



Increasing resolution of airborne pollen forecasting at a discrete sampled area in the southwest Mediterranean Basin

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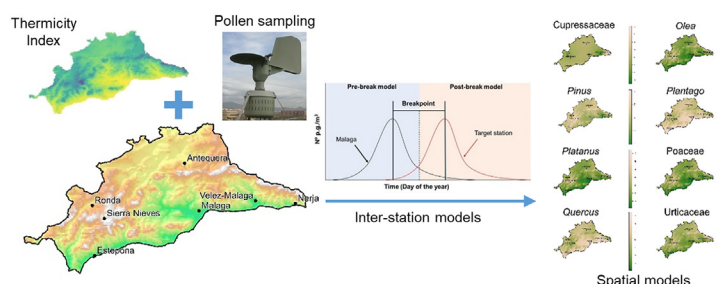
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HIGHLIGHTS

- Airborne pollen levels can be estimated at unsampled locations.
- Databases of sampling stations can be completed with data from neighbour stations.
- The Compensated Thermicity Index can be used to elaborate atmospheric pollen maps.

GRAPHICAL ABSTRACT



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ABSTRACT

Daily fluctuations of the airborne pollen concentrations produce variations on symptomatology in allergic population. Such fluctuations are influenced by local vegetal coverage, flowering phenology, geography and climatology. Since 1991, airborne pollen of Malaga province (southern Spain) has been monitored in 7 different locations. Malaga station has been kept operational uninterruptedly throughout the studied period, while the rest of the stations only worked in periods of 2–4 years. Weekly, its pollen information is updated online to inform the population in order to prevent allergic diseases. Increasing the spatial resolution of pollen information would be very useful for allergic population living at unsampled locations. Due to the impossibility of keeping operational a high number of pollen stations covering the whole province of Malaga, the aim of this study is to create spatial models to extrapolate and forecast the pollen concentrations to Malaga province by using the concentrations registered at the capital as unique input. To do so, the relationships obtained between the airborne pollen concentrations detected at Malaga city and those detected at the other stations have been used to elaborate models for the main pollen types registered at the province. These models were spatially interpolated all over the province by using co-kriging techniques and the Compensated Thermicity Index as covariable. As result of this work, pollen distribution of the 8 most prevalent taxa has been depicted all over the whole Malaga province and an allergy alert system has been set up to extrapolate pollen information from Malaga to the whole province.

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1. Introduction

Daily fluctuations of airborne pollen concentrations produce variations in symptomatology of allergic population during the main pollen season. Even people with high sensitization to pollen allergens refer changes in symptoms intensity due to such variations of pollen concentrations (Durham et al., 2014). Since local climatic and geographic conditions as well as vegetal coverage of small areas influence the pollen concentrations registered at a certain location, increasing the spatial resolution of pollen forecast would be very useful in order to keep informed allergic population about pollen concentrations (Aguilera et al., 2015; Aguilera and Ruiz Valenzuela, 2012; Kasprzyk, 2006; Oteros et al., 2014).

There is a real demand on pollen data by the society in general. Due to airborne pollen being very variable geographically, it is necessary a dense distribution of pollen samplers close to every populated area in order to provide proper information to population. Unfortunately, obtaining pollen data by following the standard methodologies is a very expensive task and it is necessary to invest a large amount of time and resources until reliable data can be obtained (Galán et al., 2014; Oteros et al., 2013). So, a convenient solution to provide enough pollen information to the society is by using spatial models (Oteros et al., 2019; Rojo et al., 2016).

Malaga province is situated in the west part of the Mediterranean Basin, a strategic area between two continents with a singular biological and geological history. The natural vegetation of the area, which has been mostly relegated to mountainous zones, is dominated by *Quercus* formations which have been replaced by repopulations of pines in many cases. The influence of the urban areas and crops have also modelled the vegetation distribution, leading to an increase of nitrophilous species and ornamental flora (E.g. Cupressaceae, *Plantago*, Poaceae and Urticaceae species), with a bigger impact in coastal areas (Fick and Hijmans, 2017; Recio et al., 2018, 1998). Inland the province, there are vast extensions of olive crops which produces high amounts of pollen grains (Recio et al., 1996). The vegetal composition of the area is also represented in the airborne pollen composition, being Cupressaceae, *Olea*, *Pinus*, *Plantago*, Poaceae, *Quercus* and Urticaceae the most abundant pollen types detected (Recio et al., 1998). Some of these pollen types (i.e. Cupressaceae, *Olea* and *Quercus*) have been cited as the most relevant sources of tree aeroallergens in many Mediterranean areas of the world and all of them have high impact on allergic population (European Academy of Allergy and Clinical Immunology, 2015; 2014). Other pollen types belonging to ornamental species such as *Platanus* have also high impact on allergic population despite not being one of the most abundant during the whole year. *Platanus* pollen concentrations can reach high levels and cause severe symptoms in allergic population during its flowering period (Alcázar et al., 2004).

Since 1991, the Aerobiology research team of the University of Malaga has been monitoring the pollen concentrations of the atmosphere of Malaga province at 7 different locations (Docampo et al., 2007; Recio et al., 2006, 2000, 1998). Despite the major part of the province has been monitored, not all the sampling stations are active at present. Malaga city station has been continuously kept operational, without interruptions, since 1991 and it is the main station of the province. Atmospheric pollen sampling during long time series enables the study of phenological tendencies and the effect of climate change on anemophilous species. Significant tendencies have been previously observed in Malaga city for herbaceous (García-Mozo et al., 2010; Recio et al., 2010, 2009) and woody taxa (Orlandi et al., 2010; Recio et al., 2018). Once a week, the airborne pollen levels recorded at the active sampled points of the province are published on the webpage of the Aerobiology research team (<http://http://www.aerobiologia.uma.es/>) to inform allergic population. A brief forecast for the following week is also included. Increasing the spatial resolution of this information can be useful for the population living at locations which are not currently being monitored.

The aim of this study is to develop spatial models in order to describe pollen distribution throughout Malaga province and to set up a system for automatically estimating pollen concentrations all over the area by using the concentrations registered at Malaga city sampling station as unique input.

2. Material and methods

At first, the relationship between pollen concentrations registered at the different historical sampling station and at the capital, Malaga city (Inter-station models) were established. Those models were based on the linear relationship of daily pollen concentrations between stations. Once the models were developed and validated, spatial interpolation was performed by spatial modelling (Spatial models) to elaborate maps with the parameters of the inter-station models and thus, to interpolate pollen concentration between historical sampling locations.

2.1. Study area

The study was conducted in 7 locations of Malaga province (southern Spain): Antequera, Estepona, Malaga, Nerja, Ronda, Sierra de las Nieves and Velez-Malaga (Fig. 1). The coastal location of the province and its Mediterranean climate are responsible of the warm temperatures registered all over the year with mild winters and hot summers. At the sampled locations, the annual mean temperature varies among 13.2 °C (Sierra de las Nieves, 1070 m a.s.l.) and 18.4 °C (Malaga, 45 m a.s.l.), being higher in the coastal area than inland. Total annual precipitation is limited in the area of study, being the maximum values registered at Sierra de la Nieves (831 mm) and the minimum at Nerja (382 mm), among the sampled locations. In general, precipitations are more abundant in the northwest part of the province, decreasing towards the southeast (Fick and Hijmans, 2017; Recio et al., 2009, 1996). The orography of Malaga is characterized by abundant mountainous formations except for the alluvial plains of Guadalmedina, Guadalhorce and Velez rivers, and a very narrow coastal strip between the mountains and the Mediterranean Sea. The depressions of Antequera and Ronda are located in the north part of the province and are totally exploited by rainfed crops (i.e. olive and cereals).

