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Tracking Montane Mediterranean grasslands: Analysis of the effects of snow with other related hydro-meteorological variables and land-use change on pollen emissions

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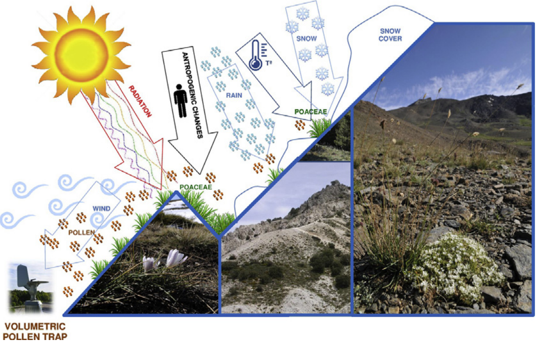
HIGHLIGHTS

- Temporal evolution of the high mountain Mediterranean grasslands was explored.
- Grass pollen emissions were used as indicators of response to environmental changes.
- Snow-packs outside the winter season is one of the most influential parameters on the pollen index.
- Changes in land use in the preferred habitats of grasses are also driver of change.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper explores the dynamics of temporal evolution of the high mountain Mediterranean grasslands, (Sierra Nevada, Spain SE). The indicator used is the emission of pollen (Pollen Index, PI) with respect to two important aspects: the incidence of the snow dynamic together with other hydro-meteorological parameters, and the changes in land use, which can Influence the evolution of the grasslands throughout time. The results reveal that pollen emissions in the last 25 years have shown a slight downward trend, with large interannual fluctuations, which are a consequence of diverse environmental factors, both general and specific to the area. One of the most influential parameters on pollen concentrations is snow cover, which reinforces the importance of the presence of snow-packs as water resource outside the winter season in the High Mediterranean Mountain environments. The changes in land use experienced in the area are a driver of change, especially due to the losses experienced in the last decades in the preferred habitats for many species of grasses. It can be concluded that the vulnerability of these ecosystems will be affected by an increase in winter temperatures and/or a decrease in rainfall (climate change) and an increase in the intensity of anthropogenic activities on land use. In this

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context, the PI is shown as a useful indicator of global change given its sensitivity to both anthropic and hydro-meteorological changes. In addition, it has a wide range of spatial detection and discrimination capacity by altitudinal dimensions.

1. Introduction

The grasses constitute a family of monocotyledonous plants that includes some 10,000 species of cosmopolitan distribution (Bouchenak-Khelladi et al., 2008). Among the outstanding species are those forming vegetation units (grasslands) present in most of the terrestrial ecozones: tropical and sub-tropical, savannas, temperate, flooded, montane, tundra, desert and xeric (Ellenberg and Mueller Dombois, 1967). In the Mediterranean Region, the grasslands, including rangeland, pastures, meadows and fodder crops, occupy up to 48% of the territory and participate in the provision of ecosystem services such as biodiversity conservation, forage and food production, carbon fixation, climate regulation, soil and water protection, pollination and nutrient storage (Hönigová et al., 2012). The pastures located in the mountainous areas of the region are also highly diversified and rich in endemic plants, with endemicity rates that can exceed 30% of the total of flora taxa in some territories (Medáil and Quézel, 1999).

Sierra Nevada is one of the highest mountain ranges in the Mediterranean Region, located in the southeast region of the Iberian Peninsula, in an east-west direction. Given its pronounced altitudinal gradient, the grasslands there present several domains. On the one hand, the psychroxerophilic grassland resides in the most developed soils, with a predominance of perennial grasses; on the other hand, starting at 2000 m a.s.l, the hygrophilous vegetation corresponds to humid grassland in summer that is covered with snow throughout most of the year, and which is known as "borreguiles" (Salazar et al., 2001). The important changes experienced in the area in the last 50 years have highlighted the serious risk of threat that these ecosystems can suffer, which is exacerbated by the particular environmental characteristics of the Mediterranean area (Beniston, 2003; Bravo et al., 2008). These important changes in the area include both pronounced climatic variations (Pérez-Palazón et al., 2015), with significant reduction of the snow cover period (Pérez-Luque et al., 2015), and changes in land use and plant cover (Jiménez-Olivencia et al., 2015).

Much of the natural wealth of this territory is given by its particular topographic, climatic, edaphic and geological conditions, which in turn are the cause of great vulnerability to any change in them. The analysis and monitoring of climatic conditions and the evolutionary dynamics of plant communities become fundamental actions both to know the trend of change and its effects. In the Sierra Nevada, the tracking and monitoring of current climate conditions and future trends have been carried out for several decades (Zamora et al., 2016) in the framework of monitoring programs such as The Sierra Nevada Global Change Observatory (OBSNEV) (Bonet et al., 2011), based on the conceptual framework and the thematic areas proposed by the Global Change in Mountain Regions initiative (GLOCHAMORE), through the UNESCO MaB program (Schaaf, 2012) and the Global Observation Research Initiative in Alpine Environments (GLORIA) (Pauli et al., 2007). The monitoring of climatic variables is carried out with a fairly extensive network of meteorological stations, which since 2004 has been expanding towards higher altitudes (Herrero et al., 2011; Algarra and Herrero, 2014, 2016), where there is almost a complete lack of data. These meteorological records are the pillars underpinning the advance towards the most precise knowledge of the hydrology of the region. This knowledge, in conjunction with distributed physically-based hydrological models (Herrero et al., 2009), allows for the obtaining of time series of hydrological variables, such as the amount and duration of snow (Pimentel et al., 2015), the potential evapotranspiration (Aguilar et al., 2010), or the soil moisture, with a spatial resolution within the tens of meters. This information is important not only for the analysis of the trends on the hydrometeorological variables themselves (Pérez-Palazón et al., 2015), but also because these abiotic variables drive the changes in the plant communities that reside in this physical environment (Zamora et al., 2016).

To obtain information on the effects that environmental changes may have on plant species and populations, it is necessary to have indicators that allow predicting the intensity of the expected change and the response to it. This is essential, especially when dealing with highly vulnerable ecosystems with low resilience capacity, such as high mountain grass communities. The amount of pollen emitted into the atmosphere by the vegetation during its reproductive process has proven to be a valid indicator to know the factors that have greater effect on the biological state of the vegetation and its response to the change. Thus, pollen records have been used to know the response and environmental behaviour of different groups of plants to arid climate conditions (Cariñanos et al., 2004, 2014), as a tool for assessing the status of endangered species (Cariñanos et al., 2014), and to estimate trends in evolution of forest-forming species (Cariñanos et al., 2016). There are also some specific studies on grasses, in which the exogenous factors and endogenous processes that intervene in the release of pollen into the atmosphere have been analyzed (García-Mozo et al., 2010; García de León et al., 2015; Hernández Plaza et al., 2012). In addition to these factors, the impact of land-cover changes on the presence of grass pollen has also been explored in some areas of the Mediterranean (García-Mozo et al., 2016), although given the ubiquity and large number of existing species in some areas, this relationship is not yet clear.

In this context, it could be considered that the high dependence of the different populations of grasses present in the Sierra Nevada to the environmental conditions, and the intensity of climate change expected in the area, makes it necessary to intensify the tracking of these communities using indicators of response to these effects. Due to the Sierra Nevada's high vulnerability to climate change, and its projections of future change, it would be hypothesized that hydro-meteorological conditions and land use change are some of the variables with the greatest effect on mountain grass populations. Therefore, an analysis of pollen emissions of grasses in the Sierra Nevada environment could be used to describe temporal and spatial variation of the different grassland communities present in it, as well as to highlight the main drivers participating in its dynamics. The aim of this paper is to explore the relationship that could exist between the evolution of the montane grasslands of the High Mediterranean Mountain with two important groups of variables not well studied until now. To this end, pollen emissions derived from grass communities and their possible response to hydrometeorological and anthropogenic factors will be analyzed. Among the first, special emphasis is placed on induced effects by the snow dynamics. The anthropogenic approach focuses on the possible influence of changes in land use that occurred in the same area during the last decades.

