Modelling fire hazard in the southern Mediterranean fire rim (Bejaia region, northern Algeria)

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Abstract The southern rim of the Mediterranean Basin (MB) has a long fire history but fire hazard is poorly investigated in comparison to the northern rim. We built a fire database using MODIS data (2001–2015) for an area typical of the northern coastal Algeria (Bejaia region) in order to decipher the role of environmental and anthropic controls on the fire frequency and the area burnt. We found a high role of bioclimate, which controls the fuel dryness, ignitability, and biomass. Maximal fire frequency and burnt areas were recorded in northern sub-humid areas with high amounts of forests and shrublands, and fire was limited in the southern sub-arid area. Humans set most fires, and preferentially burn forests, shrublands, pastures, groves, and agricultural lands. The maximal fire frequency and burnt area occurs in wildland urban interfaces characterized by forest-shrublands mosaics with disseminated habitats. Fire activity is low to medium in rural-urban interfaces characterized by agropastoral areas with high habitat density and large habitat patches. Small to large crown fires occur in forests and shrublands, while small surface fires predominate in agropastoral areas and groves. Large fires (> 100 ha) are rare (10%) but contribute for ca. 50% to the total area burnt. These fire features are typical of many rural countries of the southern rim of the MB, and contrast with those on the northern rim. Based on this, we propose to improve the prevention, the detection, and the management of forest fires in the long term and to protect forests that host high biodiversity in Algeria.

Keywords Fuel limitation · Normalized difference vegetation index · Rural urban interfaces

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Introduction

The Mediterranean basin (MB) is a fire hotspot of the world with a long fire history (Keeley et al. 2012; Hantson et al. 2015). Indeed, the MB is a zone of convergence of many factors conducive to fire including a harsh and dry climate, a high and ancient density of humans who often use fire as a tool for cultivation or pastoralism or for many motives (Meddour-Sahar et al. 2013; González-Olabarria et al. 2015), and a variety of flammable vegetation fuels (Keeley et al. 2012). However, the southern rim of the Mediterranean basin (i.e., the Maghreb including Algeria, Morocco, and Tunisia)

has been much less studied than the northern rim which includes well-known and major fire hotspots (i.e., Portugal, Spain, Greece, or Italy). It is thus of importance to assess the features and the drivers of fire regime in the southern rim of the MB, which may differ from those of the northern rim due to socioeconomic and ecological contrasts (Pausas and Fernandez-Munoz 2012).

The fire regime across the MB results from complex interactions between many environmental and socioeconomic drivers (Chergui et al. 2017). On the northern rim, socioeconomic drivers have played a considerable role in changing fire regime along the recent decades (Moreira et al. 2011; Curt et al. 2016; Viedma et al. 2018). In particular, the increasing human pressure on ignition and the urban sprawl have increased fire activity in many places, while it has decreased where fire suppression is very active (Turco et al. 2016), and the ongoing climate changes promote more large fires (Turco et al. 2018; Ruffault et al. 2017). Due to the increasing fuel amount and continuity in many rural areas of southern Europe where traditional agriculture and pastoralism have collapsed (Moreira et al. 2011), the fire regime on the northern rim has often shifted from small fires limited by low fuel amount to drought-driven fires due to the ongoing climate changes (Pausas and Fernandez-Munoz 2012). Such changes have not been documented on the southern rim, and rural activities presumably remain predominant in many regions of the southern rim, including Algeria (FAO 2018).

Northern Algeria covers half of the length of the Mediterranean coastline of Maghreb, and it is mostly characterized by a rural lifestyle with many agropastoral activities. Forests cover only 0.82% of the total surface of Algeria (2,000,000 km^2), but they are mostly concentrated in the coastal region (FAO 2018). They provide a wide range of ecosystems services and they harbor many species, ecosystems, and protected areas with high biodiversity value (WWF 2018). However, the ongoing climate changes, the overgrazing and desertification, and wildfires now threaten forests. Fire is present in Algeria but only within this coastal strip of 210,000 km^{-2}, which is large of only 250 km. This area corresponds to an east-west double mountain barrier of the Tellian Atlas and the high plains that border it. A strong north-south gradient in bioclimate and landscapes exists, as desertification degrades the vegetation and the steppes which are present under the arid climate bordering the Sahara desert (Benslimane et al. 2008). Knowledge on wildfire issues remains limited in northern Algeria. The main studies have given an overview of fire activity, then focused on the human causes for ignitions in the center of Algeria (Meddour-Sahar 2014; Meddour-Sahar et al. 2013; Meddour-Sahar 2015). Forest fire databases exist but not on a long and continuous period, but are considered as insufficient by the WWF Report (WWF 2001) in regard to their conservation value.

In this study, we compiled a fire database using MODIS data from 2001 to 2015 for the Bejaia region (northeast Algeria), together with a georeferenced database gathering the environmental and anthropogenic drivers that may control the occurrence of fire. We analyzed the main features and trends of the fire occurrence in Bejaia, which is representative of the coastal northern Algeria. We built a statistical model of fire hazard based on fire frequency and burnt areas in order to understand the part played by socioeconomic versus environmental factors, and to assess the most hazardous areas. We especially investigated if fuel amount may be limitative in the southern part of the study area. Our final objective is to explain the territorial fire hazard, and leverage it through fire risk management, prevention, and long-term mitigation.

Materials and methods

The approach of this study is displayed in Fig. 1.

Study area

The present study was conducted in the Bejaia region, which spreads over 3268 km^2 in the northeastern coastal Algeria (36° 15′ − 36° 54′ northern parallels, and 4° 27′ − 5° 33′ eastern meridians). This study area is of interest because it is highly representative of the remote rural and urbanized regions located in the northeastern Algeria (Fig. 2). Bejaia is classified as one of the main fire hotspots in Algeria (Meddour-Sahar 2014). Indeed, it has environmental and anthropogenic features conducive to fire occurrence around the MB (Pausas and Fernandez-Munoz 2012; Keeley et al. 2012), including high coverage by forests and shrublands, high agropastoral activity, high fire weather danger, and high human pressure on ignitions.

The forest heritage of Bejaia is one of the richest in Algeria with an area of 122,500 ha of forests including 38% of the total forest surface and the main species.

Fig. 1 Flow chart of the overall methodology used in the present to identify fire hazard in the Bejaia Region, north-eastern Algeria. MODIS, moderate-resolution imaging spectroradiometer, ASTER, advanced spaceborne thermal emission and reflection radiometer, DEM, digital elevation model
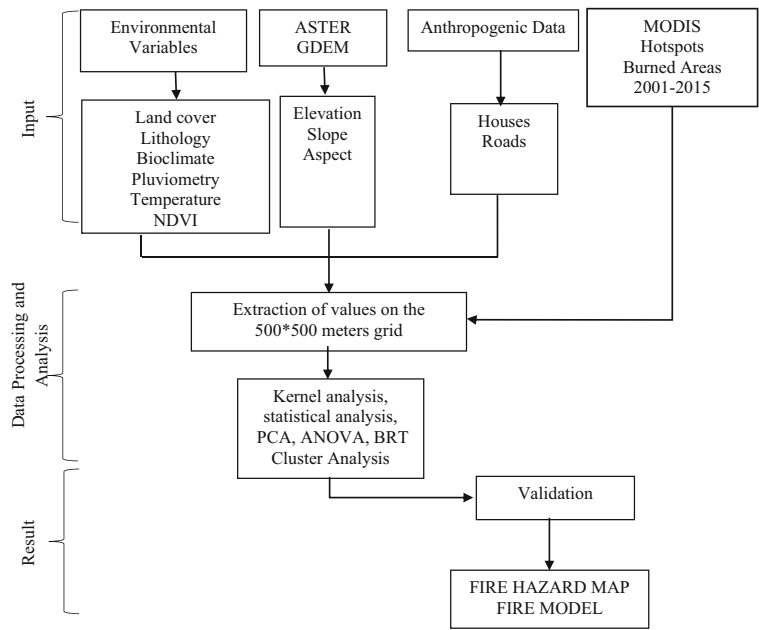
This includes the cork oak (*Quercus suber* L.) which occupies 41,774 ha of forest area, the Zen oak (*Quercus canariensis*, 6611 ha), the green oak (*Quercus ilex*, 735 ha), the Aleppo pine (*Pinus halepensis*, 10,598 ha), and the cedar (*Cedrus atlantica*, 1292 ha). In addition, the Bejaia region is a hotspot for biodiversity. It notably includes biosphere reserve of the Gouraya National Park extending over a 2080 hectares area.
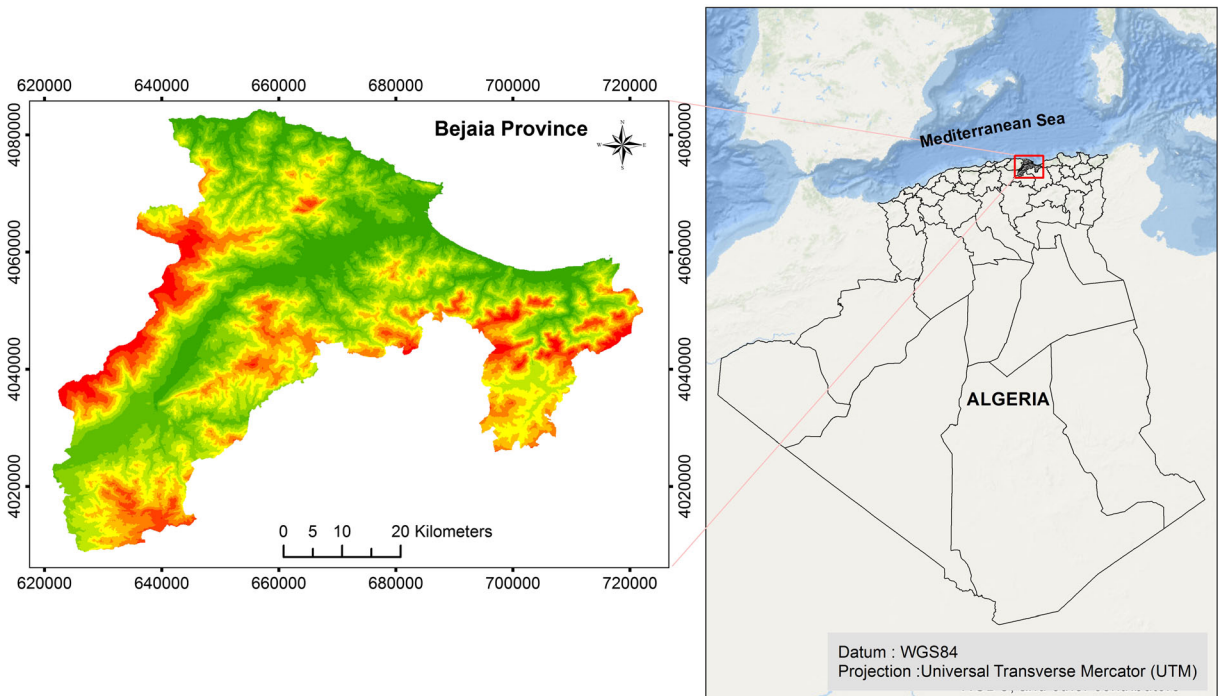