2.2. Pollen data

Airborne pollen was collected by means of Hirst-type volumetric pollen traps (Hirst, 1952). Samples were mounted and counted following the methodology proposed by the Spanish Aerobiology Network (REA) and the recommendations of the European Aeroallergen Society (EAS) (Galán et al., 2014, 2007). The pollen traps were regulated to aspire at a continuous flow of 10 l/min. For each slide, four longitudinal sweeps were read at a magnification of x400 with the aid of a light microscope. Pollen data were expressed as daily mean concentrations (number of pollen grains/m³ of air).

The historical pollen database of the Aerobiology research team of the University of Malaga was used for this study. The periods sampled for each locality are shown in Fig. 2. Pollen information was analysed and managed with “Aerobiology” package developed for R software (Rojo et al., 2019).

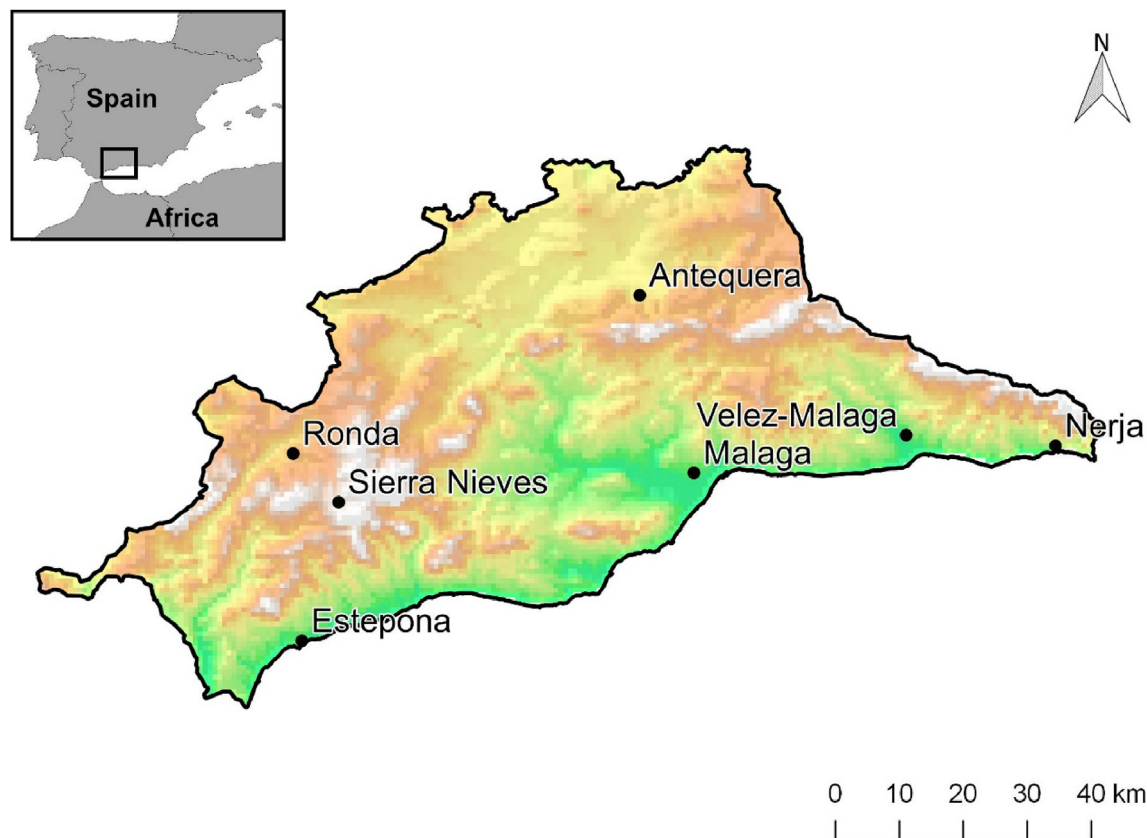


Fig. 1. Hypsometric map and location of Malaga province. Airborne pollen sampling locations are marked with points.

2.3. Elaboration of the inter-station models

For each station, data of one year were removed from the training datasets to be used during external validation (Antequera 1998; Estepona 1995; Nerja, 2000; Ronda 2018 and Velez-Malaga 2005). Additionally, Sierra de las Nieves dataset was entirely removed from the training data to be used during the second external validation (see geographical interpolation model, section 2.4.).

Models were carried out for the most abundant and relevant pollen types registered: Cupressaceae, *Olea*, *Pinus*, *Plantago*, *Platanus*, Poaceae, *Quercus* and Urticaceae.

During the training process, inter-stations models were created for each year, pollen type and location. Due to the observed differences in phenology timing between Malaga station and other locations, composed general models were necessary. The relationships between the pollen concentrations of Malaga and the other stations were different according to the time of the year. Because of that, each natural year was split in two equal parts and each part was used to train a different model: “pre-break” model and “post-break” model. The peak dates for each station were calculated and the day which was equally distanced to both peak days was selected as the breakpoint. The breakpoint is the day of the year in which the application of the “pre-break” model stops and starts the application of the “post-break” model (i.e. the day to change between models). The period of 182 days after the breakpoint was used to train the “post-break” model and the rest was used to train the “pre-break” model (Fig. 3).

The models were built by lineal regression of daily pollen concentration between every target station and Malaga, β was set to 0. The general model had 3 parameters: the “pre-break” regression coefficient, the “post-break” regression coefficient and the distance (in days) between Malaga pollen peak day and the breakpoint. Once a composed model was created for each year, the means of the 3 parameters were used to create the general inter-station model.

Models were first internally validated with the training datasets and the accuracy of the models was expressed as Mean Absolute Error (MAE) (equation (1)), which has been proved to be more easily interpretable and less unambiguous than the Root Mean Square Error (RMSE) in assessing average model performance (Willmott and Matsuura, 2005).

$$MAE = \frac{\sum_{i=1}^n |Predicted - Observed|}{n} \quad (1)$$

The models were created to give pollen information to population and, consequently, the general model output was converted into the pollen categories proposed by the REA (Galán et al., 2007) to make results easier to understand.