2. Material and methods

2.1. Description of the area of study

The Sierra Nevada (Fig. 1) is a mountain massif with a surface area of >2000 km^2 and a maximum height of 3479 m a.s.l., which extends linearly 90 km east-west and an average width of about 35 km, in the southeast region of the Iberian Peninsula. The Sierra Nevada presents important natural values, which are recognized in the figures of "Natural Park", "National Park" and "Biosphere Reserve". Moreover, it is one of the main centers of diversity of the Eastern Mediterranean

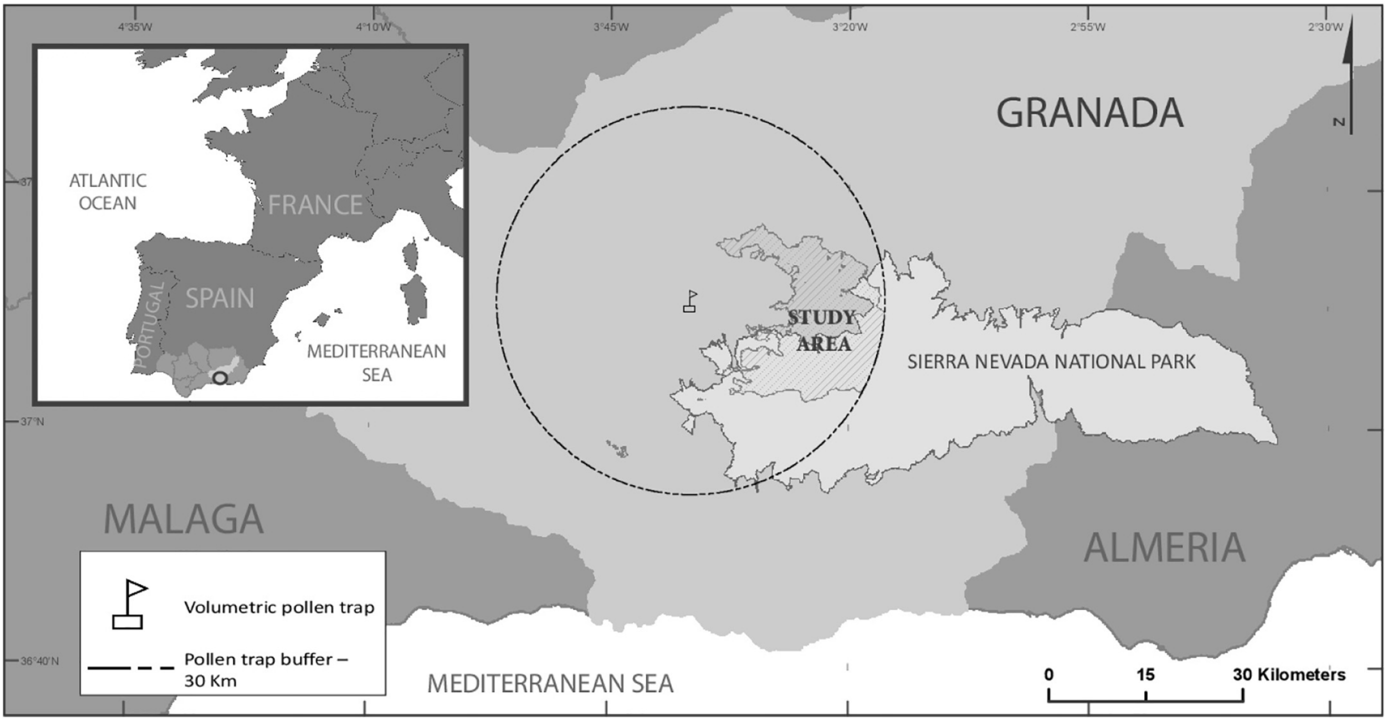

Fig. 1. Location of study area.

(Molero, 1994), has been a Long-Term Ecological Research (LTER) site since 2008 and is a biodiversity "hotspot" (Blanca et al., 1998; Myers et al., 2000; Médail and Diadema, 2009). Of the >2100 floral taxa cataloged in the area, almost 40% of them are exclusive to the massif and 80 are endemics to the Sierra Nevada (Molero and Pérez-Raya, 1987). Recently, it has been included in the first World Green List of Well Managed Protected Areas, accredited by the International Union for the Conservation of Nature (IUCN, 2014).

This mountainous massif of the Mediterranean Region has a considerable altitude, only surpassed in Western Europe by the Alps. It is located in southern latitudes (37°N) and, consequently, a continuous snow cover is likely to persist above 2500 to 3479 m a.s.l. during the winter season, often interrupted by periods of intense melting (Herrero and Polo, 2016). The expected alpine climate is modified by the proximity of the Mediterranean Sea (40 km south) which significantly affects the snow dynamics (Herrero et al., 2009).

Average temperature in the Sierra Nevada ranges from −10 °C to 10 °C above 2000 m a.s.l. during the snow season (Pérez-Palazón et al., 2015). Annual precipitation fluctuates widely (220 mm/year in the driest areas up to 1000 mm/year) with a high spatial variability throughout the area due to changes in elevation, longitude, and slope exposure (north–south). The mean annual precipitation on the western side of the Sierra is 550 mm at 1000 m a.s.l. and 750 mm at 2000 m a.s.l. On the opposite side, to the east and the northeast, there is an important rain shadow effect that diminishes this mean annual precipitation down to 300 mm at 1000 m a.s.l. and 465 mm at 2000 m a.s.l. (Herrero and Polo, 2016). The mean gradient of precipitation with elevation is about 150 mm km^{-1}. Snowfalls occur mainly from November to April at altitudes above 2000 m a.s.l. At the Refugio Poqueira weather station (2500 m a.s.l.), the average precipitation is 889 mm yr^{-1}, 59% of which occurs as snow. Precipitation oscillates annually between 1426 mm for a wet year and 520 mm for a dry one. The fraction of snowfall with respect to the total precipitation also varies between 88% and 46%, with a general tendency to be higher with lower annual precipitation values. The difference in total snowfall varies from 910 mm during a wet year to 335 mm during a dry year (Herrero and Polo, 2016). Another parameter of interest is the wind regime in Sierra Nevada. This parameter is of great relevance and it is the most extreme weather phenomenon in the Sierra Nevada both by its dominant direction, conditioned by the orientation of the massif, as by the intensity, which can reach >100 km/h. This regime affects the conditions in the city of Granada, which is characterized by the high percentage of calms (>50% per year) and prevailing winds of the 3rd quadrant (SW), which roll to the south during the months of July and August (Viedma Muñoz, 1998). It is also remarkable the daily dynamics of valley-mountain breeze, direction W-E day and vice versa in the night hours.

All these climatic and topographical particularities are reflected in the variety of existing habitats, distributed in 4 biogeographical sectors and 5 of the 6 bioclimatic belts described for the entire Mediterranean Region (Rivas-Martínez, 2007). In our study, conditioned by the location of the aerobiological sampler in the city of Granada, we will obtain representation of the communities located in the 4 upper belts: mesomediterranean, supramediterranean, oromediterranean and cryoromediterranean, that is, the altitudinal range between 700 and 3479 m a.s.l. The limits for the thermotypes come from the latest mapping of vegetation that detail the work area (Molero et al., 2001; REDIAM, 2009).

