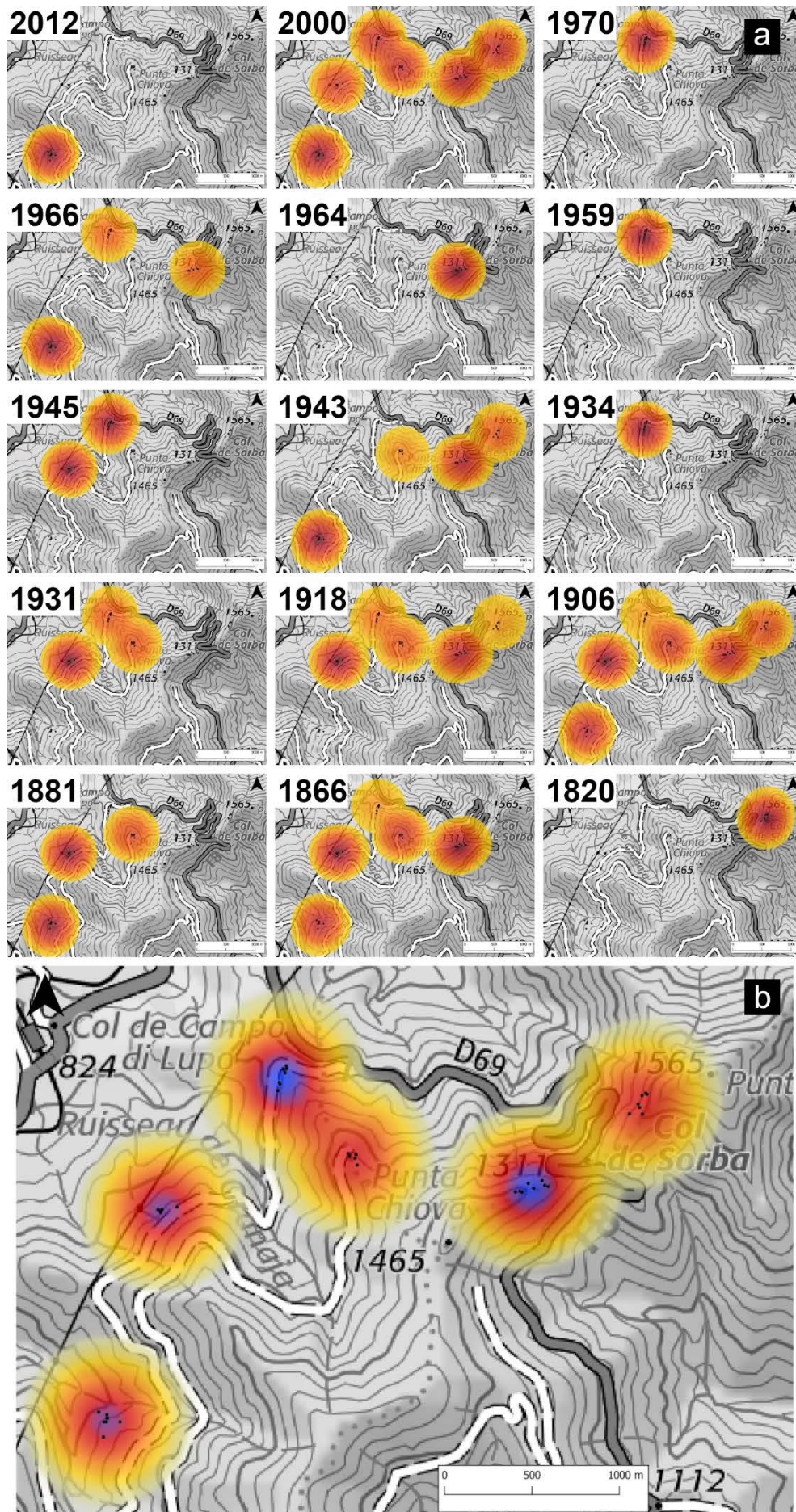
362 **3.4 Fire extent**

363 Kriging-based reconstructed areas for each of the 15 fire years recorded (Figure 5a) shows  
364 that in the case of major fires, probability densities of buffers were connected because a large  
365 part of the area experienced a common fire year, whereas in the case of minor fires, one or a  
366 few plots were affected. We also calculated the percentage of burned surface over total sampled  
367 area burned by fire year (Figure 3b; values in Table S2). However, the oldest fire of 1820 was  
368 only encountered in plot VZ06; because trees were not yet recruited in other plots, it is not  
369 possible to determine if the 1820-fire was large enough to affect other plots. Therefore, the area  
370 of the 1820-fire is a minimum area and must be considered with caution.