Fig. 2 Location of the study area, Bejaia Region, northeastern Algeria. Elevation data from the Shuttle Radar Topography Mission

MODIS fire hotspots and burned area

Algeria has long records of fire history but fires from different sources (Meddour-Sahar 2015). Therefore, many data and information on wildfires are still missing or incomplete, in a comparable manner to Tunisia (Belhadj-Khedher et al. 2018). The Forest Directorate (DGF) fire database records forest fires since decades but they are not always registered or located in a relevant and steady manner. In particular, the DGF does not systematically map the fire contours, and only maps some fires in the DGF forests while many forest fires also burn the neighboring grasslands or pastures. In comparison to the satellite-based fire data (MODIS), the DGF fires displayed many discrepancies, notably as concerns size and location. Consequently, we used two of the MODIS fire products at 1-km and 500-m spatial resolution for the 2001–2015 period (Table 1). First, we used the fire hotspots MCD14ML series processed in the Collection 5 temporal thermal analysis active fire dataset with data from both the TERRA and AQUA satellite (NASA-FIRMS 2015). This daily set ranging from January 2001 to December 2015 was downloaded from the FIRMS website (Fire Information for Resource Management System: Archiving and Distributing MODIS Active Fire Data, Collection 5; Davies et al. 2009). The fire hotspots provide point-data on the active fires burning while the satellites pass. In total, MODIS recorded 3091 hatching points during this period. Each fire point has its own metadata for location, hatch time, day, month, and year. The detection confidence level of points is $72 \pm 26\%$. It indicates the quality of individual fire pixels (varying from 0 to 100%) and it is useful in excluding false positive occurrences of fire. The 16% of points having a confidence level lower than 50% were randomly distributed in across years, seasons, and the study area. Second, we used the burned area product, i.e., the MODIS MCD64A1 Version 6 Terra and Aqua Global 500-m grid monthly product containing the burnt area and quality per pixel information

(Table 1). The quality of data was checked and we kept only data with the higher confidence level. We downloaded the data from the NASA website (https://ladsweb.modaps.eosdis.nasa.gov). Using the kernel density estimation under R with the MODIS fire hotspots, we determined where the fire hotspots were located in the Bejaia region, that is to say, the areas where fire is abundant and spatially concentrated. The median distance between points was 338 ± 305 m. We used a bandwidth (h) smoothing parameter of 845 m corresponding to 2.5 times the weighted median of distances.

Vegetation and land use data

We used the land use and land cover types from the National Office of Studies for Rural Development (BNEDER 2008), which is based on high-resolution Landsat TM satellite images and a supervised classification. It classifies land cover types into the main categories (forests, agriculture, pastures, aso). Coastal Algeria displays high bioclimatic gradients. This may affect the fuel biomass present in each cover type and, in turn, their likelihood to burn. In order to assess the fuel biomass for each land cover type, we used the normalized difference vegetation index (NDVI) from 2001 to 2015, with 1-km spatial resolution. The NDVI has been widely used worldwide for estimating the fraction of photosynthetically active radiation (FPAR) absorbed by the canopy. It fits well for estimating forest productivity and dieback in Mediterranean ecosystems (Ogaya et al., 2015). These data are derived from observations recorded by the MODIS TERRA sensor (MOD13; https://cmr.earthdata.nasa.gov). MODIS monthly NDVI composite data are generated using the 16-day vegetation index aggregated using a weighted average. As most fires occur during summer, we computed the $NDVI_{summer}$ which accounts only for the June to October period.

The fire map with the MODIS fire hotspots and burned areas shows that fire is present only in a ca. 80-km strip along the Bejaia coastline (Fig. 3), suggesting

Table 1 Summary of the MODIS products for active fires, burned areas, and vegetation indices products

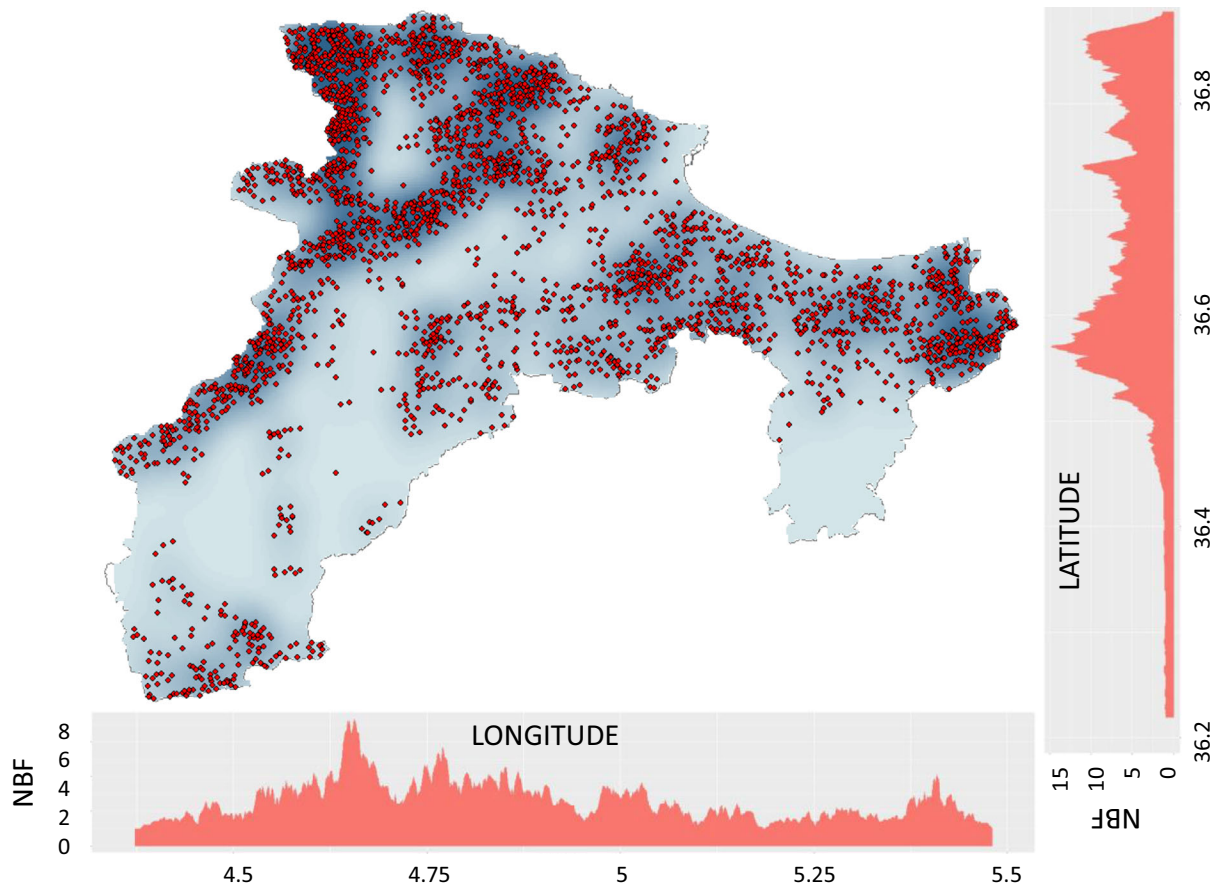| Product	Type	Source	Spatial resolution	Temporal resolution	Time coverage
MCD14ML	Hotspot fire location	MODIS Aqua and Terra	1000 m	Daily (Terra: day; Aqua: night)	2001–2015
MCD64A1	Burned area	MODIS Aqua and Terra	500 m	Monthly	2001–2015
MOD13A3	NDVI	MODIS Terra	1000 m	Monthly	2001–2015

Fig. 3 Location of the MODIS fire hotspots (red points) and kernel density (maximal density is in dark blue) in the Bejaia region (northern Algeria). The two cross-cutting red scales indicate the number of fires (NBF) for each value of latitude and of longitude. Labeled red points represent the total number of fire occurrences detected by MODIS sensor prior to spatial filtering (*n* = 3091) for the period from January 2001 to October 2015

that fire may be possible only under these conditions, and limited by the climatic conditions and by the subsequent amount of biomass at lower latitude. We investigated the variation of fire activity with latitude and longitude in the Bejaia region, and we calculated the minimum amount of rainfall necessary for fire to occur in the main land cover types. In addition, we estimated the NDVI value corresponding to this limit for each land cover type.