2.2. Description of the target taxonomic group

The grasses are represented in the Sierra Nevada by some 200 species, which constitutes 2% of the species of the Poaceae Family. Although it is not the most abundant botanical family in the area, it is the most represented in the different plant communities existing in the Sierra Nevada, especially in the absence of trees (Romero and Morales, 1996). Most taxa are widely distributed, although 7% of them (14 taxa) are exclusive to the Nevadense massif (Blanca et al., 2001). In terms of distribution, they are present both in natural and anthropized environments, from sea level to the highest peaks of the Sierra (Blanca and Algarra, 2011). In the most altered urban and peri-urban environments, ruderal species of colonizing behavior are abundant (i.e., *Bromus madritensis*, *Aegilops geniculata*, *Hordeum murinum*, *Lolium perenne*, *Dactylis glomerta*, *Holcus lanatus*, *Trisetaria panicea* or *Sorghum halepense*, etc.); while in the sierra the species will be distributed according to the altitudinal, edaphic and water availability conditions of the substratum, giving rise to very diverse communities: psychroxerophilous perennial grasses on siliceous or carbonaceous soils, pastures associated to forest formations, and hygrophilous pastures in the highest areas of the Sierra (Molero and Pérez-Raya, 1987; Molero, 1994). It is in this last zone where the artificialization of the habitat and changes in the strict climatic conditions have threatened some of these species (Suppl. 1, Suppl. 2). Although each domain has its characteristic species, remarkable genera such as *Poa* (whose *Poa annua* species is present in all biocimatic belts), *Festuca*, *Bromus* and *Stipa*, have 20, 12 and 11 species respectively. The genus *Festuca* includes some exclusive endemisms such as *F. clementei* or *F. pseudoeskia*, and threatened species such as *F. frigida*.

This diversity of habitats is reflected in the habit, with >60% of the perennial species, compared to 40% of annual species. There is also a great amplitude regarding the flowering period, since the species that grow in the lower areas, closer to the sampler, have a main flowering period between months III–VI (VII) (with the exception of *Sorghum* and *Trisetaria*), and those that grow in the different bioclimatic belts oscillate between V–VII for those of the Mesomediterranean, VI–VIII in the Supramediterranean and (VI) VII–VIII (IX) for those of the upper belts (Suppl. 2).

2.3. Aerobiological data

Poaceae pollen data were obtained from the Aerobiological Sampling Unit of Eastern Andalusia, located in the Faculty of Sciences of the University of Granada (37°11′N, 3°57′W, 685 m a.s.l.), from which a continuous data series from 1991 to 2016 was obtained. The distance to the Natural Park of Sierra Nevada is just 6.6 km in a straight line. Aerobiological sampling was carried out according to the standardized methodology of the Spanish Aerobiology Network, in its Quality and Management Manual (Galán et al., 2007), which recommends the use of Hirst-type volumetric suction samplers (Hirst, 1952) and the expression of results in pollen grains/m^3 of air/day. Based on the results of the series, some aerobiological parameters are established, such as the curve of average daily values of grass pollen and the Pollen Index (PI, sum of the daily values for each year of study), the start date of flowering, (i.e. the date from which 1 pollen grain/m^3 of air/day was recorded for at least 5 consecutive days (García-Mozo et al., 2009)) and end of the pollen season (i.e. the date in which at least 1 pollen grain/m^3 of air/day followed by 5 consecutive days with nil pollen presence is recorded).

2.4. Hydro-meteorological data

For this study, the meteorological data were obtained from all the weather stations located in the area of influence of the study area (Suppl. 3). These stations belong to different networks at the national level (The State Meteorological Agency (AEMET) and the Autonomous Organization of National Parks (OAPN)), the regional level (The Agroclimatic Information Network of Andalusia (RIA-JA)) and the local level (The Universities of Granada and Cordoba (IISTA)). Specifically, we used the data for daily and hourly precipitation (27 stations), daily temperature (30 stations), solar radiation (16 stations), wind speed (19 stations) and relative humidity (23 stations). Data correction and gap filling of the meteorological data series was assessed using cross correlation between stations. For the analysis of the general trends of temperature and precipitation in the long term, we used the Arquilla station (AEMET), at 1652 m a.s.l., which is the closest station to the study area with the most complete data series and the highest altitude.

Using these meteorological inputs, the hydro-meteorological model WiMMed (Herrero et al., 2014) is used to generate distributed maps of meteorological and hydrological variables for the whole Sierra Nevada at a spatial resolution of 90 × 90 m from 1999 to 2016. These maps are subsequently averaged for the different five bioclimatic levels defined in REDIAM (2009), and for each of the five main basins in the Sierra Nevada (Genil, Fardes, Guadalfeo, Adra and Andarax). The values were obtained independently for each region and different combinations of them were used. This facilitates the analysis of the direct relationships between the series of daily concentrations of pollen data and the most representative hydro-meteorological parameters of an entire study area, with the most homogeneous characteristics possible. The splitting up used gives a total of 21 regions (Suppl. 3).

From WiMMed, 20 representative hydrometeorological variables are extracted on a daily scale. These data series can be grouped into 10 meteorological (atmospheric) variables, 4 hydrological (snow-related) variables, and 6 accumulated (both meteorological and hydrological) variables. The meteorological variables are 1) mean daily wind speed (Ws_m), 2) daily maximum temperature (Tmx), 3) daily minimum temperature (Tmn), 4) mean daily temperature (T_m), 5) number of hours per day with temperature above freezing, total daily (Tum), 6) direct (Rdr), 7) global solar radiation (Rad), daily 8) rainfall (Pliq), 9) snowfall (P_n) and 10) total precipitation as the sum of both (Pre). The hydrological variables are 1) fraction of the surface covered by snow (SCn), 2) snow depth (h_n), 3) snowmelt (Fus), and 4) snow water equivalent – the amount of snow accumulated on the surface in mm (EAn). In addition, hydrometeorological variables are also combined and/or temporarily treated to obtain other variables representative of the processes and cycles associated with high mountain vegetation. For example, in order to jointly quantify all the contributions of liquid water on the surface, rain and snowmelt are added together by a daily simple sum (PliqMasFus). Regarding the time scale of the processes, to quantify the fact that the pollen collected in a day depends not only on the characteristics of that day but also on the previous conditions, cumulative variables of the previous 7 days are also obtained. The new variables obtained are 1) the total rainfall (PliqAcum7), 2) the total snowfall (P_n_Acum7), and 3) the total precipitation as the sum of both rainfall and snowfall (Pre_Acum7), accumulated in the last 7 days, 4) the total daily water reaching surface, rainfall plus snowmelt (PliqMasFus), 5) the total daily water reaching surface accumulated in the last 7 days (PliqMasFus_Acum7) and 6) the total snowmelt accumulated in the last 7 days (Fus_Acum7).

2.5. The land-use

The information related to the land use variation was recovered from the Corine Land Cover Project (CLC), which categorizes the changes that occurred at different geographical levels, at a 1:100.000 scale. This research attended to the second and the third level of application, which comprises 15 and 44 land use types, respectively, and indicates the main variations of the surface on the total coverage in the thermotypes considered in the zone of study, during the 1990–2012 period. Within the study area, 9 land use types from level 2, as well as 19 land use types from the level 3 were identified. Regarding the second level of application, the following Corine classes were found: urban fabric; mine, dump and construction sites; arable land; permanent crops; heterogeneous agricultural areas; forests; shrub and/or herbaceous vegetation associations; and open spaces with little or no vegetation and inland waters (Tables 1 and 2).

2.6. Statistical analysis

The variables PI, Start-date and length of the season and meteorological trends were fitted to simple linear regression models; slopes of regression equations and determination coefficients (R^2) were examined.

For the comparative analysis of the hydro-meteorological variables with the PI, all meteorological data generated above were initially considered. Taking into account the scope of the sampler and following the principle of parsimony, the exploratory analysis proceeds to limit as much as possible the hydrographic basins, by altitude and by total number of variables to obtain maximum significance with the least number of variables. To clarify the weight of each variable in the pollen emission of the mountain family Poaceae, a classical Generalized Linear Model (GLM) was applied versus the possibility of using a Principal Component Analysis (PCA, Zuur et al., 2007), due to there are relatively low correlation between hydro-meteorological variables (by a non-parametric Spearman test). In this particular case, the response variable is the PI, so a GLM is used, estimated by maximum likelihood, following a Poisson distribution model with a logarithmic link function, with a non-normal distribution of errors and non-constant variance (Faraway, 2005). When the data have a very high percentage of zeros, which is the case, because there are scattered days in the series in which there are no pollen grains, then use a variant of GLM, Zero-inflated Poisson (ZIP) regression (Long, 1997; Kleiber and Zeileis, 2008). For to know the better fit of the models was used Akaike Information Criterion (AIC) ant to compare the result of both models (GLM and ZIP) is compared by Vuong's non-nested test. Following the principle of maximum parsimony and maximum deviancy (D^2, proportion of the variance explained by the model), the analysis is applied by testing different combinations of variables and homogeneous spatial areas (combination of river basins and bioclimatic belts).