371 When we consider burned surfaces, we observe a difference between the [1866-1931] and  
372 ]1931-1970] periods. All fires between 1866 and 1931 burned at least 50% of the whole area,  
373 but after 1931, only three out of nine fires burned more than 50% of the sampled area. The  
374 difference is significant between [1866-1931] ( $n = 5, 70 \pm 24\%$  of the sampled area) and ]1931-  
375 1970] ( $n = 7, 31 \pm 22\%$ ) periods (Wilcoxon test,  $p = 0.03$ ) but not between [1866-1931] and  
376 ]1931-2012[ ( $n = 9, 38 \pm 29\%$ ) periods ( $p = 0.07$ ).

377





379 **Figure 5.** (a) Spatial pattern of all 15 recorded fires. Black dots represent cross dated samples  
380 and red-to-yellow chart indicates kriged fire areas. Densities of probabilities of fire occurrence  
381 in the past fire regime based on the number of scarred trees are displayed according to a red  
382 gradient to yellow chart (the deeper the red, the higher the probability); (b) probability density  
383 function integrated for all 15 fires over the past 202 years (kriging), from yellow (lower  
384 probabilities) to blue (higher probability). Black dots represent dated samples. *(figure in color)*

385

386 Based on the merging of all the 15 fire years and the probability density assessment, it appears  
387 that two main locations burned more frequently in the past (Figure 5b): first the VZ01 area  
388 corresponding to a slope exposed to northwest and second, in the east, the VZ05 area, in the  
389 northwest of the Sorba Pass, on the top of a talweg. The southwestern part of the study area  
390 (plots VZ03 and VZ04) is an area where fewer past fires burned, even though the 2000 fire  
391 spread there, but at lower severity. From personal observations, this southwestern part is  
392 intermingled by small stream (grey dashed line on Figure 5b), and a few beeches (*F. sylvatica*,  
393 less flammable species).

394

395

#### 396 **4. Discussion**

397 Like other *P. nigra* forests in the Mediterranean basin, the Corsican black pine forest of  
398 Vizzavona was frequently subject to fire events since the 17<sup>th</sup> century (Figure 2). In Greece,  
399 oldest evidence of fire scars was dated of 14<sup>th</sup>c. (Touchan et al., 2012), whereas in Anatolia  
400 they were from 16<sup>th</sup>c. (Sahan et al., 2022). However, the established variability in frequency  
401 and severity at Vizzavona covers the last 202 years, from 1820 to 2012, i.e., first and last events  
402 (Table 4). Wildfire regimes have changed in frequency at least twice since 1820. Finally, the  
403 most recent fire in Vizzavona, in 2000, was much more severe than all the previously recorded

404 fires that were characterized by numerous surviving scarred trees. This knowledge of fire  
 405 regimes is useful for land and forest managers, whether it is to plan fire control policies  
 406 (Alcasena et al., 2019) or in ecosystem management that bases sustainable forest management  
 407 on natural disturbance regimes through Nature-Based Solution processes (Gauthier et al.,  
 408 2009).

409 **Table 4.** Synthesis of fire regimes in natural black pine forests in the Mediterranean basin,  
 410 inferred from fire-scars and tree-ring analyses; studies are presented from west to east; fire  
 411 frequency was calculated only on major fires, which are those that scarred 25% of trees, over  
 412 the 19<sup>th</sup>, 20<sup>th</sup> and 21<sup>st</sup> centuries that is the comparable covered period of all studies.

| Country           | Fire year |      | Fire years number |       | Frequency of major fires |                 |                          | Reference                 |
|-------------------|-----------|------|-------------------|-------|--------------------------|-----------------|--------------------------|---------------------------|
|                   | First     | Last | All               | Major | Period for frequency     | Number of years | Fire.years <sup>-1</sup> |                           |
| Spain             | 1834      | 2003 | 11                | n/a   | 1834-2005                | 171             | 0.064                    | Fulé et al., 2008         |
| Corsica           | 1684      | 2012 | 15                | 8     | 1820-2012                | 193             | 0.041                    | Present study             |
| Corsica           | 1800      | 2000 | 6                 | n/a   | -                        | -               | -                        | Szymczak et al., 2020     |
| Greece            | 1309      | 1891 | 16                | n/a   | -                        | -               | -                        | Touchan et al., 2012      |
| Greece            | 1801      | 2007 | 38                | 11    | 1845-2007                | 165             | 0.067                    | Cristopoulou et al., 2013 |
| Anatolia (Turkey) | 1726      | 2005 | 88                | 12    | 1800-2005                | 205             | 0.059                    | Sahan et al., 2022        |