The external validation was performed with the years which were not included during the training process. Results were expressed as accuracy rates (equation (2)).

$$Accuracy\ rate = \frac{N^{\circ}\ correct\ forecast}{N^{\circ}\ total\ forecast} \quad (2)$$

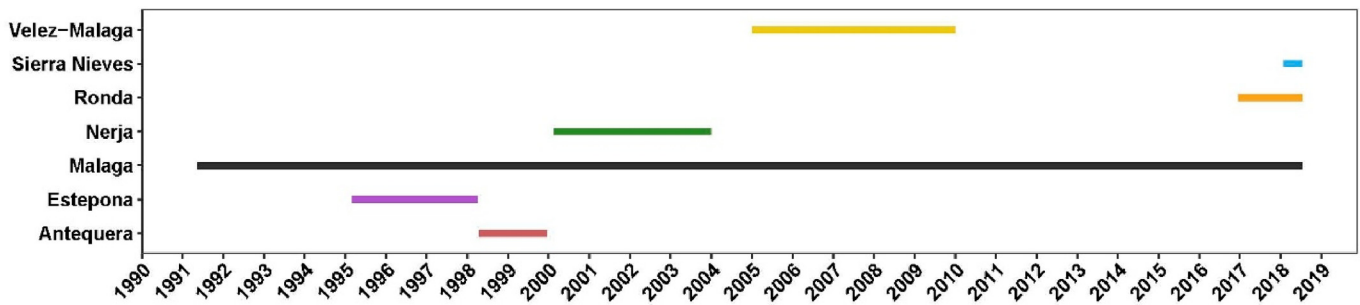


Fig. 2. Sampling periods and available pollen data for each aerobiological station in Malaga province.

2.4. Spatial models

Co-kriging techniques were used to elaborate spatial models and maps for the parameters of the inter-station models, with a resolution of 1 km². These techniques have been previously used by other authors to spatially interpolate the pollen concentrations detected at different areas which are continuously and simultaneously sampled (Alba et al., 2006; Oteros et al., 2019; Rojo et al., 2016; Rojo and Pérez-Badia, 2015). Once a composed model was created for each sampled location of Malaga province, their parameters were spatially interpolated at unsampled points of the province according to their relationship with the Compensated Thermicity Index. This index was designed to compensate the Thermicity Index in extratropical territories of Earth. In this case, it compensates the winter warmth of Malaga province due to its oceanic climate (Rivas-Martinez et al., 1997). The Compensated Thermicity Index has been proved to be a limiting factor in the distribution of plants and plants communities and, moreover, to have a big impact in plants phenology and pollen forecasting (Pesaresi et al., 2014; Valencia-Barrera et al., 2002). It was calculated as in equation (3) with the climatic data obtained from WorldClim (years 1970–2000; with a resolution of 1 km²) (Fick and Hijmans, 2017). Data were processed with a combination of

different R software packages: “envirem”, “raster”, “gstat”, “sp” and “geoR” (Hijmans and van Etten, 2014; Pebesma and Bivand, 2005; Pebesma, 2004; Ribeiro and Diggle, 2015; Title and Bemmels, 2018)

$$Itc = (T + m + M) * 10 + C \quad (3)$$

where *I*tc, Compensated Thermicity Index; *T*, mean annual temperature; *m*, mean minimum temperature of the coldest month; *M*, mean maximum temperature of the coldest month; *C*, compensated value dependent of the Ombrothermic Index (Rivas-Martinez et al., 1997).

Three maps were created for each pollen type (one map for each parameter of the composed inter-station model). The theoretical parameters of the composed inter-station model for Sierra de las Nieves were calculated by the spatial model and extracted from the maps. The model was used to perform a forecast of daily pollen concentrations for this location (January–July 2018) using the pollen concentration of Malaga station of the same period as input. The results of the model were converted into the pollen categories proposed by the REA (Galán et al., 2007) and were externally validated with the real levels detected at this location during this period. Results were expressed as accuracy rates (see equation (2)).

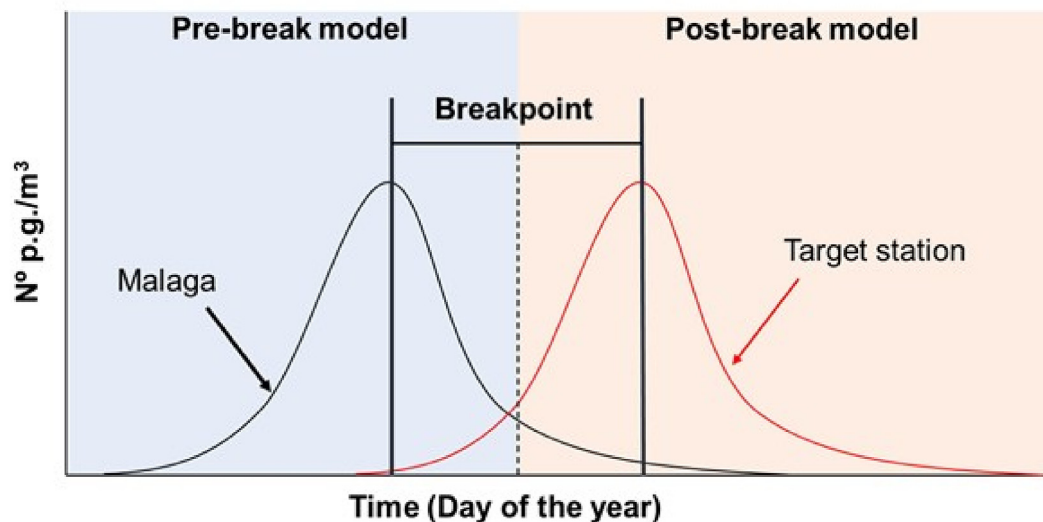


Fig. 3. Theoretical diagram of the inter-station model elaboration. In black, pollen curve of Malaga station; in red, pollen curve of the target station. Vertical black lines mark the peak days of the main pollen season in each station. Dashed line marks the breakpoint to change between pre-break and post-break model, which is the half of the time distance between peak days. The period in which each model is applied is marked with different background colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