To explore the incidence of changes in land use on vegetation, we compare the average PI data with the variation of the area obtained from the spatial analysis, by means of a comparative analysis of parametric means (t-Student). All analyses were performed with the R software (R Core Team, 2016).

3. Results

3.1. Aerobiological data

Grass pollen is detected in the atmosphere of Granada from mid-February to mid-October, showing several peaks corresponding to the flowering of species in different habitats. The first part of the curve corresponds to the flowering of the ruderal species near the city and the lower bioclimatic belt, while in May the blooming of the species that grows in the upper bioclimatic belt of the Sierra Nevada begins (Fig. 2). Between June and September, coinciding with the maximum peak of the curve, the flowering of the species forming the pastures takes place in the cacuminal zones of the Sierra, being able to reach values of 40 pollen grains/m^3 of air/day.

The trend of the aerobiological parameters, despite the lack of statistically significant changes in 1991–2016, shows that, in the case of the PI, the annual value has been close to 500 in some years (1995, 2012), while in others, the records have exceeded 3000 (2002, 2004 and 2007). Although the trend along the series is slightly downward ($s = -1.7746$, $R^2 = 0.002$), there is a slight rise towards the end (Suppl. 4). In the case of the dates of the start and the end of pollen season, opposite tendencies are obtained: a delay in the beginning ($s = 0.3608$, $R^2 = 0.0293$) and an advance in the end ($s = -0.1123$, $R^2 = 0.001$), so the pollen seasons are getting shorter in terms of duration (Suppl. 4).

3.2. Hydro-meteorological data

Through WiMMed, 20 maps were obtained, the same number of selected variables (Fig. 3). The time range is limited to the 1999–2016 interval in order to ensure consistency in the data. This limitation comes from the great shortage of meteorological stations installed in the years before 1999 in high mountain areas and the lack of hourly data in those that did exist, which prevents having a good knowledge of precipitation in the form of snow. The high correlation between meteorological variables is a frequent occurrence and usually causes misuse when it is overlooked (Statheropoulos et al., 1998; von Storch and Navarra, 1999). As a result, an exploratory correlation analysis is first carried out (Spearman test) showing a high correlation only among 9 of the 20 variables (Spearman nonparametric test, D values > 0.80, Fig. 3). For the exploratory statistical treatment, the results of the 20 variables selected for the 25 established areas are averaged (by combination of river basins and thermotypes).

The analysis of the series of meteorological data from the Arquilla station, selected to analyze general trends, shows that during the 1989–2016 period (Suppl. 5), there is a downward trend in maximum and minimum temperatures, also in the case of maximums ($s = -0.08392$, $R^2 = 0.08303$, $p = 0.137$, $s = -0.05874$, $R^2 = 0.07589$, $p = 0.1559$, respectively), although in no case is it significant. A decrease in the annual amount of rainfall was recorded ($s = -3.919$, $R^2 = 0.02207$, $p = 0.4506$) although the records have large oscillations between years (Suppl. 5) and meaning that this decrease is insignificant. The precipitations in the form of snow in the Sierra Nevada present a slightly ascending tendency for the available series of this parameter (2000 to 2014).

3.3. Relationship between daily pollen and hydro-meteorological data

Thanks to the GLM, a model is generated that shows which variables have the greatest influence on the pollen records. The best fit of the model selected the Genil river basin in the top three thermotypes (Fig. 3, Suppl. 3) and only 9 parameters of the initial 20 (Table 3, Fig. 4): wind speed (Ws_m), maximum Tª (Tmx), minimum Tª (Tmn), number of hours per day with temperature above 0 °C (Tum), fraction of surface covered by snow (SCn), direct radiation (Rdr), global radiation (Rad), total precipitation (Pre) and snow melt (Fus). With these parameters, a 62.1% explanation of the response variable is obtained. There is a lower significance in the contribution of water by direct precipitation ($p = 0.29224$) compared to the higher significance due to snow melting ($p < 0.001$).

Although this first result is very satisfactory, the series of daily concentration pollen counts shows a very high percentage of zeros (Suppl. 6), which justifies the exploration of a variant of the GLM, Zero-inflated Poisson (ZIP) regression. The result of both models is compared by Vuong's non-nested test and a better model is obtained by applying the ZIP (AIC. ordinary-glm: 53080.13; AIC. zero-inflated: 48536.79; $p < 0.001$). The result of the ZIP slightly modified the result

Table 1

Land uses-types from the Corine Land Cover 2nd level of application and variation of the area (in hectares), as a percentage of the total coverage during the period 1990–2012. LEVEL 2: level 2 of geographical application for land use categorization; Δ (YY-YY): Variation of the surface, in total hectares, attending level 2 between the revisions of 1990, 2000, 2006 and 2012; L2 S%: Variation of the area, as a percentage of the total coverage, taking into account level 2 between the revisions of 1990 and 2012. #Anthropogenic types.

LEVEL 2		Δ (90-00)	Δ (01-06)	Δ (07-12)	Δ (90-12)L2	L2 S%
11	Urban fabric#	0.00	0.00	6.18	6.18	0.02%
13	Mine, dump and construction sites#	0.00	0.67	−5.09	−4.42	−0.01%
21	Arable land#	18.47	0.00	−221.30	−202.83	−0.53%
22	Permanent crops#	−0.81	0.00	220.18	219.37	0.57%
24	Heterogeneous agricultural areas#	72.17	0.00	867.15	939.32	2.43%
31	Forests	−25.30	0.00	−1191.47	−1216.77	−3.15%
32	Shrub and/or herbaceous vegetation associations	−64.49	−0.67	5797.95	5732.80	14.86%
33	Open spaces with little or no vegetation	−0.05	0.00	−5476.52	−5476.57	−14.19%
51	Inland waters	0.00	0.00	2.91	2.91	0.01%

Table 2
Land uses-types from the Corine Land Cover 3rd level of application and variation of the area (in hectares), as a percentage of the total coverage during the period 1990–2012. LEVEL 3: level 3 of geographical application for land use categorization; 1990 to 2012: Year of actualization, surface in hectares (ha); Δ (YY-YY): variation of the surface, in total hectares, attending level 2 between the revisions of 1990, 2000, 2006 and 2012; L3 S%: variation of the area, as a percentage of the total coverage, taking into account level 2 between the revisions of 1990 and 2012; **: major Surface increase stemmed from Land Cover Change (together they exceed 25% of the total area); *: major surface loss stemmed from Land Cover Change (together they exceed 25% of the total area). #Anthropogenic types.

LEVEL 3		Δ (90-00)	Δ (01-06)	Δ (07-12)	Δ (90-12)L3	L3 S%	
112	Discontinuous urban fabric#	0.00	0.00	6.18	6.18	0.02%	
131	Mineral extraction sites#	0.00	0.67	−5.09	−4.42	−0.01%	
211	Non-irrigated arable land#	18.47	0.00	−221.30	−202.83	−0.53%	
212	Permanently irrigated land#	0.00	0.00	0.00	0.00	0.00%	
222	Fruit trees and berry plantations#	0.00	0.00	254.98	254.98	0.66%	
223	Olive groves#	−0.81	0.00	−34.79	−35.60	−0.09%	
242	Complex cultivation patterns#	0.01	0.00	85.84	85.85	0.22%	
243	Land principally occupied by agriculture, with significant areas of natural vegetation#	72.16	0.00	−176.85	−104.70	−0.27%	
244	Agro-forestry areas#	0.00	0.00	958.17	958.17	2.48%	
311	Broad-leaved forest	−25.39	0.00	−609.01	−634.40	−1.64%	
312	Coniferous forest	0.07	0.00	−905.04	−904.96	−2.35%	*
313	Mixed forest	0.01	0.00	322.58	322.60	0.84%	
321	Natural grasslands	0.00	0.00	4262.28	4262.28	11.04%	**
322	Moors and heathland	0.00	0.00	2104.71	2104.71	5.45%	**
323	Sclerophyllous vegetation	−38.04	−0.67	6309.23	6270.53	16.25%	**
324	Transitional woodland-shrub	−26.45	0.00	−6878.27	−6904.72	−17.89%	*
332	Bare rocks	0.00	0.00	−1184.24	−1184.25	−3.07%	
333	Sparsely vegetated areas	−0.04	0.00	−4292.28	−4292.32	−11.12%	*
512	Water bodies	0.00	0.00	2.91	2.91	0.01%	

obtained in the ordinary GLM (Table 3), increasing the level of significance of direct precipitation (Pre), although to a lesser extent than the contribution by melting snow (Fus).