Bioclimatic data and fire danger indices

The climate in the Bejaia region is of the Mediterranean type, but it presents heterogeneity from one locality to another due to the orographic configuration of the territories. In addition, a strong latitudinal gradient exists from humid areas along the northern coast to semi-arid areas in the south, close to the desert. In this context, we

expected that the daily fire danger indices (i.e., the quantitative indices estimating of ignition, rate of spread, difficulty of control, and impact from weather variables); EUROFINET 2012) varied considerably across the study area. However, such daily weather database was not fully available in Algeria, and accurate wind speed data were notably missing. In consequence, we used a bioclimatic map established by National Hydric Resources Agency (A.N.R.H). It distinguished three main types of bioclimate: humid, sub-humid, and sub-arid. Each bioclimate has variants based on the temperature and the mean annual rainfall. A preliminary test indicated that these bioclimates fitted well the levels of fire activity in the Bejaia region. In order to get quantitative climatic data for characterizing each bioclimate, we used monthly cumulative datasets for rainfall and temperature, derived from CHELSA Climate Data high resolution from January 2001 to

December 2015 at 30 arc sec (~ 1 km) spatial resolution. These data were compared between bioclimates and subtypes of bioclimates using a one-way analysis of variance. The humid bioclimates had rainfall greater than 900 mm per year, sub-humid had rainfall ranging from 600 to 900 mm per year, and the semi-arid had low rainfall ranging from 400 to 600 mm per year and slightly higher temperatures ranging from 26 to 30 °C.

Topographic features

About 75% of the total area of the Bejaia region is made of remote mountain areas with steep slopes greater than 25%. The Soummam valley that separates the "Akfadou Gouraya" complex to the north and the Biban chain to the south. It appears as a narrow band sinuous 80 km long inside the region on a maximum width of 4 km around El Kseur. The coastal zone, more than 90 km long, alternating between rocky coves and sandy beaches, extends east from the mouth of Wadi Soummam to that of Oued Agrioun and west of Cape Carbon to the locality of Azaghar. Bejaia is crossed by several wadis formed by alluvial deposits of mountainous origin where Wadi Soummam, Djemâa, Agrioun, Zitoun, Oued Bousellam, and Amassin are the most important. The Bejaia region is thus a remote area in which topographic features may affect fire activity. The land cover types are linked for a part to topography, the aspect affects solar radiation and then fuel dryness, and the slope affects fire propagation. We downloaded a digital elevation model ASTER GDEM V2 imagery (30 m) from the NASA Earth data site. This allowed computing elevation, slope, and aspect on a 500 × 500 m grid. (Fig. A1)

Anthropogenic data and impact on ignitions

About 60% of the fire causes are still unknown in Algeria, but it is undoubted from the remaining (well-known) fraction that almost all ignitions are human-set (Meddour-Sahar et al. 2013) as in most of the MB (Curt et al. 2016). Humans play a major role in fire activity of the MB since they manage the land covers in the landscape, they burn them selectively, or because they cause unwanted ignitions. No georeferenced database on fire causes exist in Algeria, making difficult to attribute a given ignition to a specific cause. However, Meddour-Sahar et al. (2013, 2014, 2015) have stated that deliberate ignitions predominate in the fire-prone forests and shrublands in order to clear vegetation and burn the forest residues, to urbanize in the coastal areas, or to

political fires (i.e., ignited by the Algerian army to prevent terrorism). In agricultural lands and groves, humans ignite fires on purpose for clearing the vegetation and burning the residues of agriculture. Pastoral fires are also very common because the shepherds burn the pastures or the shrublands in order to favor the regrowth of grasses. In this study, we correlated and determined which land cover types were affected by fire, using the MODIS hospots and the burned areas. The human pressure on ignitions can also be estimated through surrogates like the density of habitations and of infrastructures, as most ignitions are close areas with high human presence in the MB (Viedma et al. 2018). We mapped the road network and the presence of habitations using Sentinel-2 images with a resolution of 10 m.We made a super-classified classification on the images, and then it was rectified manually under ArcGis. For this purpose, we made a proximity analysis which calculated the nearest distance between centroid of each fire ignition (MODIS hospots) and the houses or the roads, using the Arc Tools Box "Distance to." The precision is ca. 10 m.

Preparation and validation of the datasets

Fire hazard modelling used the MODIS fire hotspots and the burned areas as target variables and the set of 12 environmental and anthropic variables (Table 2) as explanative variables. All these data were georeferenced using ArcMap v.10.6 on a regular cell grid (raster) with a spatial resolution of 500 m using the ArcGis fishnet tool. The study area thus included a matrix of 12,877 cells. The number of cells with fire was 3091 (ca. 25% of the total number of cells), and the total number of non-fire cells was 9786 (ca. 75%).

Modelling fire hazard

First, we computed the basic features of fire activity using the MODIS hotspots and burned areas. This included the number of fires, their seasonal and interannual distribution, the distribution of burned areas values, and several indices that sum up the incidence of fires in the Bejaia region, such as the total area burned in reference to the total area of flammable land covers

The model of fire occurrence has been computed using the presence/absence of fire per pixel and the 12 environmental and anthropic variables (Fig. 1). First, we computed and principal component analysis (PCA) was used in order

Table 2 Description of the environmental and anthropic variables used in the data modelling procedure

Variables	Description	Data type	Source/method
MODIS fire Hotspots	The product includes fire occurrence location both day/night (2001–2015)	Point shape	National Aeronautics and Space Administration (NASA) (MCD14ML)
Land cover	Classes of land cover	Polygon shape	National Office of Studies for Rural Development. December 2008
Precipitation	Monthly precipitation (2001–2015) (mm)	Grid- continuous variable	CHELSA Climate
Temperature	Monthly temperature (2001–2015) (C°)	Grid- continuous variable	CHELSA Climate
Bioclimate	Bioclimatic zone	Polygon shape	Digitalized from rainfall map for Northern Algeria (ANRH, National Hydric Resources Agency, 1993).
Elevation (ALTI)	Elevation above sea level (m)	Grid- continuous variable	Digital elevation model (DEM) derived from the DEM (ASTER GDEM version 2)
Aspect	Slope aspect	Grid-ordinal variable	Derived from the DEM (ASTER GDEM version 2)
Slope	Slope angle (°)	Grid- continuous variable	Derived from the DEM (ASTER GDEM version 2)
Housing density	Cumulated area by houses (m)	Polygon shape	Derived from sentinel-2 satellite image
Roads	Cumulated length of roads (m)	Line shape	Derived from sentinel-2 satellite image
NDVI summer	Monthly standardized difference vegetation index (2001–2015)	Grid- continuous variable	Derived from MODIS Terra (MOD13A3)
Lithology	Lithological classes	Polygon shape	Digitalized from geological map of Bejaia (Geological Survey of Algeria 1977)

to test for correlation among variables (Fig. 4). Second, we modelled the presence/absence of fire using a boosted regression tree analysis (BRT) which are efficient machine-learning techniques (Elith et al. 2008) well suited for assessing how environmental or anthropogenic factors drive the different sizes of fires. It can enhance prediction in comparison to classical statistical methods such as logistic regression (Rodrigues and de la Riva 2014). BRTs model fire occurrence was based on using binary data (presence/absence). They explore environmental data without the restrictive assumptions of parametric statistics