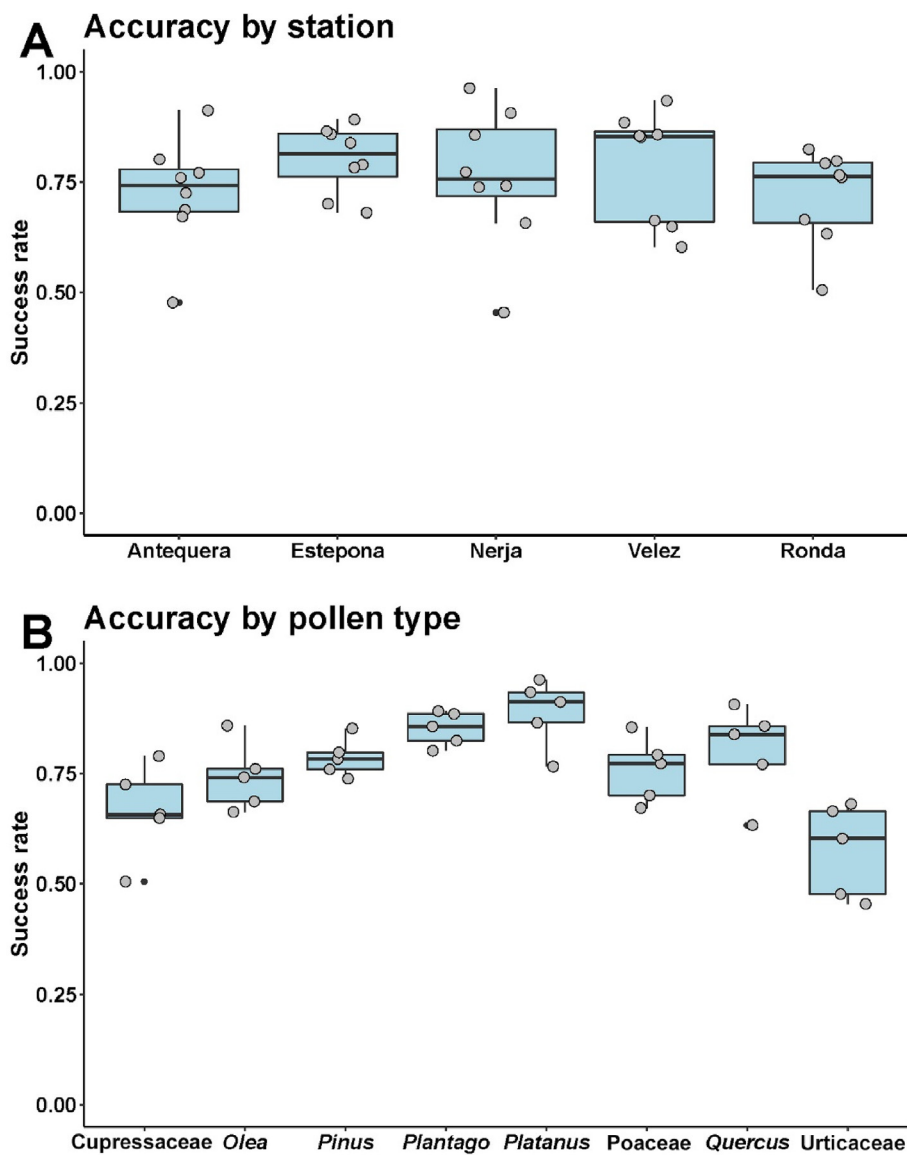


Fig. 4. Accuracy of the performance of the models obtained during the external validation. A) Accuracy of the models by station. Each dot represents the accuracy obtained by each pollen type for this station. B) Accuracy of the models by pollen type. Each dot represents the accuracy obtained by each station for this pollen type. Each box includes the 50% of the data. The median is marked with a bold line.

3. Results and discussion

3.1. Performance of the models

During the internal validation, the performance of the models obtained an average MAE of 9.36 pollen grains/m³ of air. More detailed information of the MAE for a concrete pollen type, year and station can be consulted in the Appendix.

The accuracy rates of the models during the external validation are shown in Fig. 4. In all the cases, the accuracy rate was higher than 0.70 and in the most part of the cases was higher than 0.75.

The highest accuracy rate by station was reached by Estepona (0.80) and the lowest by Ronda (0.72) (Fig. 4A). Coastal locations (e.g. Estepona, Nerja and Velez-Málaga) had higher accuracy rates than inland locations (e.g. Antequera and Ronda) and pollen concentrations registered in these groups of stations were more similar than between groups. Such similarities detected inside these groups can be explained by the similar land use coverage in their nearby locations and by their Compensated Thermicity Index (lower in Ronda and Antequera than in the other locations). Moreover, the coastal mountainous formations of the province reduce the exchange of air masses between coastal and inland locations, reducing also the amount of airborne pollen which is shared between them. Since models were based in the pollen concentrations registered at a coastal location (Málaga) the performance of the models had higher accuracy rates for other coastal locations.

The highest accuracy rate by pollen type was reached by *Platanus* (0.88) and the lowest by Urticaceae (0.57) (Fig. 4B). Urticaceae family is represented in the area by nitrophilous herbs (such as *Parietaria* species) whose abundance depends on the local characteristics of the surrounding areas of the pollen traps (e.g. abandoned houses or unbuilt plots of land) and therefore, their pollen concentrations in the air are more difficult to predict by using the levels of other station (Recio et al., 2009). Other pollen types such as Cupressaceae are also difficult to predict since they are highly influenced by ornamental species such as *Cupressus sempervirens* L. and *Cupressus arizonica* Greene whose distribution and abundance change widely between sampled stations (Trigo et al., 1997; Velasco-Jiménez et al., 2014). *Olea*, *Pinus*, *Plantago*, *Platanus*, Poaceae and *Quercus* have high accuracy rates.

3.2. Geographical interpolation of the models

The results of calculating the Compensated Thermicity Index for the whole area of Málaga province are shown in Fig. 5. In general, the index had a similar distribution to altitude, being higher at the coast and river valleys, and lower at the mountainous areas. Nevertheless, there were slight differences with altitude due to the terrain orientation and microclimatic conditions.

The geographical interpolation of the parameters of the models are shown in Figs. 6 and 7. In general, the parameters of the models are more similar at coastal areas and at inland areas than in between these areas.

The results of the external validation of the interpolated model for Sierra de las Nieves station are shown in Fig. 8. In general, the accuracy rates of the model were over 0.60. The highest rate was reached by Poaceae (0.82) pollen type and the lowest by Cupressaceae (0.19). Cupressaceae populations in the area are represented by high mountain species such as *Juniperus sabina* L. and *Juniperus communis* L., which are not present in the other sampled locations of the province (Pérez Latorre and Cabezudo Artero, 2002; Pérez Latorre et al., 1999; 1998). These species have differences in phenology timing and pollen production with the ornamental Cupressaceae species mentioned in the section 3.1. and which are not present in the area. Consequently, pollen predictions based on Málaga pollen concentrations are not accurate for this pollen type. *Quercus* pollen type had also a low rate of accuracy. The pollen trap installed in Sierra de las Nieves is located inside an oak tree forest (*Quercus rotundifolia* L.) and *Quercus* pollen type is overrepresented in the pollen counts of this station. Urticaceae accuracy rate can be explained as mentioned in section 3.1. The accuracy rates of the remaining pollen types were similar to the rates obtained during the external validation of the composed models (section 3.1.) with some differences due to the local conditions of Sierra de las Nieves stations (i.e. land use coverage and flowering timing of local populations).