3.4. Relationship between PI and changes in land use

The total surface that presents a change in land use is different depending on the level of aggregation observed. Level 2 presents a net change in 17.19% of the study area while level 3 reaches up to 36.97% of the territory. In both cases, 2 of the units collect practically all the changes (Tables 1 and 2). The difference in total area is due to a change between two units integrated in the same group. The same trend has been identified in terms of Land Cover transformation from a CLC class into another. One of the areas identified with the greatest increase is "321 Natural grasslands," which partially stemmed from the transformation of "324 Sparsely vegetated areas" and "323 Sclerophyllous vegetation" areas. In terms of surface loss, the land use types most affected by the land cover change over time are "324 Transitional woodland-shrub" and "324 Sparsely vegetated areas," transforming their class mainly into "323 Sclerophyllous vegetation" and "321 Natural grasslands" (Fig. 5). The influence of human activity is observed in the lower layers of the mountain and especially on the surface transformed into "321 Natural grassland".

Evaluating the exchange rate within each period and its total computation (Table 4), the exchange rates in the first two periods do not exceed 1%, while in the last period the exchange rate does not exceed

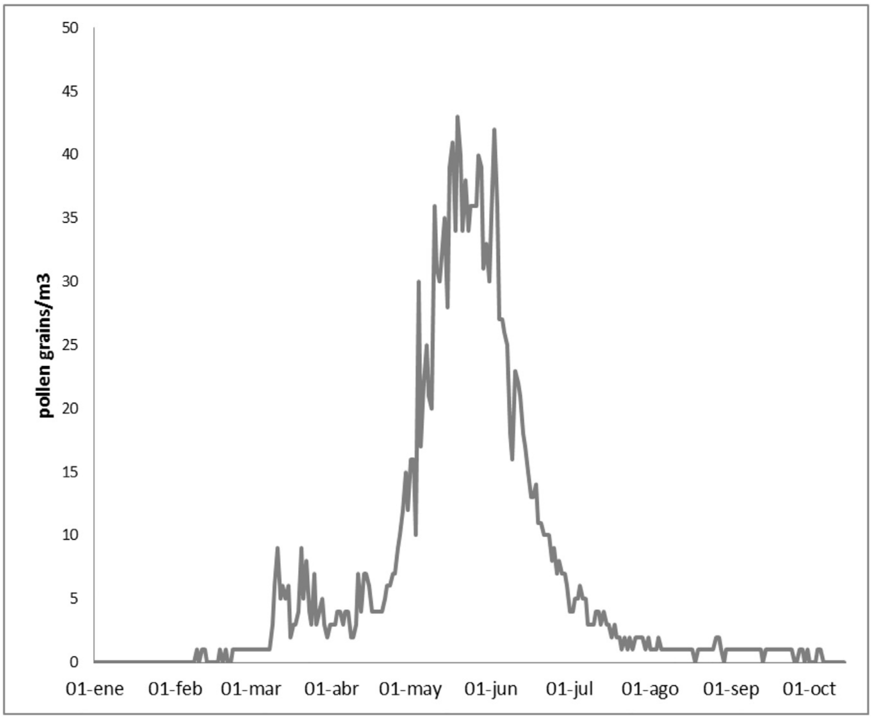

Fig. 2. Daily mean airborne Grass pollen counts for Sierra Nevada (Spain) over the period 1991–2016.

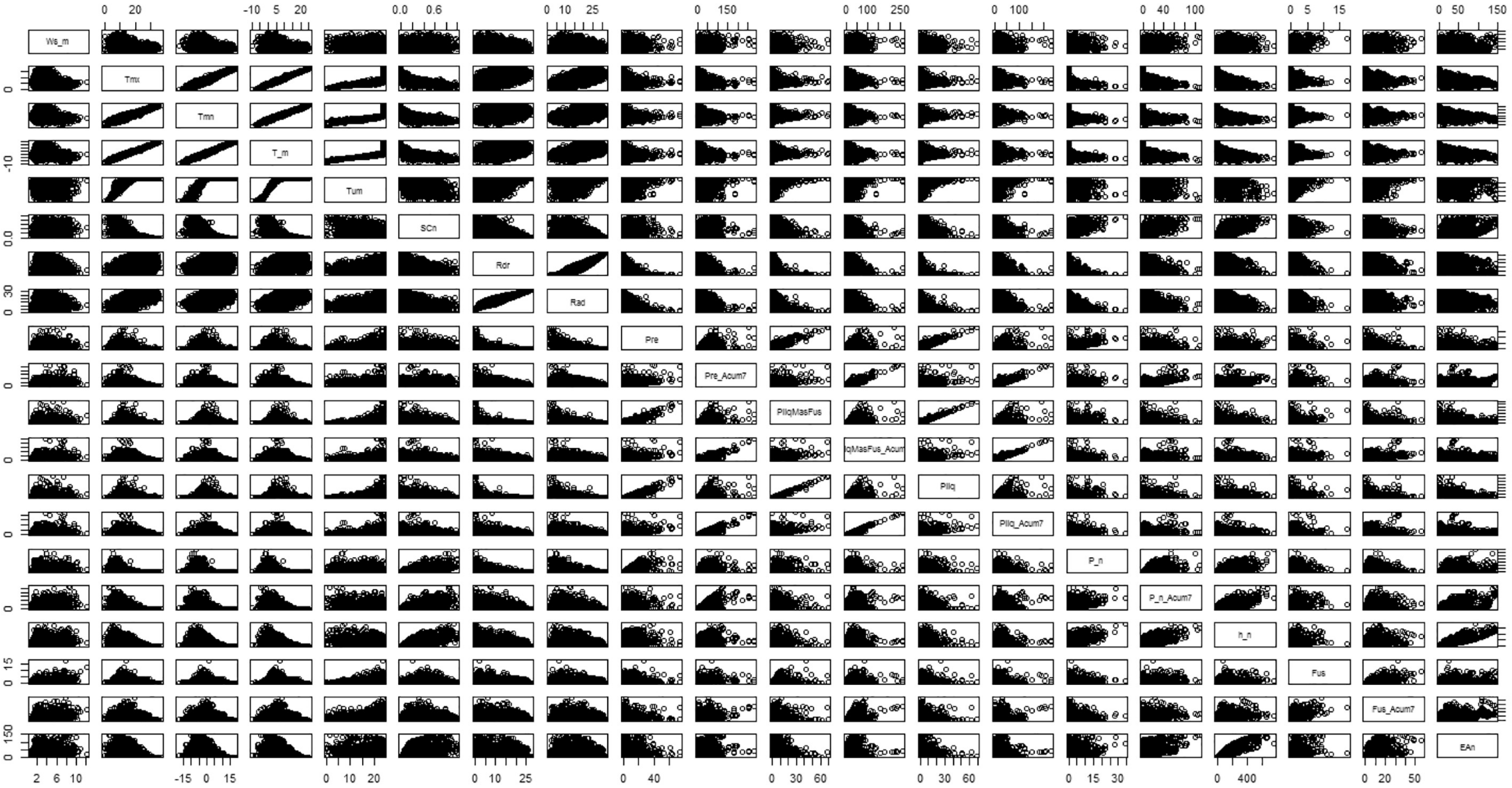

Fig. 3. Correlation graph between the 20 meteorological and hydrological variables analyzed. **Ws_m**: wind speed in m/s; **Tmx**: maximum temperature; **Tmn**: minimum temperature; **T_m**: average temperature; **Tum**: number of hours per day with temperature above 0 °C; **SCn**: fraction of snow covered surface (in decimal); **Rdr**: direct radiation (in MJ); **Rad**: global radiation (in MJ); **Pre**: total precipitation (mm); **Pre_Acum7**: total precipitation accumulated in the last 7-days; **PliqMasFus**: precipitation (rain plus snow melt) in mm; **PLiqMasFus_Acum7**: precipitation (rain plus snowmelt) accumulated in the last 7-days; **Pliq**: precipitation (rain) in mm; **PLiqAcum7**: precipitation (rain) accumulated in the last 7-days; **P_n**: precipitation (snow) in mm; **P_n_Acum7**: precipitation (snow) accumulated in the last 7-days; **h_n**: snow depth; **Fus**: snowmelt; **Fus_Acum7**: snowmelt accumulated in the last 7-days; **EAn**: amount of snow accumulated on surface in mm.