(e.g., Aertsen et al. 2010; Curt et al. 2015), optimize the predictive performance (De'ath, 2007), are flexible and easy to interpret, and account for collinearity (Elith et al. 2008). The BRT model was built using the "gbm" *R* package (Ridgeway 2013). A training dataset (50% of the data) was used for building the model, then a second 50% to evaluate the accuracy of the classification. The number of trees was set to 20-fold cross-validation (Elith et al. 2018). The training data randomly selected for computing each tree was of 0.5, a learning rate of 0.005 which controls the learning speed of the algorithm, and a tree size
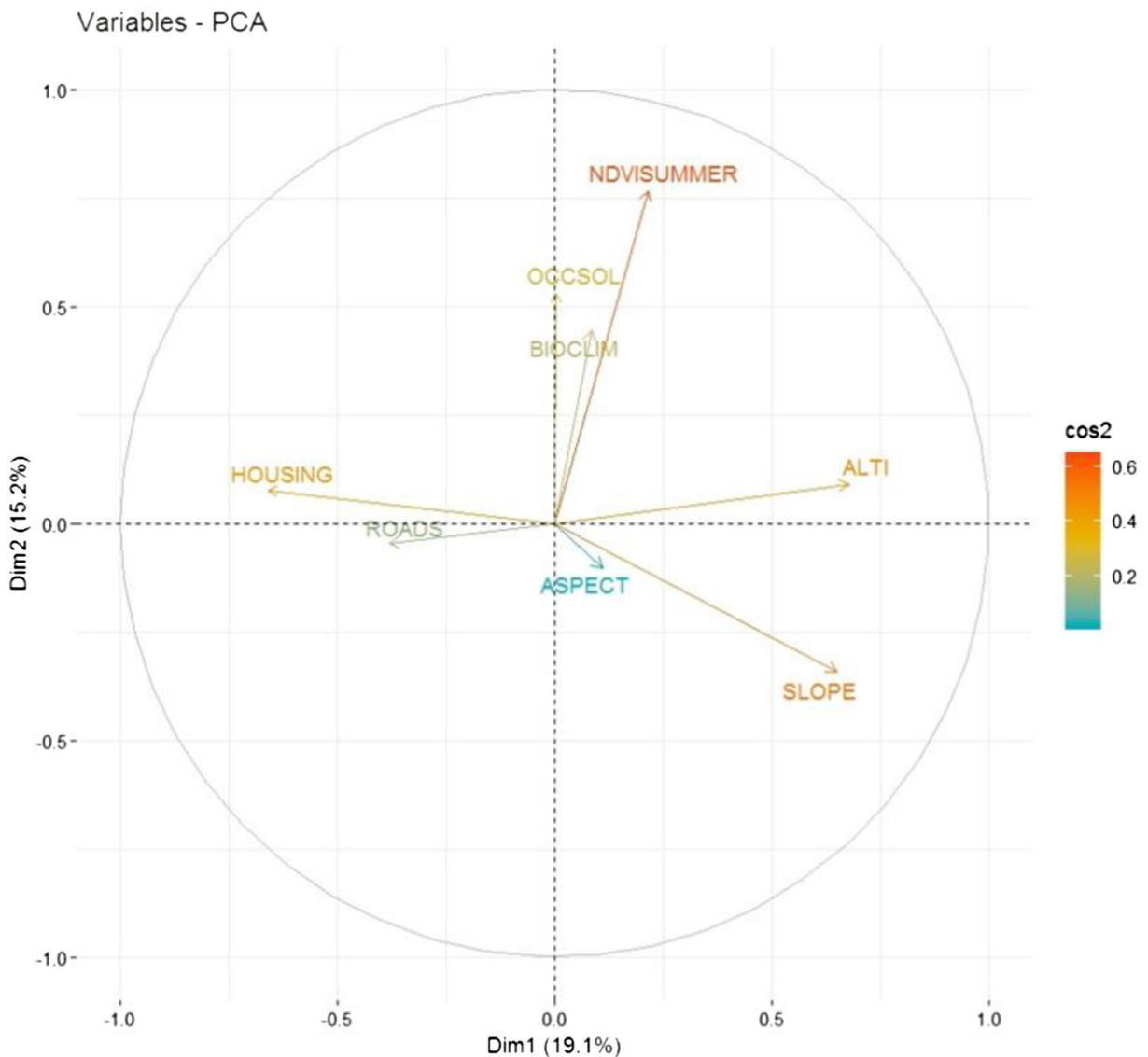

Fig. 4 Principal component analysis (PCA) for the main environmental and anthropogenic variables in Bejaia. The variables are described in Table 2

of 5. This resulted in a minimum of 3000 trees. The predictive performance of the model was assessed using the AUC (area under the receiving operator curve; Pearce and Ferrier 2000) and is considered moderately well for AUC 0.6 to 0.9 and excellent for AUC > 0.9.

We performed an additional test of prevalence using the MODIS burned areas in order to determine if the largest fires (> 100 ha) burned selectively certain land covers more or less than expected according to their total surface in the study area. For this purpose, we superposed the burned areas to the land cover map, and we extracted the burned area for each land cover type. The distribution of the burned areas for each land cover type ("observed") was compared to the distribution of simulated values (10,000 Monte Carlo replications) based on the real distribution of patches of the land cover type in the landscape. If the value "observed" is within the values given the thresholds of significance for the simulated distribution, it can be concluded that this given land cover type is burned. The index of prevalence indicates for a given land cover type if it is burned much lower (−1), non-significantly (0), or much higher (+1) than expected to the total surface.

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We also performed a cluster analysis dedicated to discriminate specific assemblages of environmental and anthropogenic variables (that is to say, some kind of landscape-bioclimate types) then test these clusters against fire activity. This analysis was performed using the main environmental and anthropic variables determined by the BRT analysis. These variables were clustered into landscape-bioclimates units using a *k*-means analysis under R with the stats R package v. 3.6.0.

Results

Features of fire regime

The fire regime of Bejaia is characterized by a high concentration of fires and of burned areas in summer: 95% of fires and 97% of burnt area occur from July to October (Fig. 5). The mean annual burned area varies strongly with some years especially high (Fig. 6); The mean annual fire season length is of 130 days, and it does not change significantly according to the land cover types which are almost all burned during summer. The monthly distribution of fire number is highly similar among land cover types. The days with summer fires

had significantly higher temperature and lower rainfall and air humidity than the non-fire summer days (Wilcoxon *p* value < 0.005; Fig. 7).

The fire size distribution is highly asymmetric with many small (< 10 ha) and medium fires (< 50 ha) and few large fires (> 100 ha; Fig. 8). The largest fires (> 100 ha) represent only 11% of the total number of fires but they account for 67% of the total area burnt from 2001 to 2015. Only one very large fire higher than 1000 ha has been recorded in the period studied (1231 ha).

Forests and shrublands fuels cover 36% of the Bejaia region. When accounting for all the land cover types, which are potentially, burnable (i.e., forests, shrublands, agricultural lands, pastures, and groves) and which are effectively burned, the total burnable area is 98% of the region. On average, 2.5% of forests and shrublands of the region are burned annually and 6.6% of all burnable fuels. This value is much higher than the mean value for northern Algeria (i.e., 0.85% according to Meddour-Sahar 2015) and those for the neighboring Tunisia (0.19%; Belhadj-Khedher et al. 2018). Consequently, the fire cycle necessary for burning an area equivalent to the Bejaia region is of 41 years. According to oral testimonies, surface fires are predominant in pastures and in agricultural lands and olive groves, whereas surface fires and crown fires coexist in forests and shrublands.

Vegetation fuels were burned selectively according to their intrinsic flammability but also to the human motives for setting fires, notably the agrosilvopastoral practices. The tests of fire prevalence for the different fuel types indicated clearly that the forests and shrublands were burned much more than expected according to their surface, and that they were frequently burned by large fires (Table 3). The agricultural lands and groves were burned frequently but with a predominance of small fires, and a very low probability of generating large fires. The pastures were moderately burned and with a balanced repartition of fire size (Table 3).

The model of fire hazard

The BRT analysis allowed predicting fire activity with a very high predictive performance and an AUC value = 0.92 (Fig. 9) and it fits very well the MODIS fire hotspots (Fig. 10 compared to Fig. 3). The 8% of errors were almost randomly distributed within the study area (data not shown). It showed that the occurrence of fire in the Bejaia region is firstly explained by bioclimate, with

Fig. 5 Monthly number of fires and burnt area (ha) in the Bejaia region for the 2001–2015 period, according to MODIS fire data. The vertical bars for the number of fires correspond to the standard error. BA is the burnt area, and NBF is the number of fires
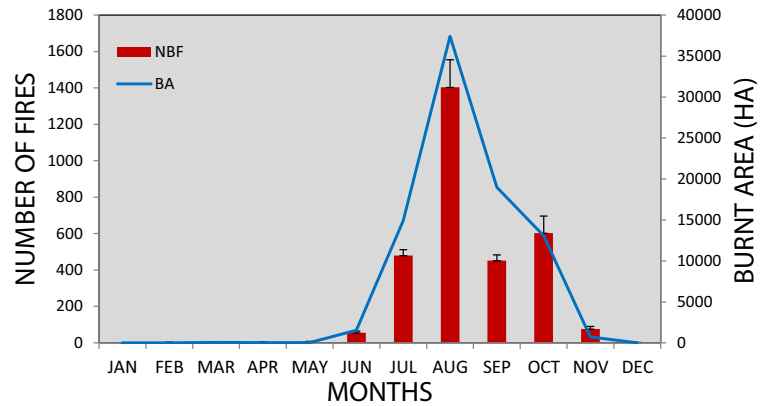
the humid bioclimatic types (1–3; Fig.11) regrouping 63% of the total number of MODIS fire hotspots and 85% of the total area burned. These humid bioclimates perfectly fit with the main fire hotspots calculated with the kernel density estimation. The three sub-humid bioclimates correspond to low fire frequency, and fire is almost absent from the two sub-arid bioclimates. The rainfall decreases, and the mean annual temperature increases from the humid to the sub-arid bioclimates. In the same time, bioclimates clearly correlate to different land cover types (i.e., fuel types) and different values of NDVI (i.e., fuel biomass).

Second, the land cover types also drive fire frequency because some types are preferentially burned. The forests, shrublands, and wooded shrublands are the most fire-prone types (Fig. 12), which are burned much more

than expected according to a random law. Pastures are moderately burned, and agricultural lands and groves are burned at low frequency, much less than expected according to their total area. Dense urban areas higher than 25% of coverage by houses exhibit almost no fires. The Monte Carlo calculation showed no effect of land cover type on the area burned by large fires (> 100 ha) versus small and medium fires (< 100 ha). The summer NDVI value has also an effect with maximal fire frequency at values above 0.5, and very low probability of fire at values below 0.2.