The rate accuracy of these models could be improved coverage in future studies by adding detailed information of the spatial distribution of real vegetation and land use. A detailed research of the vegetal coverage of each taxon should be done in order to unify and complete the land use information available at the moment for the area (e.g. satellite images, distribution of vegetal communities, crops and distribution of ornamental species in urban areas). Due to

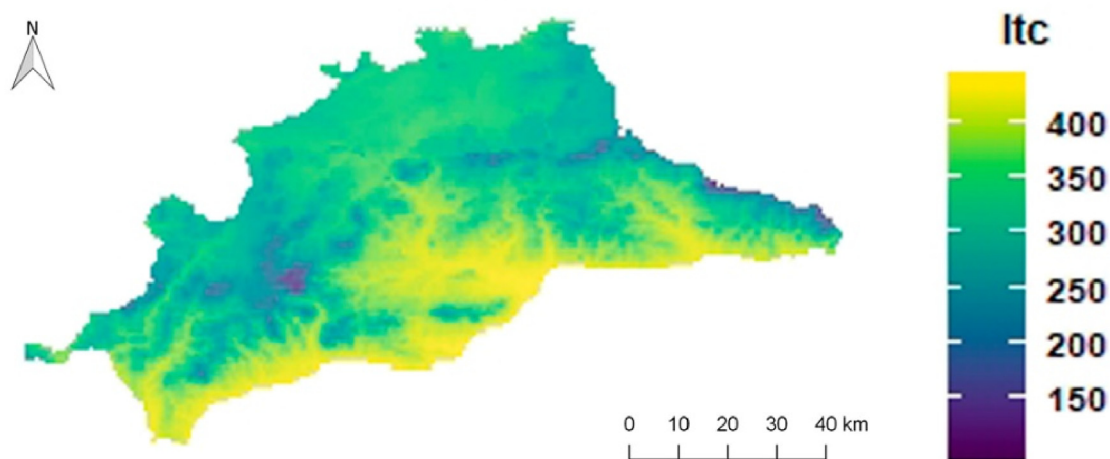


Fig. 5. Compensated Thermicity Index (Itc) in Málaga province. Calculated with climatic data obtained from WorldClim (years 1970–2000; with a resolution of 1 km²).

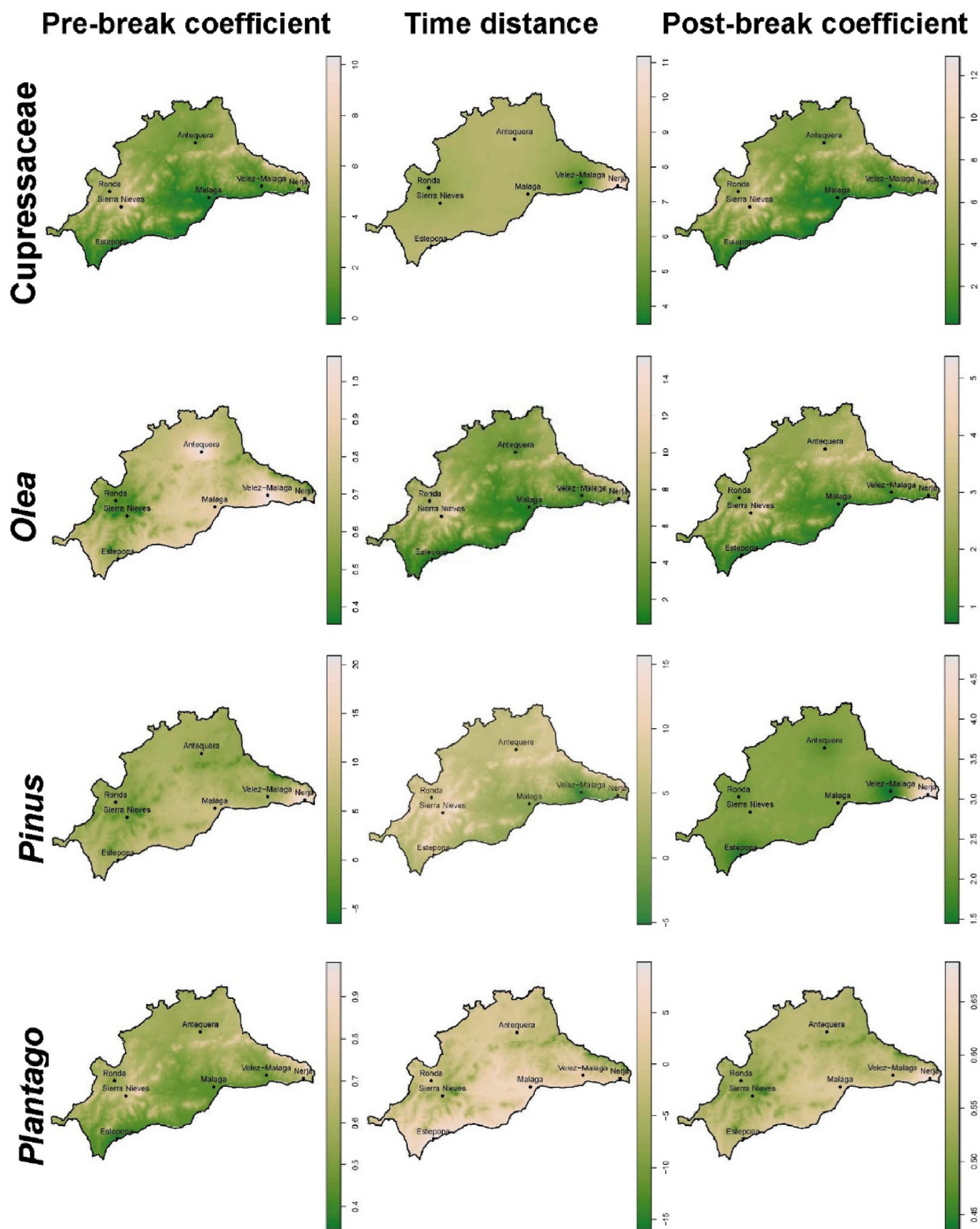


Fig. 6. Spatial representation of the regression coefficient of the pre-break model (pre-break coefficient), regression coefficient of the post-break model (post-break coefficient), and the time distance (in days) between the peak date of Malaga and the breakpoint of the models (time distance). Obtained by co-kriging techniques for *Cupressaceae*, *Olea*, *Pinus* and *Plantago* pollen types. Sampled stations are marked over the map.