413

#### 414 **4.1 A 202-year chronology with changes in fire frequency**

415 The Corsican chronology cover 202 years, similar in coverage with the studies in southern  
 416 Greece (Christopoulou et al. 2013) and eastern Spain (Fulé et al., 2008). The only longer  
 417 chronology is the one in Anatolia with 553 years (Sahan et al., 2022). In total, we found 15 fire  
 418 years in 193 years, including 8 major fires that result a frequency of 4.1 major fires per 100  
 419 years (Table 4). These values are little lower than those found elsewhere in the Mediterranean  
 420 basin since the 19<sup>th</sup> century: 5.9 fires.100 yrs<sup>-1</sup> in Anatolia, 6.7 fires.100 yrs<sup>-1</sup> in Greece; in  
 421 Spain, 6.4 fires.100 yrs<sup>-1</sup> is also close to the general trend if, in this case, we consider all fire



422 events and not major fires only (Table 4). The comparison of fire intervals with the other studies  
423 in Corsica (Szymczak et al., 2020) or Greece (Touchan et al., 2012) was not possible as they  
424 did not explore this aspect in depth, since they had a limited number of sampled trees, or only  
425 one scar per fire. The Mediterranean-wide results correspond to an average frequency of one  
426 major fire every 18 years in black pine forests since the beginning of 19<sup>th</sup> c., meaning that the  
427 overall mean frequency has been high during the past centuries.

428 However, the fire frequency changed twice at Vizzavona, first during the 1930's and second  
429 after 1970 (Figure 3a). Between 1931 and 1970, the frequency was high, characterized by a  
430 short MFI of  $6 \pm 4$  years [2-14 years], while it was  $22 \pm 14$  from 1820 to 1930 (Table 3). In  
431 Anatolia, the fire frequency has also changed twice over the last 200 years, first around 1852  
432 corresponding to an increase in frequency and then in 1934 with a drop in frequency (Sahan et  
433 al., 2022). In Spain, the frequency changed four times (Fulé et al., 2008). Finally, in southern  
434 Greece, the trend is less obvious; the 100-year long period before 1945 had lower frequency  
435 and the period since 1945 had an increase in frequency. The years after 1853 seemed notable  
436 both in Anatolia and Spain, corresponding to a brief period of increase in frequency. It partially  
437 matched increasing frequencies in Corsica (Figure 3a) between 1820 and 1931. This year of  
438 1931 characterized a tipping point in our study as frequency increased from 1820 to this date  
439 (Figure 3a). During the 1930's, this trend of frequency was similar in Spain (Fulé et al., 2008)  
440 but is the reverse in Anatolia where it corresponded to a drop in frequency (Sahan et al., 2022).  
441 These substantial differences in timing of increasing/decreasing frequencies between studies  
442 mean that local trends cannot be upscaled to the entire Mediterranean basin; each trajectory has  
443 local drivers, because of site-specific variability (altitude, average precipitation, pastoralism,  
444 etc.) and local fire suppression policies (timing of initiation of fire suppression during the 19<sup>th</sup>  
445 c. and level of restrictions of laws).

## 446 **4.2 Potential drivers**

447 A common pattern corresponds with the Second World War (WW2): 1943 in Corsica  
448 corresponded to severe fights the 9<sup>th</sup> September and the 4<sup>th</sup> October between the German forces  
449 and the Allied forces that led to the bombing of forests by German army to cover their retreat  
450 and as an act of retaliation against Corsican resistors (Ministry of Armed Forces, France:  
451 [www.cheminsdememoire.gouv.fr/fr/la-liberation-de-la-corse-9-septembre-4-octobre-1943](http://www.cheminsdememoire.gouv.fr/fr/la-liberation-de-la-corse-9-septembre-4-octobre-1943)).  
452 Similarly, in southern Greece, fire events occurred at the time of multiple battles in 1944 and  
453 1945, burning respectively 38% of samples during the first year and 49% of samples during the  
454 second year (Christopoulou et al., 2013).