Elevation influences fire frequency, with fire being located preferentially above 500 m of elevation, with a maximum at ca. 110–1200 m. This corresponds to forests and their associated shrublands, and to the humid bioclimates. Slope and aspect have very low impact on
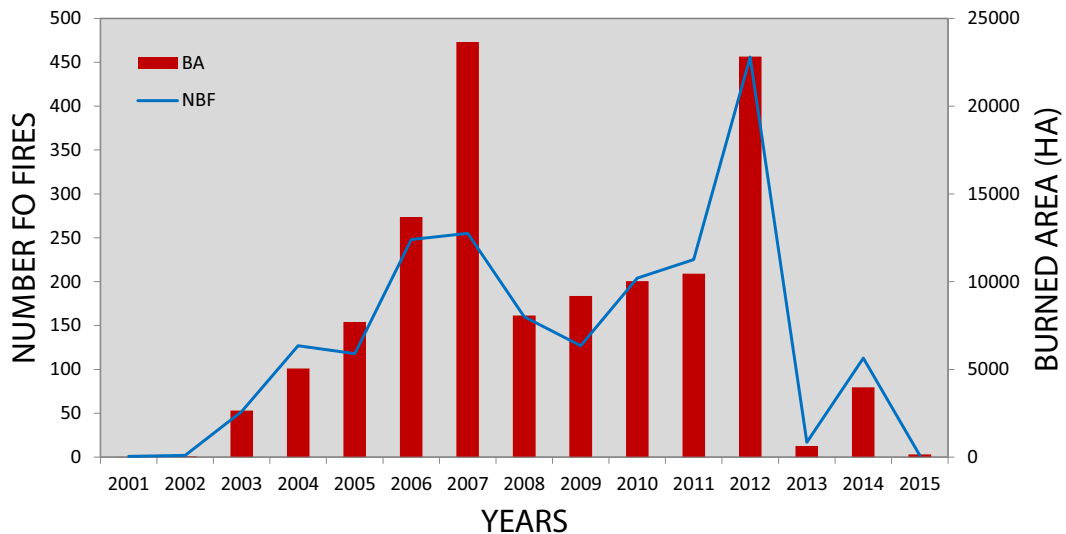

Fig. 6 Yearly number of fires and burnt area (ha) in the Bejaia region for the 2001–2015 period, according to MODIS fire data. BA is the burnt area, and NBF is the number of fires
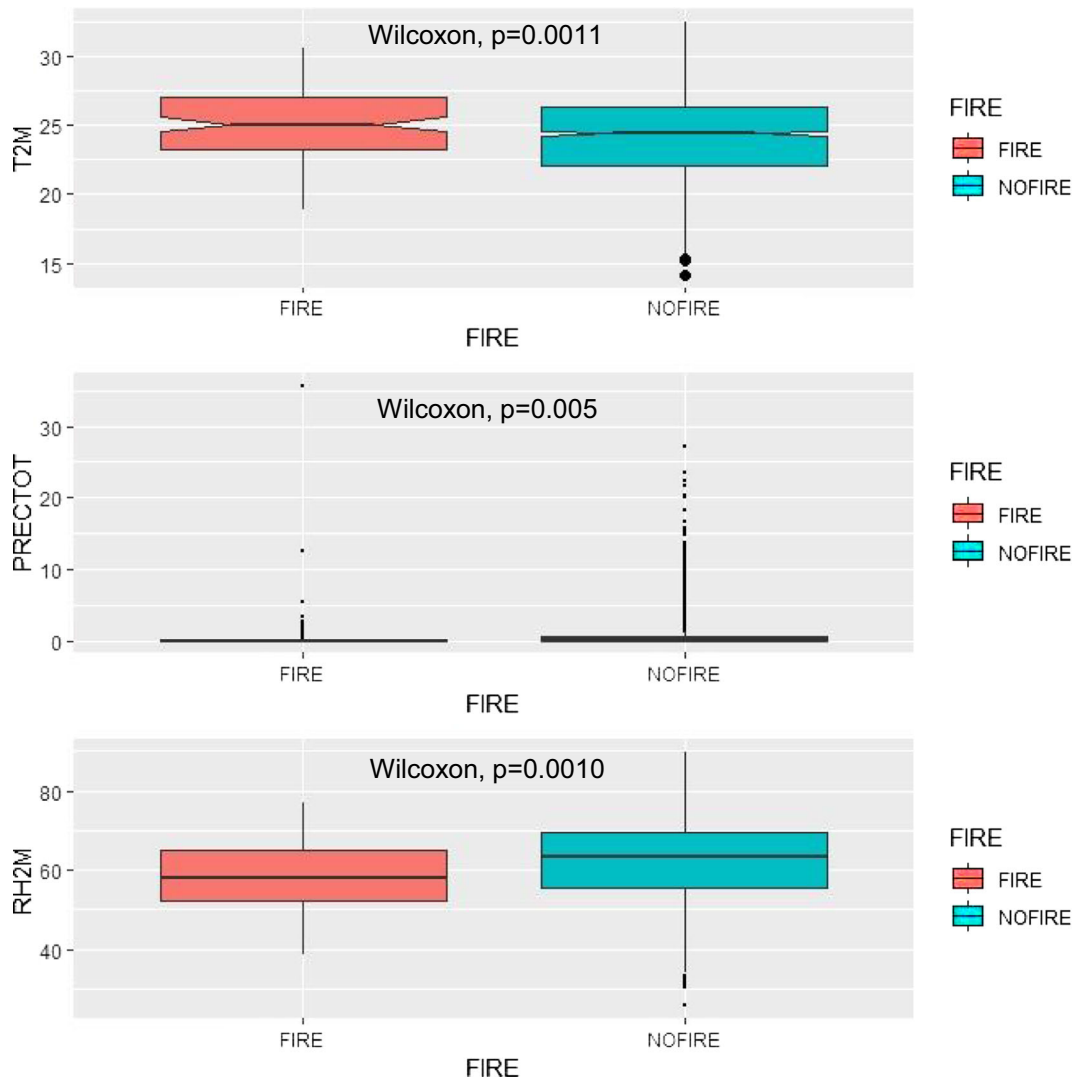
Fig. 7 Test of analysis of variance on the weather parameters for the non-fire pixels and the fire pixels in the Bejaia region. T2M is the mean temperature (°C), PRECTOT is the rainfall (mm) and

RH2M is the mean air humidity (%). The *p* values of Wilcoxon tests under 0.05 indicate statistically significant difference between fire and non-fire
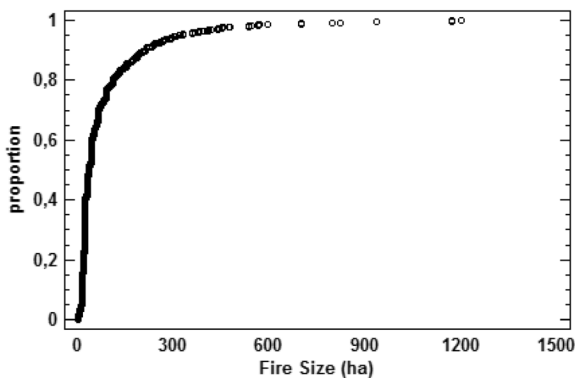

Fig. 8 Fire size distribution in the Bejaia region

fire frequency. Similarly, to the housing density, the maximal fire activity is registered at a distance of ca. 400 m from a road, and it decreases exponentially but with a tail of distribution higher than for housing (see Fig. 9).

Anthropic factors also play a role in fire activity: housing density has an impact equivalent to elevation, with maximal fire activity corresponding to pixels with low density of habitations (< 15%). The figure A4 shows that maximal fire activity is registered at ca. 400 m of distance from houses, and it decreases according to an inverse exponential function. Almost no fire occurs at more than 2 km from a house (Fig. A5). The density of

Table 3 Prevalence of different land cover types for fire or large fires in the Bejaia region. The numbers indicate the percentage of each land cover type in reference to the total area in the study area, to the number of fires, and to the number of large fires. Values in italics indicate values much lower than expected to the total surface according to 10,000 Monte Carlo simulations, and bold values indicate values much higher than expected to the total surface according to the 10,000 Monte Carlo simulations. Forests include forests and reforestation. Groves include olive groves and arboriculture. Shrublands include bare shrublands and wooded shrublands

Land cover types	(%) Total area	(%) Fires	(%) Large fires
Agriculture	32.3	*19.6*	*8.8*
Forests	19.3	**31.1**	**41.9**
Groves	20.1	*13.6*	*8.0*
Pastures	10.2	10.9	13.9

roads has a low statistical effect but inverse to that of the other anthropogenic drivers (i.e., housing density) because high density or roads promotes high fire frequency.

Overall, we found major limitations to fire activity in the Bejaia region. The main limitation is climate-driven and climate-induced: almost no fire occurs if the mean

annual rainfall is below 800 mm and if the fuel biomass is low ($NDVI_{summer} < 0.2$). Conversely, fire activity peaks if $NDVI_{summer}$ is greater than 0.5 (Fig. 12; Fig. 13). In addition, we found that almost no fire occurs if the housing density is higher than 25% in a 500 × 500 m pixel. Consequently, the fire activity in the Bejaia region is traced on the level of NDVI (Fig. 14).