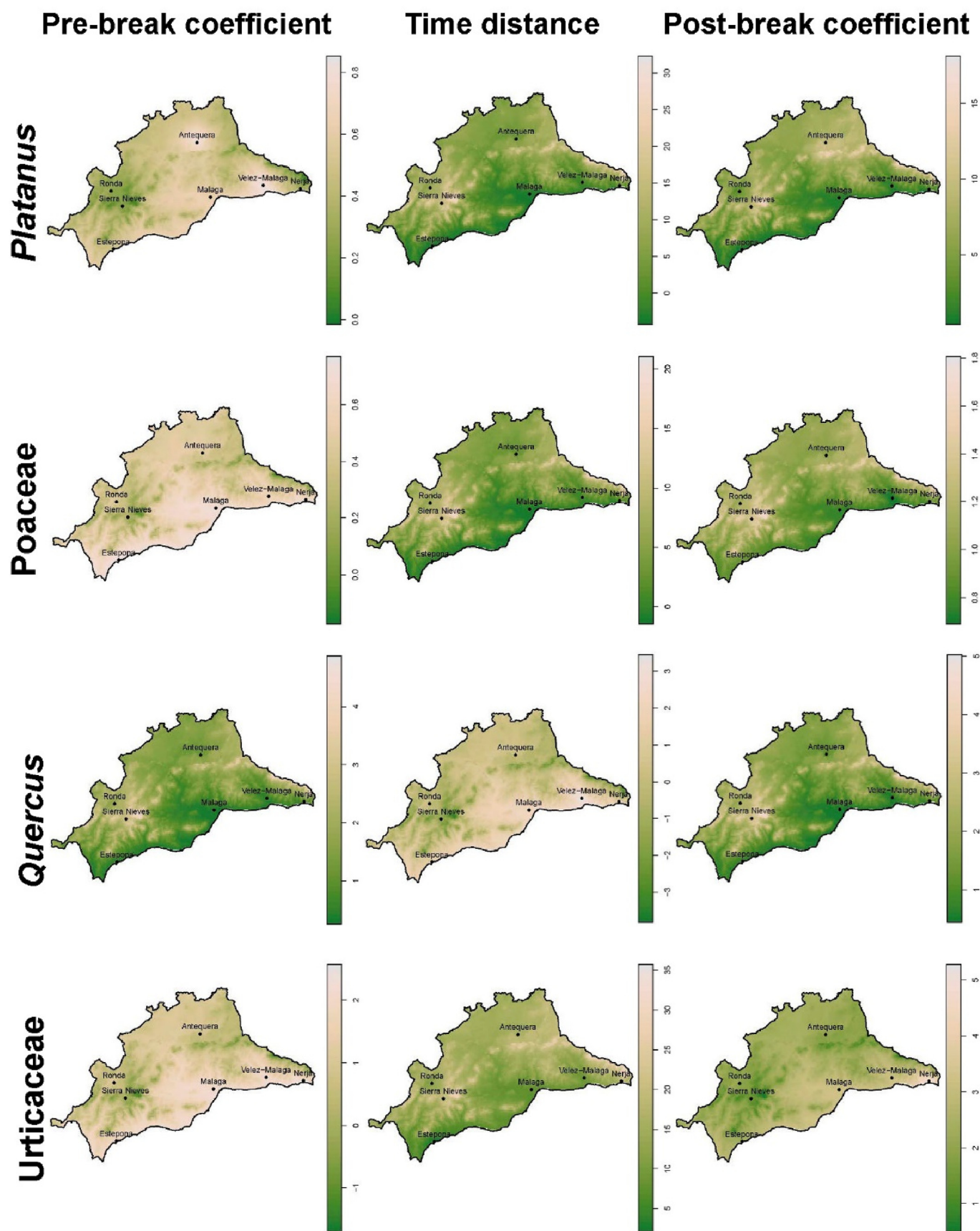


Fig. 7. Spatial representation of the regression coefficient of the pre-break model (pre-break coefficient), regression coefficient of the post-break model (post-break coefficient), and the time distance (in days) between the peak date of Malaga and the breakpoint of the models (time distance). Obtained by co-kriging techniques for *Platanus*, *Poaceae*, *Quercus* and *Urticaceae* pollen types. Sampled stations are marked over the map.

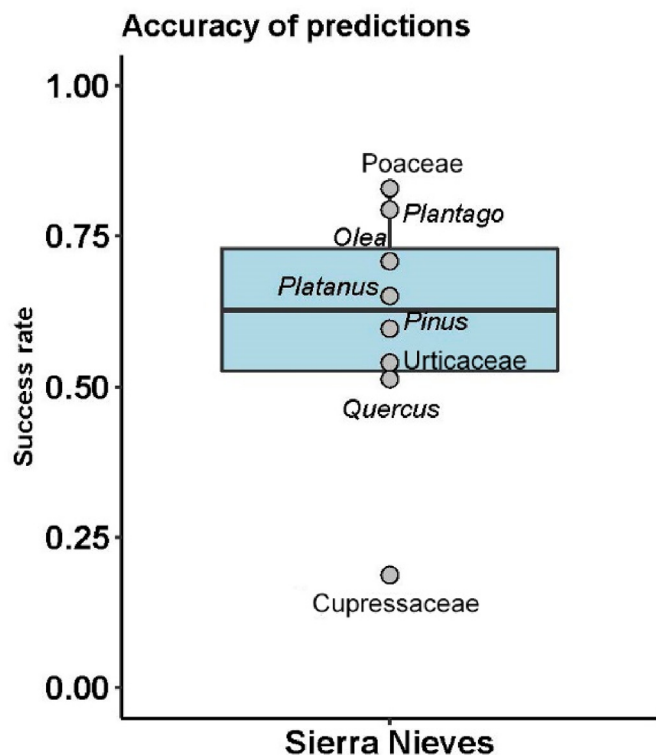


Fig. 8. Accuracy of the performance of the model elaborated for Sierra de las Nieves station. Rate of correct prediction for each pollen type. The box includes the 50% of the data. The median is marked with a bold line.

the characteristics of our study, these models should also take into account changes in vegetal coverage during the studied period (27 years), the wind influence over pollen transport and possible changes in flowering phenology and pollen production along time. Nevertheless, the methodology developed in this study may contribute to improve the pollen information given to people living at unmonitored locations and allow us to set up an automatic alert system for allergy risk very valuable for the inhabitants of the whole province.

4. Conclusions

1. With the models obtained, atmospheric pollen concentrations of Poaceae, *Plantago*, *Olea* and *Platanus* pollen types can be estimated for the whole Malaga province by using the pollen atmospheric concentrations detected in Malaga station. Those

models are the central part of a system for warning population about pollen concentration. The system only requires daily pollen concentration of Malaga to automatically deliver pollen information for the whole area.