37.07%. The exchange rate in this period is slightly higher than the rate observed throughout the period (1990–2012). It is noteworthy that the highest areas (cryoromediterranean) have a 0% change in the first two periods, while the latter reaches 6.11% of total thermotype despite being highly stable habitats.

When the PI is compared to the net surface change in the 3 intervals (1990–2000, 2001–2006, 2007–2012) of the CLC that includes the preferred grass habitats in the Sierra Nevada, there are no significant differences between the means of the intervals with the mean of the complete PI series (t-student; $p = 0.1979$, $p = 0.2229$; $p = 0.7013$, respectively). This is consistent with the scarce variation observed in the first two intervals; however, it is not consistent with the variation of the last period (33.15%, Table 4).

4. Discussion

4.1. Relationship between pollen and hydro-meteorological data

The analysis of pollen emissions derived from the different grassland formations present in the Sierra Nevada highlights the diversity of factors involved in them, since in addition to the high number of existing taxa, >200, the altitudinal gradient favors the existence of numerous ecosystems, with particular environmental conditions of each bioclimatic belt. This makes a general analysis more complex. In this study, the meteorological parameters indicated as the main exogenous factors with a direct effect on flowering attributes, temperatures and rainfall were considered. Both parameters showed an altered trend with respect to historical values, more pronounced at higher altitudes (Bonet et al., 2015), and with negative values in the case of rainfall (Ruiz Sinoga et al., 2011). This could explain the dynamics observed in the aerobiological parameters of the start and end of flowering, which also have very oscillating values throughout the series, in direct relation with the conditions of temperature and water availability. Nevertheless, the influence of these parameters will be different depending on the environmental and topographic characteristics in which the grasslands are located. Thus, in grassland communities that extend through the lower and middle zones of the mountain range, the rainfall regime directly affects the optimal development of flowering, especially if they occur in the period of 1 to 2 weeks prior to the onset (Fernández-González et al., 1999; Cariñanos et al., 2004; García-Mozo et al., 2010). Ascending in height, other specific parameters are incorporated, as it has been revealed by the GLM. The variables showing most significant and positive relationship with PI were the snow covered surface fraction (SCn), the global radiation (Rad), the direct radiation (Rdr) or the number of hours per day in which the temperatures are higher than 0 °C (Tum) stand out, which allows for knowing the optimal conditions for the phenological development of grassland forming species in the highest bioclimatic belts.

The most consistent relationships were found with the indicators averaged in the Genil basin. In itself, this fact is a positive indicator of the method since the sampler (Fig. 1) is located in the lower area of the Genil basin. And at this point it is exposed to the majority influences of the basin not only when the easterly winds prevail, but also with the Katabatic nocturnal winds coming from the high mountain levels that run down the valley in the same direction (Herrero and Polo, 2016; Montávez et al., 2000).

The statistical analysis revealed that the variable with greater weight in the PI was the fraction of surface covered with snow (SCn), even ahead of variables related to temperature or water supply that could be expected to have greater weight. Firstly, this result supports our starting hypothesis regarding the importance of snow in the dynamics of mountain grasses. On the other hand, the correlation between variables is positive, which could be indicative of the adaptation of this group of grasses to the presence of snow on the peaks, and the harsh climatic conditions that these species can withstand. SCn could also behave as a complex variable that represents and encompasses other factors and variables that allow its presence and permanence in the peaks: temperature, water supply, vernalization period and even radiation.

Temperatures have proven to be one of the parameters with the most influence on the phenological behavior of grasses, as it has been shown in several studies (Myszkowska, 2014; García-Mozo et al., 2009). While some models have used the weighted sum of temperatures above a certain value as a parameter for predicting pollen concentrations (Cannell and Smith, 1983), in other studies the chilling units, defined as the number of cold hours that accumulate below a certain threshold, have been used. In the studied area, the effective temperature threshold to promote flowering would be closer to that of alpine grasslands, in which the vernalization process and short-day conditions (short photoperiod) would place the accumulated temperature threshold at around 9 °C (King and Heide, 2009). This could explain that the peak of the daily average curve values throughout the series is recorded between June and July, since as it is characteristic in alpine ecotypes. Plant species in high mountain areas usually present a shorter vernalization period (Colasanti and Coneva, 2009) and a secondary induction that requires a transition to long days enhanced by moderate-high temperatures and a photoperiod of >10 h, permitting the development of inflorescences and anthesis (Heide, 1990, 1994; Evans, 1969). In this process, the global radiation (Rad), variable with which it has shown a positive relationship would also had an effect. This variable is very high in the Sierra Nevada on the frequent sunny days during the flowering season (Aguilar et al., 2010; Herrero et al., 2011).

The water supply, both directly in the form of rain and that from snow melting, is another parameter that has resulted in a significant positive relationship with the PI. Grasses, as a majority group of herbaceous plants, have a rapid response to precipitation both in the periods immediately before flowering (Recio et al., 2010), as during the growing

Table 3

Results of standard GLM and Zero-inflated Poisson, coefficients and significance levels. **Ws_m**: wind speed in m/s; **Tmx**: maximum temperature; **Tmn**: minimum temperature; **Tum**: number of hours per day with temperature above 0 °C; **SCn**: fraction of snow covered surface (in decimal); **Rdr**: direct radiation (in MJ); **Rad**: global radiation (in MJ); **Pre**: total precipitation (mm); **Fus**: snowmelt.

	Standard generalized linear model					Zero-inflated Poisson				
Factor	Estimate	Std. error	z value	Pr(>|z|)	Signif.	Estimate	Std. error	z value	Pr(>|z|)	Signif.
(Intercept)	−8,292,894	0,108,903	−76,149	<2e−16	***	−5,861,971	0,120,724	−48,557	<2e−16	***
Ws_m	0,005012	0,001657	3026	0,002	**	0,006049	0,001690	3580	0,0003	***
Tmx	−0,015467	0,001221	−12,663	<2e−16	***	−0,016094	0,001238	−13,002	<2e−16	***
Tmn	−0,034269	0,001332	−25,729	<2e−16	***	−0,027621	0,001349	−20,478	3,40E−93	***
Tum	0,058038	0,001039	55,835	<2e−16	***	0,051883	0,001094	47,426	<2e−16	***
SCn	0,278,409	0,017868	15,581	<2e−16	***	0,161,051	0,018705	8610	<2e−16	***
Rdr	−0,097326	0,001046	−93,029	<2e−16	***	−0,073502	0,001189	−61,819	<2e−16	***
Rad	0,172,709	0,001440	119,970	<2e−16	***	0,131,258	0,001711	76,712	<2e−16	***
Pre	0,000761	0,000723	1053	0,292		0,002458	0,000743	3310	0,0009	***
Fus	0,034213	0,000593	57,744	<2e−16	***	0,033494	0,000610	54,871	<2e−16	***