455 After the WW2, the population began to drop in Corsica (Figure S5). The village of Ghisoni  
456 (figure 1a) followed this demographic trend, while the village of Vivario (figure 1a) followed  
457 a different trajectory as population started to fall earlier, during the 1900's (Figure S5). The  
458 timing of these two demographic decreases was different and did not coincide with change in  
459 fire frequency at Vizzavona. Furthermore, the fire frequency was not different before and after  
460 1945 in the Vizzavona forest. This indicates that the WW2 did not change the fire frequency,  
461 and 1945 was not a tipping point. However, out of the 8 major fires, 7 happened before 1945,  
462 while only one major fire occurred after, i.e., 2000. According to Gilbert (1989), abandonment  
463 of farming lands started around 1920's-1930's and ended around the 1950's. First,  
464 abandonment of farming lands led to an increase in slash-and-burn practice to increase pastoral  
465 resources. Second, once abandonment of farming was definitely established, fire numbers  
466 decreased followed by a biomass accumulation. Thus, the weight of drivers changed between  
467 the first and second part of the 20<sup>th</sup>c.

468 The Vizzavona area is a key socio-economic area in Corsica. The Sorba pass connects the  
469 center to the southeast of Corsica, whereas the Vizzavona pass connect the northeast to the  
470 southwest of the island (Figure 1). Although local population decreased, the usage of the  
471 Vizzavona area for socio-economic purposes has remains significant, and provides a source of

472 ignition. A significant example of risk linked to the traffic is the 1970 fire which is well  
473 documented: the fire started from the roadside and spread toward the top of the slope through  
474 a talweg. Because Sorba and Vizzavona passes are important traffic points, this makes this area  
475 potentially sensitive to social-made fires.

### 476 **4.3 A high fire frequency regime**

477 Our results and those from Greece, Anatolia and Spain (Sahan et al., 2022, Christopoulou et  
478 al., 2013, Fulé et al., 2008) reveal a regime of high frequency in black pine forests whatever the  
479 country, their geographical location and cultural habits. In Vizzavona, considering all fires, the  
480 mean fire interval of 14 years corresponds to a high fire frequency (*sensu* Sugihara et al., 2006),  
481 with mainly surface fires. This MFI was lower than the ones from other studies: 23 years (Sahan  
482 et al., 2022), and 30 years (Christopoulou et al., 2013). However, considering only major fire  
483 years at Vizzavona, we obtained a MFI of 26 years, which remains in the category of high fire  
484 frequency. Plot number VZ06 differs from the others as the MFI is 60 years which correspond  
485 to a middle frequency.

486 At Vizzavona, the frequency changed twice around 1931 (increase) and 1970 (decrease),  
487 indicating that within a short period of two centuries, there was substantial variability.  
488 Interestingly, the data of human demography (Figure S5), show that 1931 corresponded to the  
489 start of a second drop of the Vivario population (first was in 1906), ending in 1962.  
490 Demographic censuses of 1962 and 1968 constituted the lowest inhabitant numbers since 1800  
491 and before the third drop in population around 2010.

492 Despite the different nature of samples and data compared to dendrochronology, palynological  
493 study can be complementary to understanding fire history (Clark, 1990). Paleoecological study  
494 on the temporal variability of fire in Corsica using sedimentary charcoal and historical  
495 documents (Camarero et al., 2018) was at millennial scale with a 20-year resolution (Leys et

496 al., 2014). Results showed two maxima of fire frequency during the last 4500 years, attaining  
497 0.012 fires yr<sup>-1</sup> (1.2 fires 100 yrs<sup>-1</sup>; MFI of about 80 yrs). In total, the reconstructed MFI over  
498 the Holocene (12,000 years) varied between 30 and 490 years (Leys et al., 2014). These larger  
499 values might correspond to major fires knowing that charcoal peaks corresponded mainly to  
500 large and severe fires and did not probably capture low severity and small fires, which were  
501 well recorded in the present study. Further, the Leys et al study (2014) was based on a  
502 climatologically wetter area in western Corsica, which could explain the longer FI. The current  
503 Vizzavona study site is on the eastern side of the Corsican mountain range, and thus drier  
504 (leeward slopes, rain-shadow effect).

505 Flammability increased over time in both analysis periods before and after 1931 as shown by  
506 the *c* parameter Weibull values of 1.89 (1820-1931) and 1.48 (1931-1970). This result means  
507 that burning hazard is dependent on processes that happened between fires and not only drivers  
508 during the fire year. The reduced fire regime during the 20<sup>th</sup> century and the long gap since the  
509 previous fire could have contributed to the severity of the 2000 fire through allowing fuel to  
510 accumulate. Such a pattern happened in Greece (Christopoulou et al., 2013), where the longest  
511 interval was reported between 1973 and 2007 (34 years), resulting in fuel accumulation  
512 followed in 2007 by a severe crown fire. The policy of suppression of traditional fires in France  
513 since the king Louis XIV (AD 1669), including in Corsica since the French Revolution, was  
514 strengthened first during the 1920's (Chalvet, 2016) and later during the 1980's (Alexandrian,  
515 2008). This latest fire suppression policy has probably contributed to the large fire of 2000 that  
516 was expected by increasing the time since last fire combined with a severe drought (Piñol et al.,  
517 2007; Evin et al., 2018).