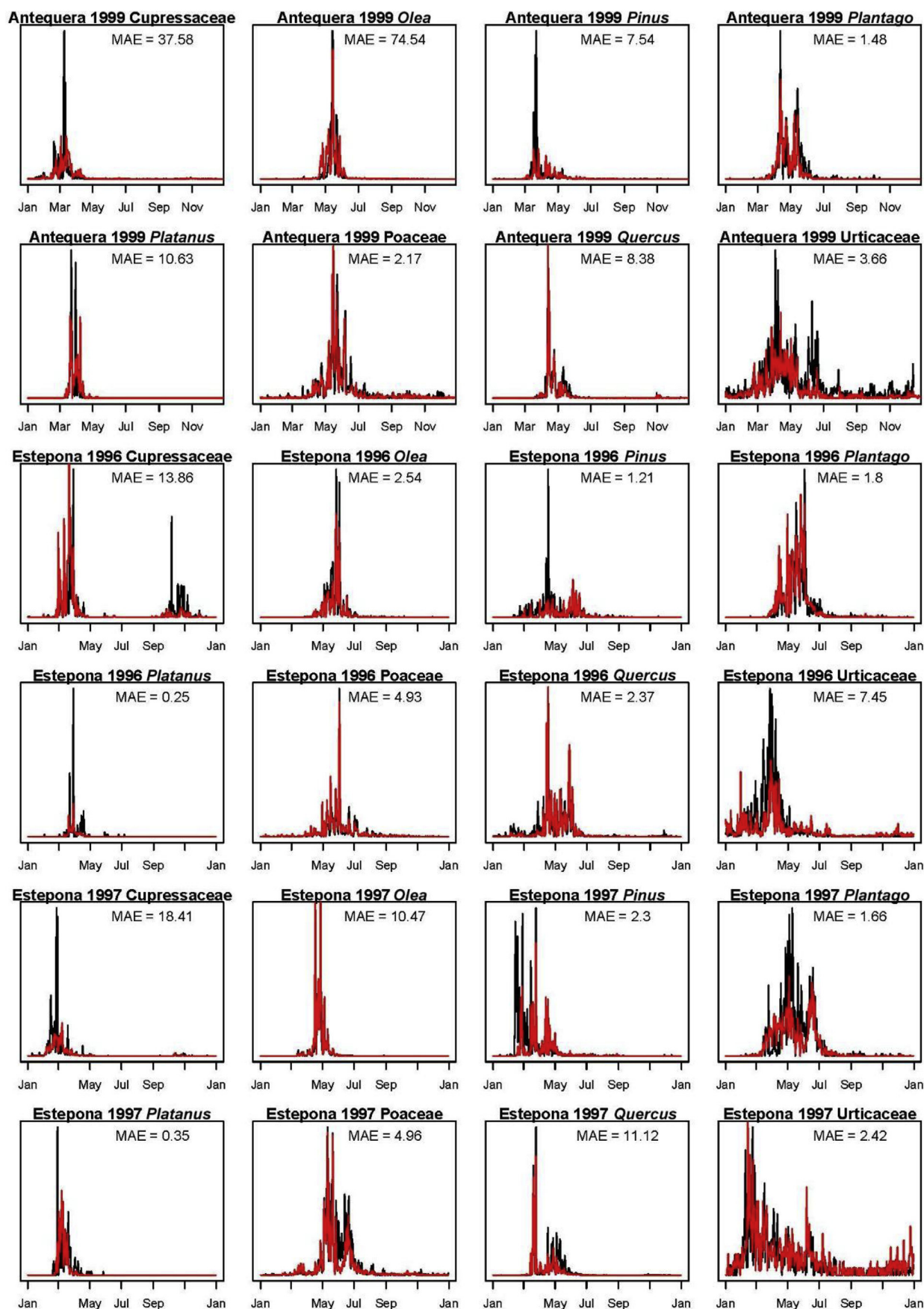
2. Due to the influence of local environmental conditions and ornamental species, the accuracy of the models can be improved by doing separate models for each group of stations: one model for coastal locations and other for inland locations. For this purpose, sampling continuously at two different locations would be necessary: a coastal location and an inland location. The accuracy of the models could also be improved by doing separate studies for each pollen type and taking into account changes in vegetal coverage during the studied period.
3. The methodology developed in this study can be used to increase the resolution of pollen forecasting in areas which have been discretely sampled at different locations and different periods. Furthermore, this method is useful to complete missing data of a sampling station by using the pollen concentrations of a nearby station.