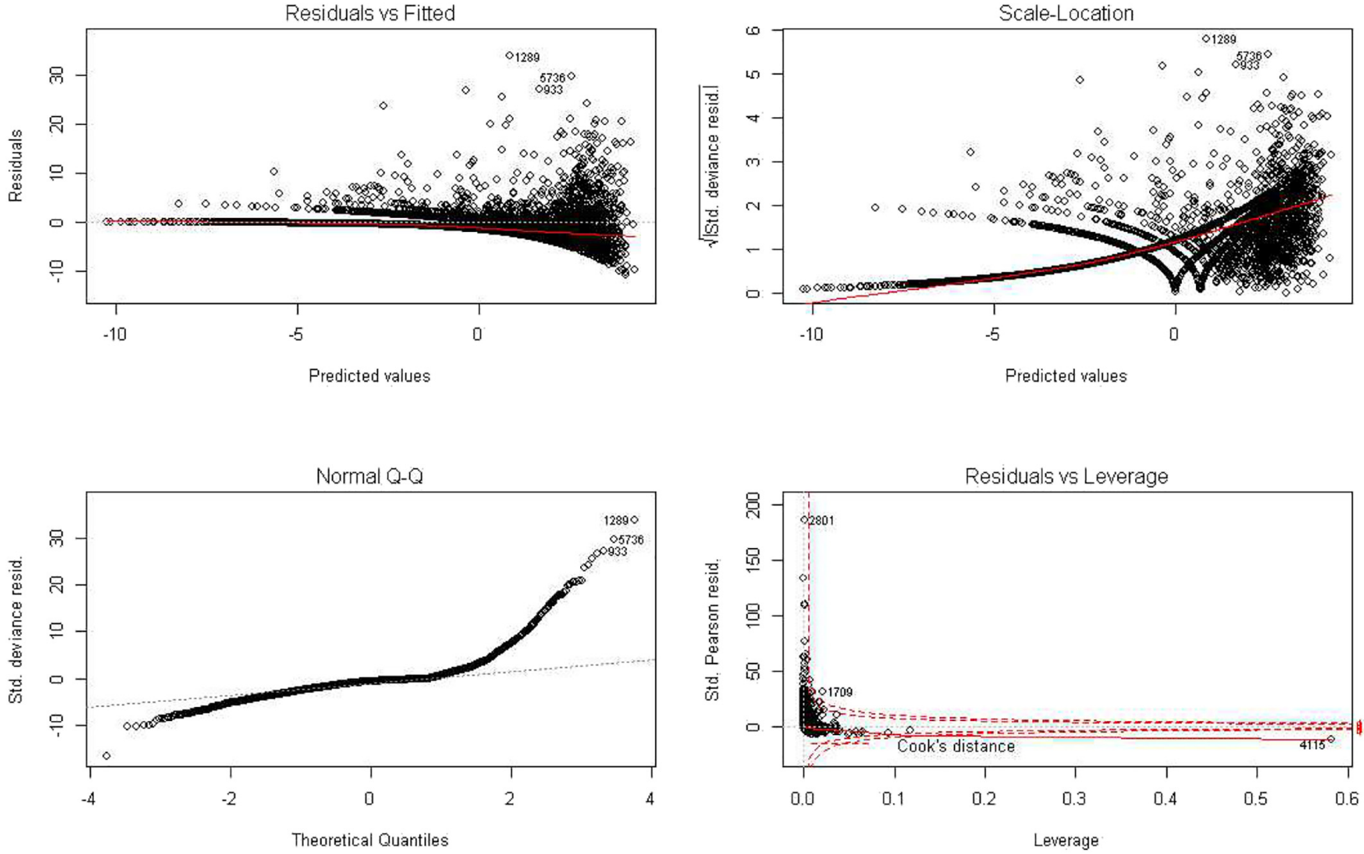

Fig. 4. GLM Poisson graphics results for 9 variables selected (red lines: mean of the data; dot lines: Cook's distance). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

season (Craine et al., 2010), which can even favor the successive flowering in different periods of the year (González-Minero et al., 1998). The water coming from the melting of snow becomes a fundamental resource in the area since the oromediterranean hygrophilic grasslands (which grow on flooded soils after thawing) depend on it (Salazar et al., 2001). This confirms the great importance of the presence of accumulations of snow outside the winter season (the so-called "neveros"), which occasionally persist until the following winter. On the one hand, the analysis yields the highest positive values such as those related to the presence of snow and contribution of water by fusion (SCn and Fus). And on the other hand, the direct precipitation factor (Pre) appears with a much lower value and significance. In the previous analysis, this variable lacked any significance (standard GLM). This is consistent with the usual characteristics in the high Mediterranean mountain, where the precipitation in summer is scarce or totally absent. So it reinforces the hypothesis about the high dependence of the vegetation on the contribution of water by melting snow in these environments (Giménez-Benavides et al., 2007). As it has already been observed in the other high mountain areas of the world, increasingly shorter and faster periods of snow melt can generate pronounced changes in pitlands and alpine grasslands (Rühland et al., 2006; Burrows, 1977; Zimmermann and Kienast, 1999). In the Sierra Nevada, although in the last 25 years no significant differences in the composition and in the abundance of flowering of the borreguiles-forming species have been detected, significant changes have been observed in the flowering attributes (Pérez-Luque et al., 2015), and in the diversity and increase of the endemicity rate (Fernández-Calzado et al., 2012).

The wind speed (Ws_m) is another influential parameter with which correlation is obtained. It is a prominent agent in the process of snow accumulation and in the dynamics of dispersion and accumulation of pollen emitted at high altitude (Navares and Aznarte, 2016; Cariñanos et al., 2013), permitting the transport of pollen grains made at medium and even long distance (Oteros et al., 2015; Rojo et al., 2015). Although some authors consider pollen from Poaceae to have a limited dispersion capability, and they are mainly recorded near the source of the emission (Peel et al., 2014), other studies consider that an aerobiological sampler may collect pollen grains of emission sources located within a radius of 30 km, and even greater depending on the characteristics of the pollen and the sampling site (Katelaris et al., 2004; Rojo et al., 2016). In the studied area, the wind regime is strongly conditioned by the orientation of the massif, which generates a daily dynamic of valley-mountain breeze, direction W-E, which facilitates the transport of pollen emissions originated in the mountains to the city during night hours. This process would also be facilitated by the smaller size of the pollen grains of grassland-forming species in relation to the grasses that participate in other mixed vegetation formations (i.e. forests), which have a larger size as an adaptation to lower dynamics of wind flow (Radaeski et al., 2016). Although the entire Poaceae family shares the same pollen morphology, analysis by optical microscopy allows differentiating size ranges. In the samples obtained in the aerobiological sampler located in the city of Granada, Poaceae pollen grains of size range between 24 and 31 μm were frequently observed, compatible with those of *Festuca* and *Poa* species (Geisler, 1945).

4.2. Relationship between pollen and changes in land use

The changes in land use experienced in the area highlight the transformations suffered by the territorial surface, and in direct relation, by the plant cover. These changes are considered a factor of influence on pollen emissions (Rojo et al., 2016; Maya-Manzano et al., 2017). The series of maps analyzed confirm that the typologies of soil that have had the greatest loss have been the "324 Transitional woodland-shrub" (6904.72 ha) and the "333 Sparsely vegetated areas" (4292.32 ha). Together, the total number of cases includes some of the preferred habitats