The landscape clusters analysis

The PCA analysis and the BRT results have shown that the main drivers of fire frequency (i.e., bioclimates, land cover types, elevation, housing density, the summer NDVI value, and the road density) can vary together in the Bejaia region (Fig. 4). Their combination results in landscape clusters characterized by associations between bioclimate, land cover, and human activities. An analysis of variance showed that the level of fire hazard varied among these landscape clusters (or units) which area described in Table 4. A cluster corresponds to the main fire hotspots and is characterized by humid mountains covered with forests and associated shrublands, with high levels of summer NDVI, and low-density and disseminated houses, and low density of roads (i.e., wildland urban interfaces; Fig. A6). The low elevation
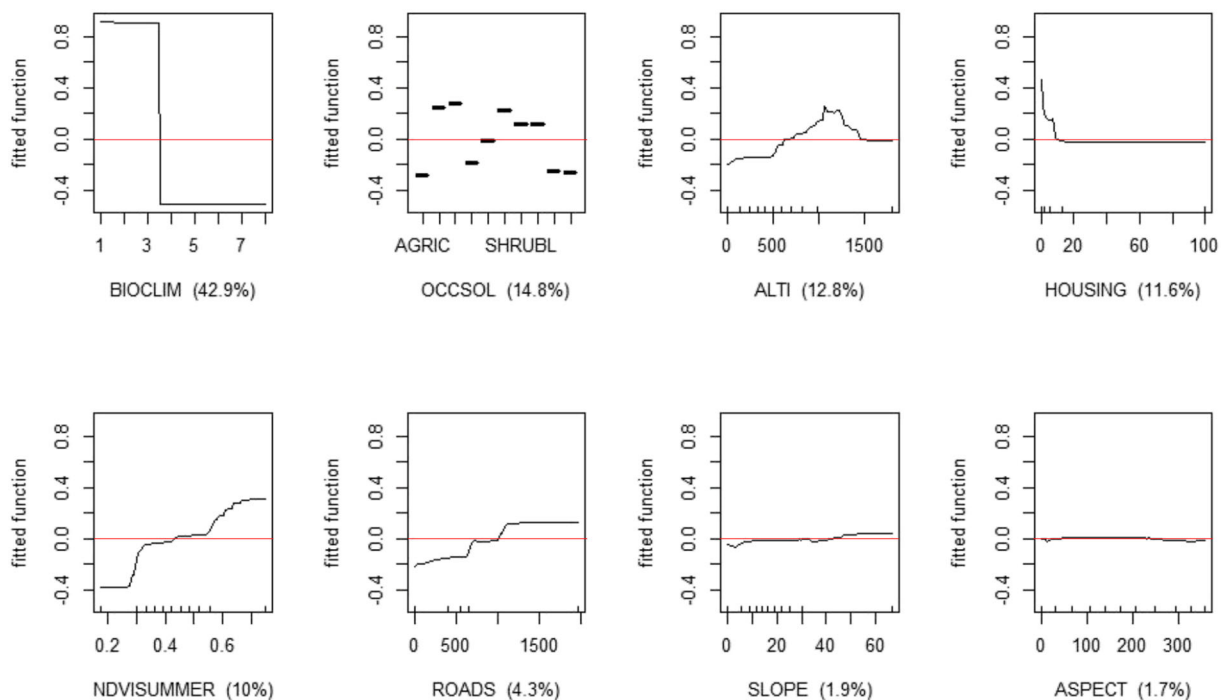

Fig. 9 Results of the boosted regression model (BRT) for fire activity in Bejaia. The fitted function values above zero indicate for each variable a positive effect, and the values below zero indicate a negative effect. The final variables selected by the model are explained in Table 2
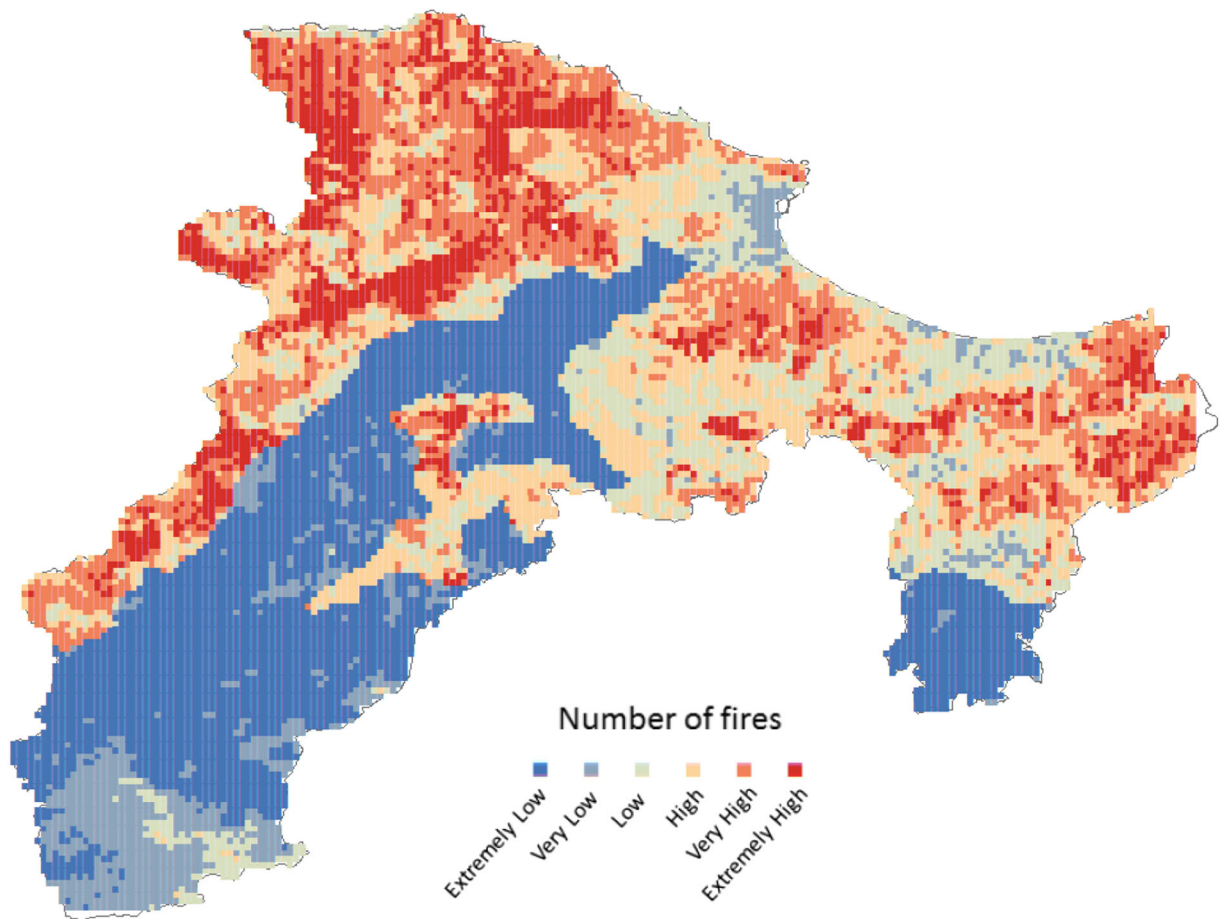
Fig. 10 Fire activity predicted by the BRT model in the Bejaia region. Dark blue pixels correspond to extremely low fire number and dark red pixels correspond to extremely high activity

areas along the Soummam valley are dominated by groves of olive trees and agriculture under sub-humid bioclimate; they exhibit high housing and roads density (dense habitat corresponding to large villages) and they have moderate fire frequency. The eastern part of the Bejaia region under humid bioclimate is dominated by agriculture and pastures at low to moderate elevation, with low summer NDVI values due to overgrazing and summer droughts, and it also has a moderate fire frequency. The two latter types are typically rural urban interfaces.

Discussion

The features of fire regime in coastal Algeria

The fire regime of Bejaia is typical of that of the coastal Algeria. Fires occur in summer irrespective to years and to land cover types, and almost null from autumn to spring. This is a typical feature of the southern rim whereas fire activity remains high in many Euro-Mediterranean countries of the norther rim (in example, France) where many agropastoral and forest fires are ignited to manage vegetation from October to June (Curt et al. 2016). The unimodal seasonal regime of Bejaia and the short fire season length suggest that fire is mainly driven by weather and restricted to a narrow meteorological window of opportunity in this part of Algeria. This may also stem from traditional practices: people rarely ignite fires from autumn to spring in order to manage vegetation in pastures and cultivated lands.

We found no clear trend in fire frequency or burned area in Bejaia from 2001 to 2015, but rather a high interannual variability which likely

Fig. 11 Analysis of variance of number fire hotspots versus bioclimate
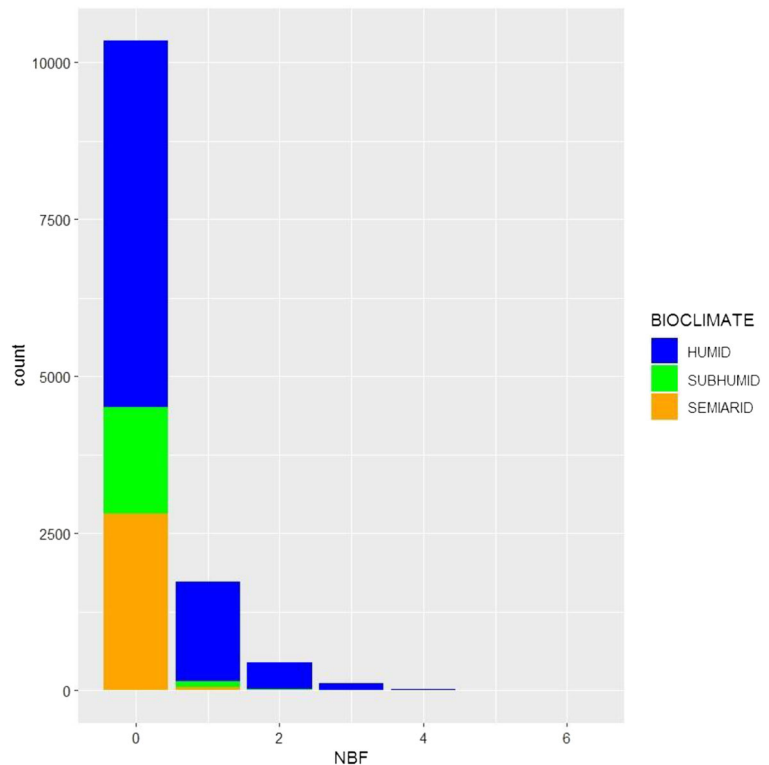
reflects the onset of weather conditions favorable to fire. This feature is very common all around the MB (EFFIS 2016), with years of very high fire activity (here, 2006, 2007, and 2012 represent about half of the total area burned) and years of low activity.