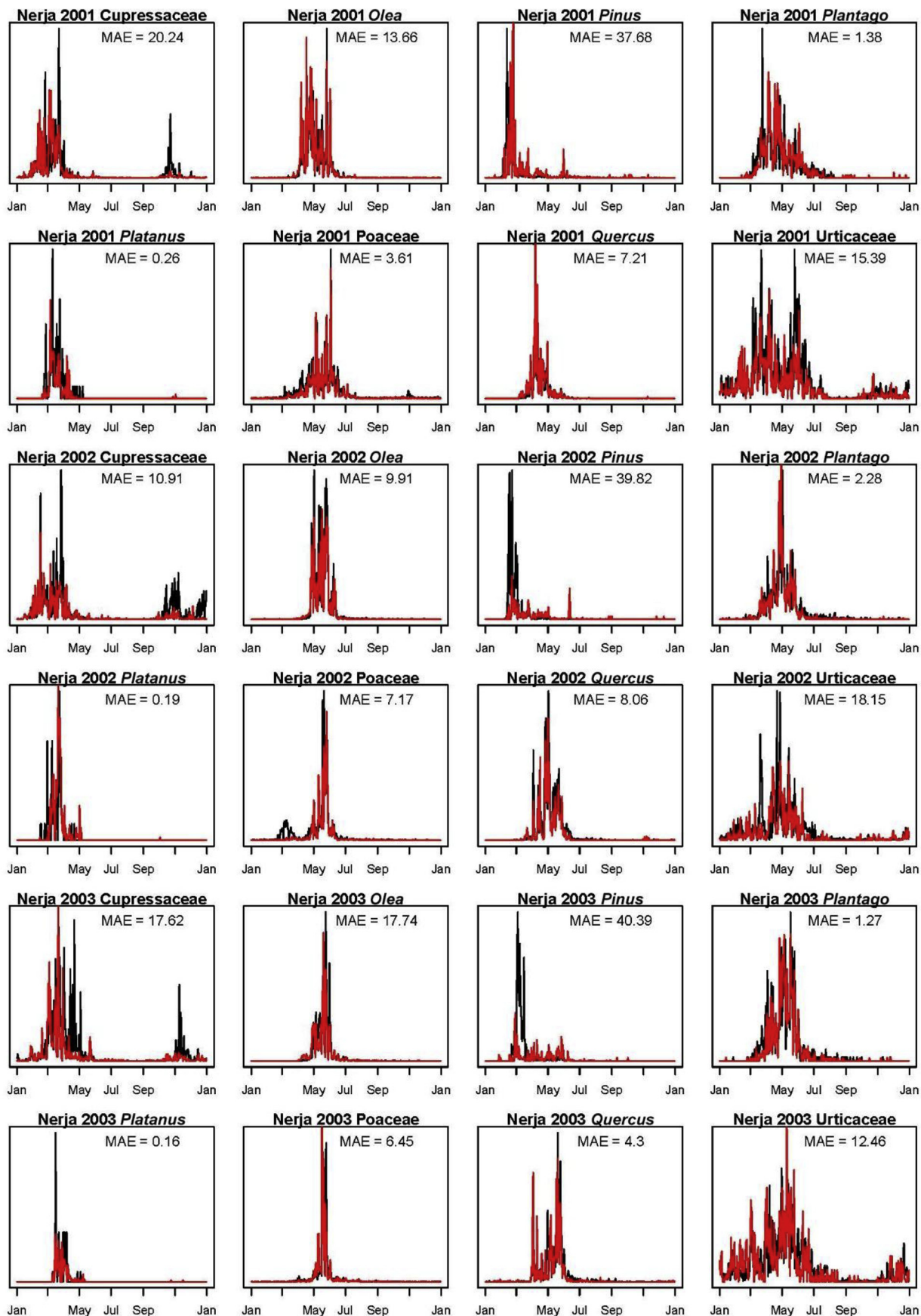
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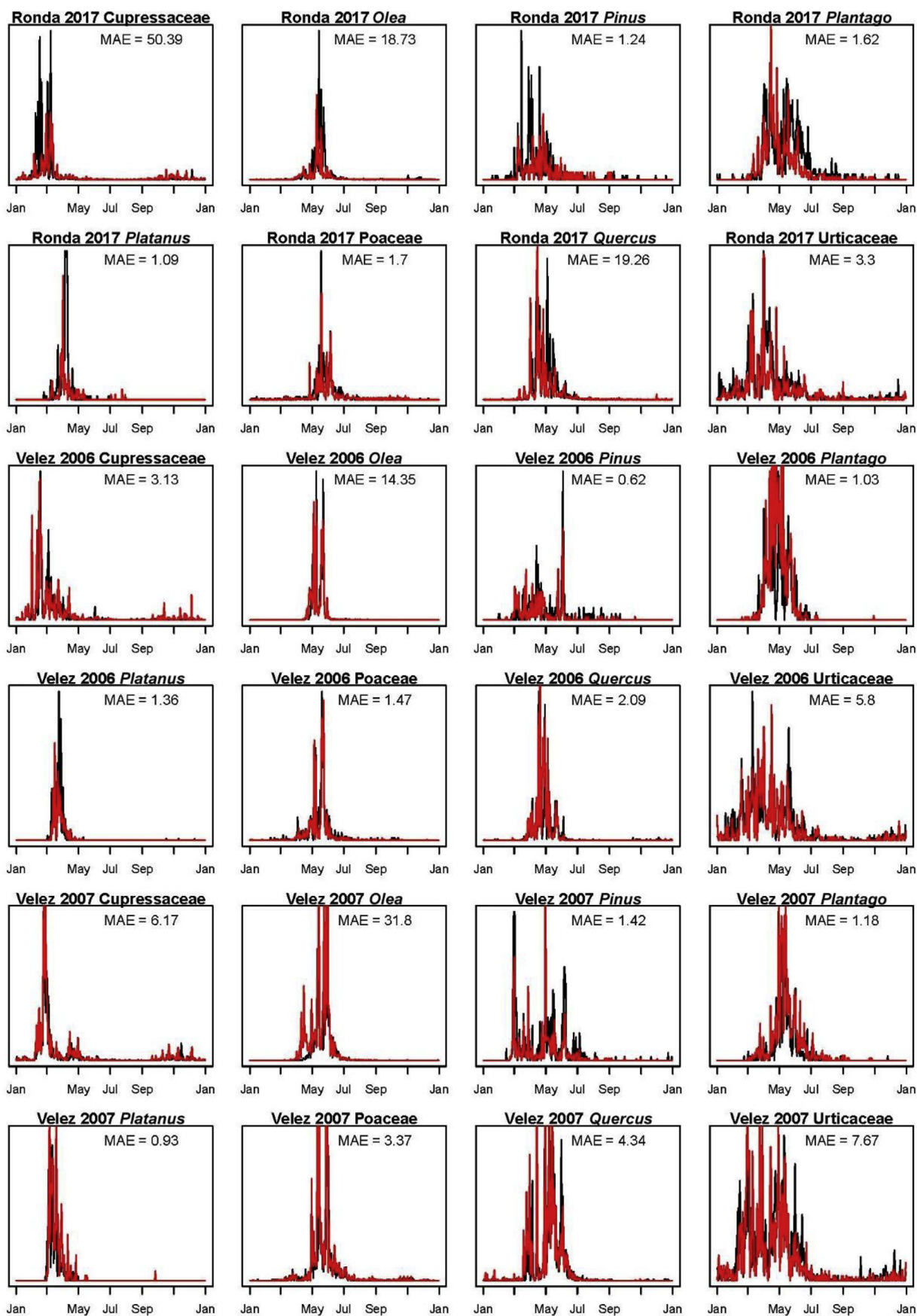
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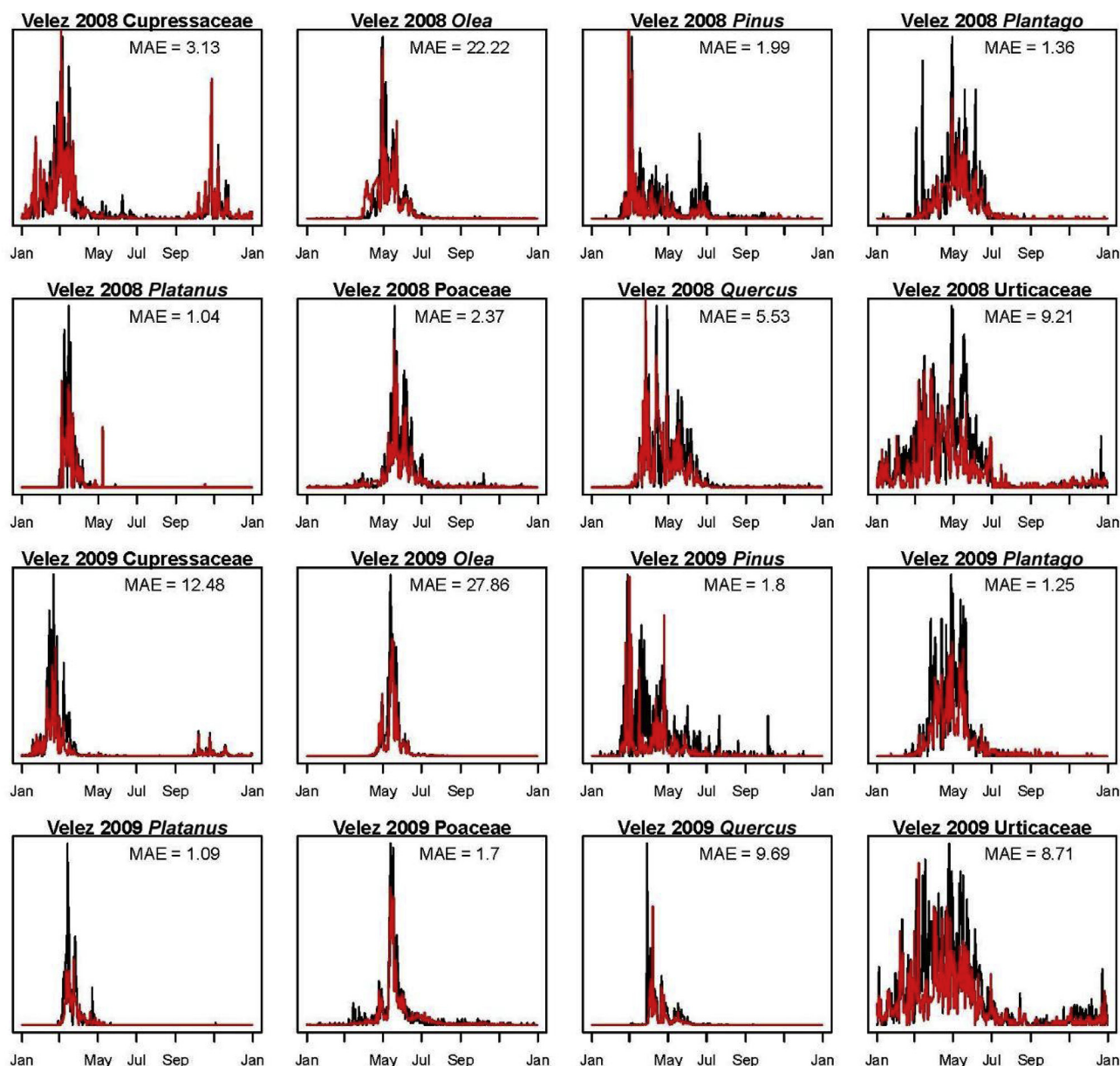
Appendix

Performance of the models during the internal validation. In black, the real pollen concentrations; in red, the pollen concentrations predicted by the models. MAE, Mean Absolute Error.









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