#### 518 **4.4 No change in fire season for 202 years**

519 The majority of scars were formed in latewood and adjacent ring positions corresponding to  
520 summer and the first weeks of autumn (Häusser et al., 2021), which is the driest period of the

521 year for Mediterranean climate (Ozturk et al., 2015). These results are similar to other studies  
522 (Fulé et al., 2008; Touchan et al., 2012; Christoupoulou et al., 2013; Sahan et al., 2022), which  
523 revealed that the majority of fire scars occurred mostly within latewood and during dormant  
524 season. Further, ring position of scars were similar through the whole studied period, indicating  
525 that the fire season was steady through fire years. Notably, this was also the season of the latest  
526 major fire in 2000 which happened on 27<sup>th</sup> of August.

## 527 **5. Fire management and conclusion**

528 To sum-up, our 202 year-long history of wildfire regime in a black pine forest of central  
529 Corsica provides rational elements for improving forest management. Fire frequency changed  
530 twice since 1820, first around 1931 and then after 1970, and peaked significantly between 1931  
531 and 1970 with short intervals. The fire season was steady, but most larger fires (7 out of 8)  
532 occurred before 1945. However, the largest and likely most severe ever recorded has occurred  
533 very recently in August 2000.

534 The forest was subject to frequent fires with ignition sources sometimes independent from  
535 drought; the relationships with human activities remain to explain, excepted the 1943 fire that  
536 is iconic of an anthropogenic event, the Second World War. Regarding the importance of fire  
537 frequency before 1970, and the highest number of major fires before 1945, human pressures  
538 could partly explain these changes in fire size and frequency. Indeed, forest uses decreased  
539 progressively throughout the 20<sup>th</sup>c. However, Vizzavona is a key socio-economic crossroad in  
540 Corsica since centuries until today. Generally speaking, the land use is linked with ignition: the  
541 higher the land use, the higher the ignition risk (Bowman et al., 2011; Moritz et al., 2014).

542 The synthetic mapping of fires (Figure 5b) suggests that topography and landforms probably  
543 control the fire spread at landscape scale in the black pine forest. A more fragmented landscape  
544 decreases the risk of severe fires. To define a management strategy, it is necessary to keep in  
545 mind that even though the main ignition source are land uses, drought episodes are currently

546 more frequent and longer fostering more flammability. Rare ignition can result in large fires,  
547 like in 2000. Further, the increasing time since last fire (Figure 3a) increases the fire hazard (*c*  
548 parameter), and the landscape homogeneity favors the spread of wildfires.

549 The fire regime of the 19<sup>th</sup> c. until 1930's that was about 80 years must be recover. It was  
550 characterized by low severity fires, probably surface fires, preventing fuel accumulation on the  
551 ground and improving seedbed for black pines by consuming litter and humus that contain  
552 abundant inhibiting components like polyphenols. By consuming fuel bed, such strategy should  
553 decrease the risk of large and severe fires. The hot and dry weather has only contributed to  
554 improve the fuel quality for burning. Sustainable forest management must consider low severity  
555 surface fire in the management of black pine forest, for instance based on prescribed burning.  
556 In such case, medium-sized pines (i.e. neither mature overstory trees nor regeneration) should  
557 be thinned to break up the fuel ladder and, a fuel break should be established around the area to  
558 be burned. Larger trees should mostly be unaffected by surface fires due to their insulating  
559 characteristics, such as trunk diameter and bark thickness, as well as crown height, which  
560 protects the black pine from damage (Fréjaville et al., 2018b; Ferrat et al., 2021).

561

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569

## 570 **Authors' contributions**

571 **Justin Badeau:** methodology, validation, formal analysis, investigation, writing - original draft,  
 572 visualization. **Frédéric Guibal:** methodology, validation, investigation, resources, writing – review &  
 573 editing. **Peter Z. Fulé:** conceptualization, methodology, validation, investigation, resources, writing –  
 574 review & editing, supervision, funding acquisition. **Sandrine Chauchard:** validation, investigation,  
 575 writing – review & editing, visualization. **Pasquale Moneglia:** writing – review & editing, project  
 576 administration, funding acquisition. **Christopher Carcaillet:** conceptualization, methodology,  
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## 578 **Declaration of Competing Interest**

579 The authors declare that none of them has an interest financial or personal which may be  
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581

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586

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