The fire size distribution is typically left-skewed with many small fires and few large ones as it is almost worldwide and notably in the MB (Turco et al. 2018). But it shows no occurrence of megafires of thousands of hectares like many countries of the northern Mediterranean rim such as Portugal, Spain, Greece, or France. This may be due to the high proportion of cultivated land, pastures or groves which have low fuel biomass. Indeed, traditional agrosilvopastoral practices are still very active in Bejaia. In addition, overgrazing, desertification, and climate limit fuels in the southern part of the region, close to the Sahara border.

In total, the fire incidence is moderate in Bejaia due to a short fire season limited to summer in early autumn, and to drought and overgrazing which remove a large part of biomass. However, it is higher than in many areas of Tunisia and Algeria (Meddour-Sahar 2014).

The drivers of fire ignitions and burned areas

Bioclimate is undoubtedly a dominant driver of fire activity in the Bejaia region. Fire activity peaks in the three humid bioclimates where rainfall is maximal and always above 800 mm year^{-1}. The two sub-arid bioclimates with minimal annual rainfall (< 500 mm year^{-1}) have the lowest fire activity, while the three intermediate sub-humid bioclimates have moderate fire activity. The finding that fire activity is maximal where rainfall is maximal is counterintuitive in the northern rim of the MB, but this is logic for the southern rim. Fuel amount is clearly limited by bioclimate in southern Algeria, and high fuel amount (i.e., high fuel flammability and propensity of fire to propagate) is promoted by high rainfall amount during winter and spring followed by high temperature and drought during summer. Land uses, land cover types, and vegetation fuels also play a major role, in connection with bioclimates and anthropic activities. Indeed, certain fuels correspond to certain bioclimates, and fuels are also ignited preferentially by humans for certain purposes. Fire frequency is high in agricultural lands, in groves, in pastures, and in forests and shrublands (including wooded shrublands).
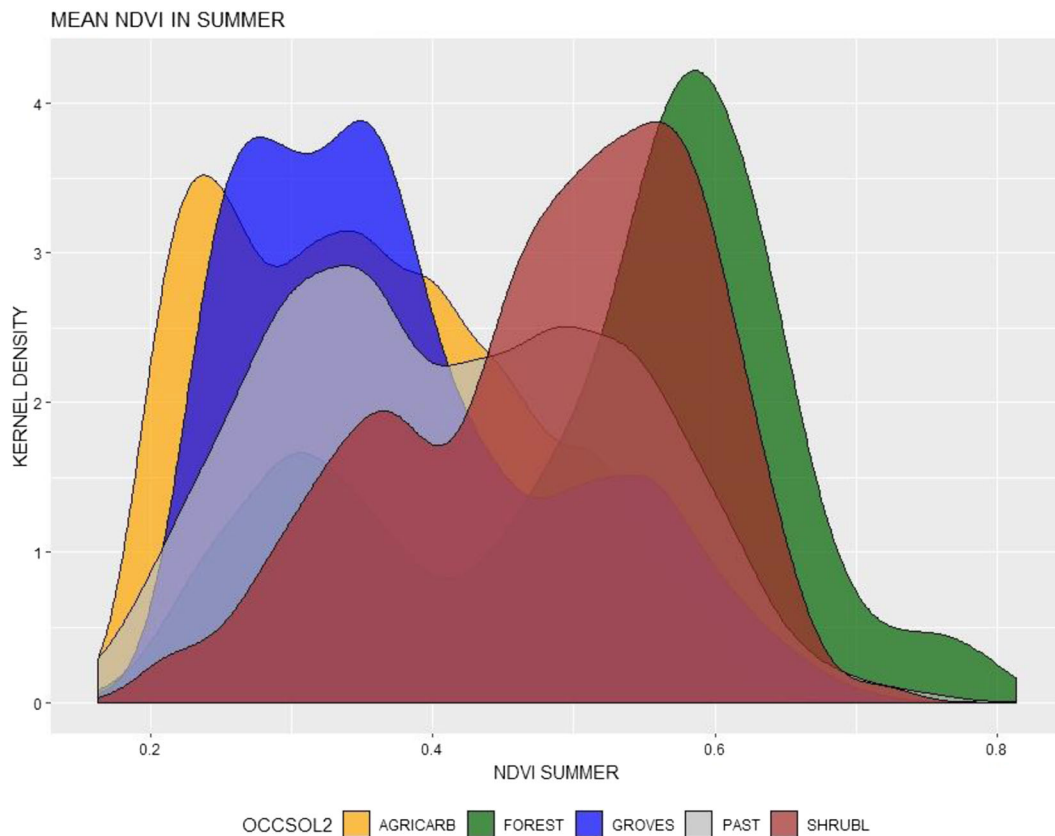
Fig. 12 Kernel density of NDVI (normalized difference vegetation index) summer values in the Bejaia region for the main land cover types. AGRIARB corresponds to agricultural areas and arboriculture; FOREST includes all forest types; GROVES includes all groves; PAST includes all pastures; SHRUBL includes all shrublands (naked shrublands and wooded shrublands)

Humans play a major role in fire ignition, which is clearly captured by the density of housing and of roads. These variables indicate the human pressure on ignitions. Higher density of houses or roads favors fire outbreaks, with maximal effect at a distance of ca. 400 m from houses and roads.

Regionalization in Bejaia

Many interactions exist between bioclimate, fuels, the landscape, and human activities (Table 4). The cluster approach has resulted in five types of landscapes characterized by specific association between these factors, and specific fire activity. The highest fire frequency and burned area occur preferentially in oak evergreen forests and shrublands of the humid and sub-humid bioclimates at high elevation (600–1200 m) and with disseminated habitations and roads. It is clearly driven by bioclimate and fuels. Another cluster with high fire activity corresponds to agricultural lands, pastures and arboriculture at mid elevation with medium habitation density, and moderate fuel biomass.

Fire limitation: the role of bioclimate and fuels

The window of opportunity for fire in Bejaia is rather limited in time each year: rainfall is quite abundant during winter and spring, and mean summer temperature is moderate (25 °C in August). Under these conditions, fire is enhanced only during few summer months. Conversely, fire is limited by low amounts and high dryness of vegetation fuels in summer. This study has shown that the presence of fire is very unlikely when the summer NDVI value is lower than 0.25, which corresponds mainly to forests under semiarid climate (mean annual rainfall < 350 mm) or to pastures and overexploited agricultural areas in sub-humid areas. Southern xeric forests of *Pinus halepensis* or oaks under semiarid climate thus rarely burn due to a sparse and low-stature shrub or grass understory (WWF 2018). The
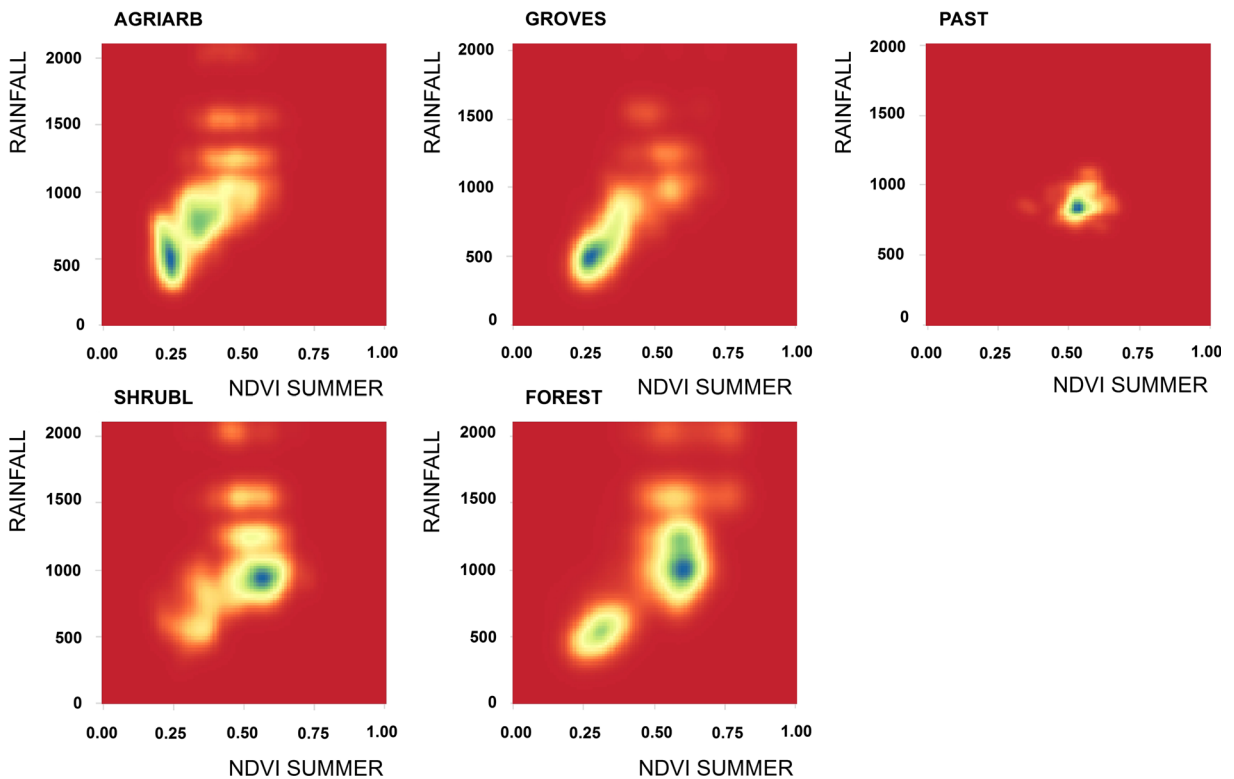
Fig. 13 Density of NDVI and rainfall for the main land cover types in Bejaia. Blue value indicates high density. AGRIARB corresponds to agricultural areas and arboriculture; FOREST includes all forest types; GROVES includes all groves; PAST includes all pastures; SHRUBL includes all shrublands (naked shrublands and wooded shrublands)