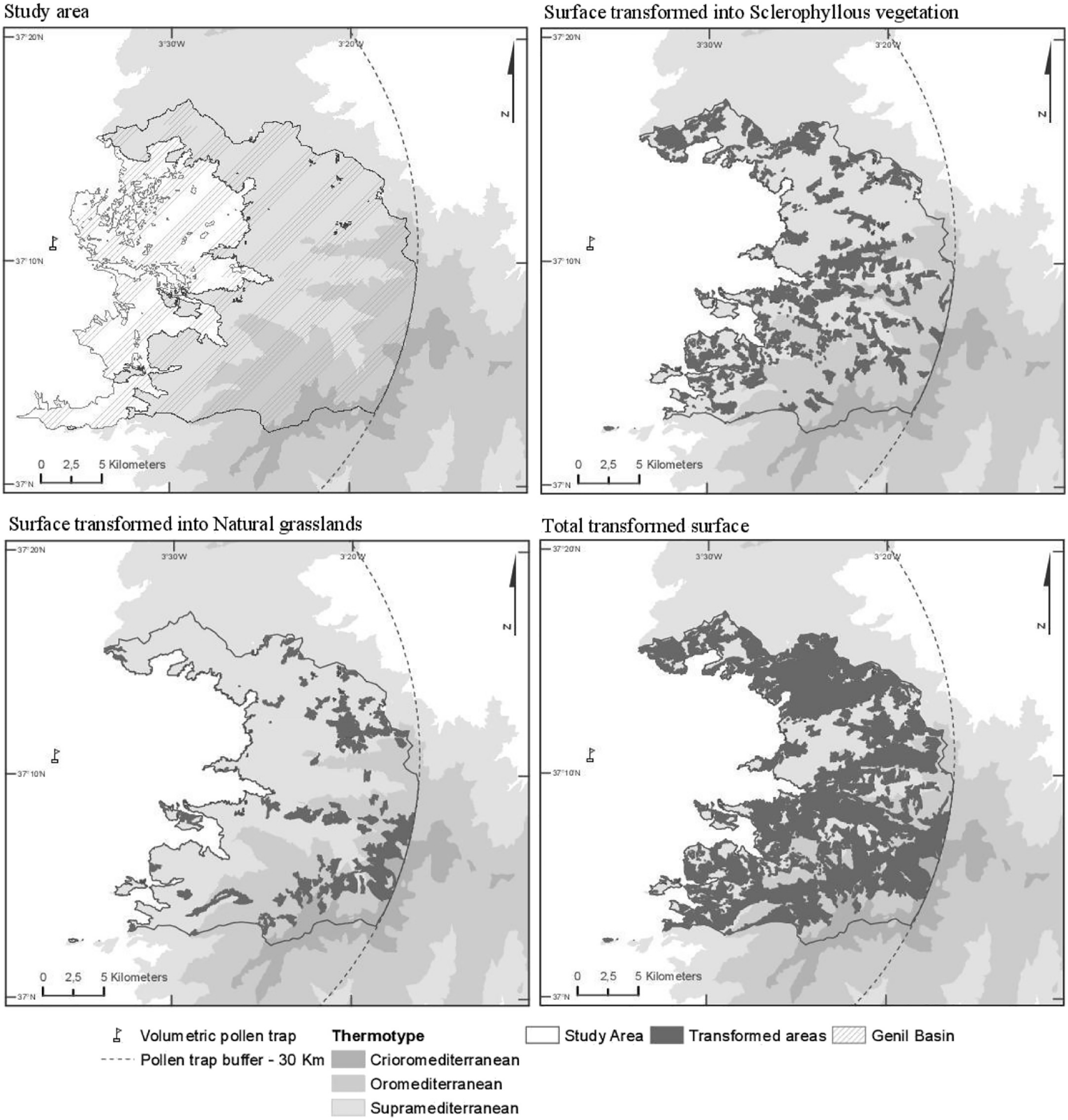

Fig. 5. Change in land use during the period 1990–2012. CLC in the framework of grass population, scale 1: 100,000.

for many species of grasses such as high mountain grasslands or agricultural lands with important natural vegetation, in which some of the most contributive species to the atmospheric pollen spectrum, such as *Dactylis glomerata*, *Lolium rigidum*, *Trisetaria panicea* and *Vulpia geniculate*, are abundant (León-Ruiz et al., 2011). This process could explain the general downward trend of the PI of grasses along the series, by adding to the remoteness of the ruderal populations, the impact of anthropogenic activities (Chen et al., 2014; García-Mozo et al., 2016). Something similar has been detected in the pollen levels of other herbaceous species in which changes in land use have been drivers of a significant decline in the PI, (Cariñanos et al., 2014; Tormo-Molina et al., 2001). In the communities of grasses that live in the Sierra Nevada, the situation has been similar, since up to 40% of the formations of scrubland and grassland have been replaced by extensive plantations of conifers, in particular of *Pinus sylvestris* (Jiménez-Olivencia et al., 2015), in which the high density of individuals and the low light intensity from under the canopy do not favor an adequate development of herbaceous.

An increase of nearly 10% of the total area is observed in one of the CLC types that can contribute the most to pollen records (“321 Natural grasslands”) and, in general, the types that contribute the most to grass (almost in the third period). However, the recorded pollen data

Table 4
Changes in land uses compared to pollen records by intervals and by thermotypes, with total and partial net change. Δ Surface: surface net variation between intervals in hectares and percentage of total study area. PI Mean: PI are calculated by means of each interval (mean ± standard deviation).

	1990–2000	2001–2006	2007–2012	Total net change
Δ Surface	181.64 (0.47%)	1.33 (0.00%)	28,729.01 (74.44%)	14,268.19 (36.97%)
Cryoromediterranean	0.00	0.00	79.46	79.46 (6.11%)
Oromediterranean	4.39	0.00	11,056.01	11,056.01 (89.44%)
Supramediterranean	177.25	1.33	17,593.53	17,593.53 (70.57%)
PI Mean	1611.00 ± 661.75	2658.83 ± 1079.14	1871.67 ± 1000.71	1920.71 ± 934.03

does not seem to reflect an expected increase consistent with this data. It is also seen that changes in the upper layers, as expected, are very light in terms of total area and regional. In the cryoromediterranean belt, changes are registered only in the last period, with most of them being a decrease of "333 Sparsely vegetated areas" and a similar increase of "321 Natural grasslands".

However, the two types with greater surface gain (up to 27.29% of the total) turn out to be two types that, a priori, would provide a large amount of grasses with their corresponding pollen emissions (Table 3): "323 Sclerophyllous vegetation" (6309.23 ha) and "321 Natural grasslands" (4262.28 ha). To this apparent contradiction are added two observations of interest: 1) the fact that a large part of the surface of the cryoromediterranean belt has varied, which is inconsistent with the real change of vegetation in these heights. And 2) the value of the area lost in "333 Sparsely vegetated areas" is practically the same as that gained in "321 Natural grasslands" (Table 3). These inconsistencies are explained when a methodological change is discovered in the cartography generated by the CLC (García-Álvarez, 2018). The last update of 2012 was developed from SIOSE (Land occupation information system in Spain), a database of land occupation at a national level with a scale higher than that used in the CLC (equivalent 1:25,000). This increase in the degree of detail, together with the different cartographic origin, seems to explain the sudden appearance of new land uses in 2012 (i.e. fruit trees and berry plantations or Agro-forestry areas) and certain substitutions between types (i.e. "321 Natural grasslands" and "333 Sparsely vegetated areas"). Therefore, it can be assumed that there is a slight change in land use that creates a slight decrease in pollen records, while the changes reflected in the last period are of little help. Likewise, this situation would have a lesser effect at higher elevations, where changes in land use have been less intense, and therefore climatic conditions continue to be the main drivers of changes detected in plant communities.

5. Conclusions

The results obtained in this work highlight the important role that different factors, both natural and derived from changes in land use, have in the development and maintenance of the high mountain Mediterranean grasslands, in particular, in the case of the Sierra Nevada (Spain SE).

Of the most influential variables, snow coverage stands out, followed by radiation, temperature and indirect water supply (snow melting). Conversely, direct water input (precipitation) and wind speed are revealed as the least relevant variables. In relation to snow, the importance of the presence of snow accumulations outside the winter season (snow cover) is pointed out, since they become reservoirs of water available for the grassland-forming species in the periods of greatest reproductive activity. This point to the enormous sensitivity of the high mountain Mediterranean grasslands in the face of climate change. A decrease in these resources can have direct effects on the diversity, stability and response of the most vulnerable and threatened plant communities. Changes in land use made in recent years, in which there have been significant losses in some of the preferred habitats of high mountain grasses, have also contributed to the adequate development of the Alpine Grasslands communities, being of greater intensity in areas of anthropogenic influence. As a follow-up measure of the changes that take place, accurate cartographic information must be counted, although the spatial analysis must rely on the collection of specific data in the field. In this context, the PI is shown as a useful indicator of global change given its sensitivity to both anthropogenic and hydrometeorological changes. In addition, it has a wide range of spatial detection and discrimination capacity by altitudinal dimensions.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.08.311.

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