ongoing climate changes may add to this limitation since increased periods of drought (Sahnoune et al. 2013) and the desertification which has increased due to increasing drought and overgrazing: it is now alarming high (Djeddaoui et al. 2017).

Long-term changes and possible changes in fire risk

As in many countries around the MB, the fire activity in coastal Algeria is a result of bioclimatic constraints together with human pressure on ignitions and selective fire setting in land covers. The climate constraints fire through a fuel limitation along a latitudinal gradient, which superimposes to the other environmental and anthropogenic features. However, it is not certain that the ongoing climate changes will promote large fires in this study area, because increased droughts and fuel dryness, overgrazing, and desertification may limit fuels in the southern part.

The analysis of causes for fire ignitions has stated showed that the most fire-prone areas covered with forests and shrublands are due to deliberate ignitions in order to clear vegetation to urbanize or to political fires (i.e., ignited by the Algerian army to prevent terrorism), or to forest practices (Meddour-Sahar 2015). As the demographic pressure and urbanization still progress, these fires will unlikely regress. In agricultural lands and groves, most fires are ignited on purpose for clearing the vegetation and burning the residues of agriculture. Pastoral fires are very common: shepherds burn the pastures or the shrublands in order to favor the regrowth of grasses. As the prevention, detection, and suppression of fires is not very active, fires will still persist or increase in the next decades.

The broad picture shows that northern Algeria is still a traditional rural society which uses fire
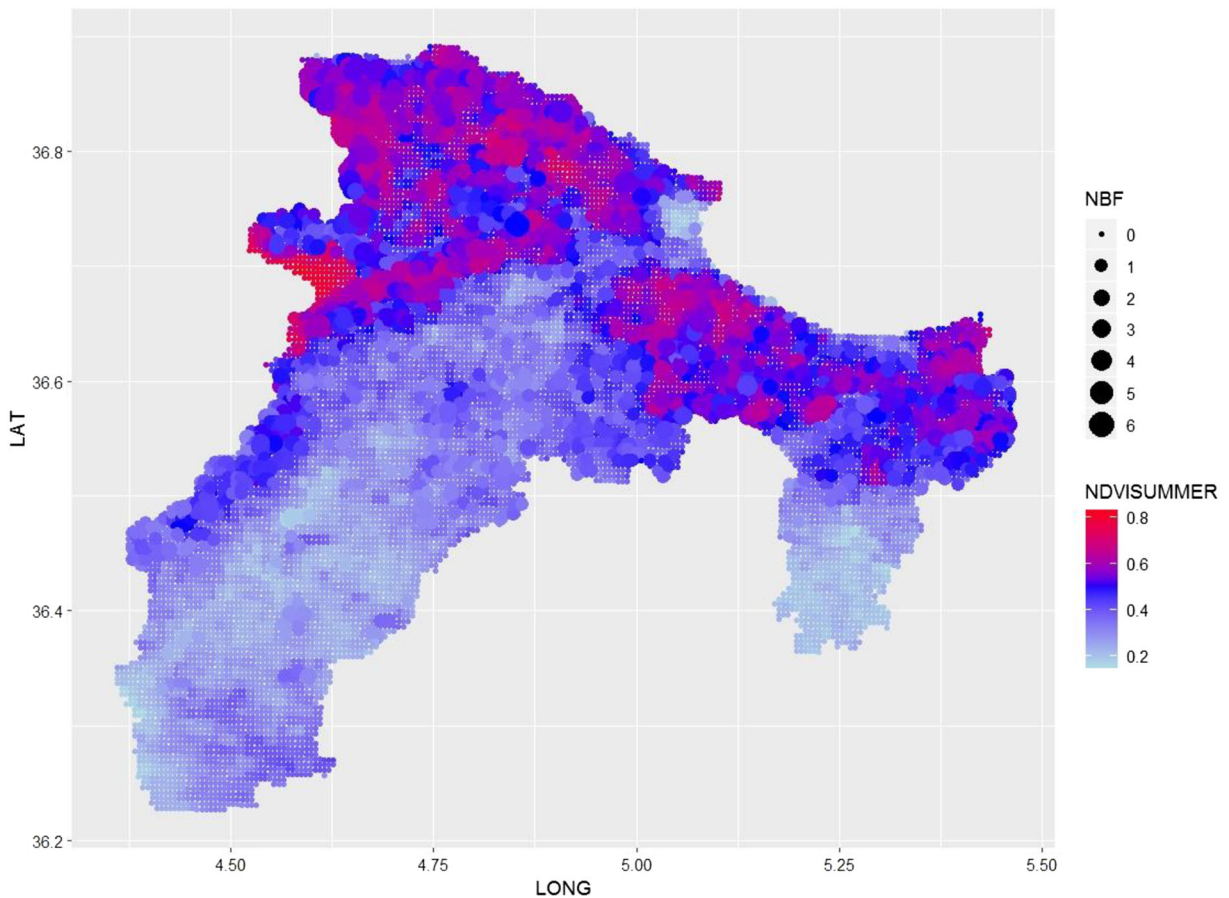
Fig. 14 Map of the number of fires (NBF) and of the NDVI (normalized difference vegetation index) summer values in the Bejaia region. Red values indicate high fuel biomass and coverage, and light blue values indicate low fuel biomass and coverage). The size of points is proportional to the number of fires

for many purposes, notably for managing vegetation. In such traditional systems, fire is active and this regulates the amount of fuel in landscapes. As these landscapes are regularly burned and managed by agriculture, pastoralism, or forestry, the probability of having very large fires (that is, of thousands of hectares) is low. The Bejaia region

perfectly fits with the past fire regime hypothesis developed by Chergui et al. (2017): the current "rural" fire regime remains dominated by small and infrequent fires. It resembles to the past fire regime of Mediterranean Europe before the massive rural collapse and landscape closure by fuels described Moreira et al. (2011).

Table 4 Features of landscapes units subregions and fire activity

Areas valley	Land cover types	Urbanization and infrastructures	Fire activity
Soummam Valley	Intensive agriculture	RUI	Low
Seddouk Mounts	Mountain agriculture	RUI	Medium
Eastern Bejaia Massif Ighil Ali Mounts	Agro-sylvopastoral	RUI	High
Western Soummam Valley	Mountain agriculture	RUI	Medium
Western Bejaia Massif	Forests and shrublands	WUI	High

Implications for fire prevention, suppression, and long-term management forests/territories

Algeria faces fire issues as all countries around the MB (EFIMED 2011; FAO/EFIMED 2011). As fire suppression means are rather limited, fuel management and prevention and education could help limiting unwanted fires. Prevention on high daily fire danger may be enhanced using the calculation of fire danger indices such as the FWI (Chergui et al. 2017). Many countries now converge towards an integrated forest fire management (EFIMED 2011) which proposes to use fire as tool but also to manage forests and fuels in order to limit unwanted ignitions and large fires in the long term. Forests and their associated shrublands are frequently burned, notably for national security purpose and for urbanization. However, these wildlands are also major hotspots for diversity, and they deserve conservation. Land use planning should focus on areas at fire risk, which have been put into evidence here.

Conclusion

This study provided the first model of fire activity for the humid coastal Algeria (Bejaia region). The fire regime is characterized by a moderate fire frequency, concentrated during summer, with small to medium fires. Fire activity concentrates within a narrow 70 km strip close to the Mediterranean rim (the *Tellian Atlas*) with sufficient rainfall and temperature, many forest and shrublands fuels, and high human-set fires in the rural areas. Fire frequency strongly decreases along a north-to-south bioclimatic gradient that controls fuel dryness, enhance fuel biomass (in subhumid areas), or limit it (in sub-arid areas). This study may help to improve the prevention, the detection, and the management of fires in the long term, especially in biodiverse forests of high-conservation value.

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