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Effects of climate change on *Platanus* flowering in Western Mediterranean cities: Current trends and future projections

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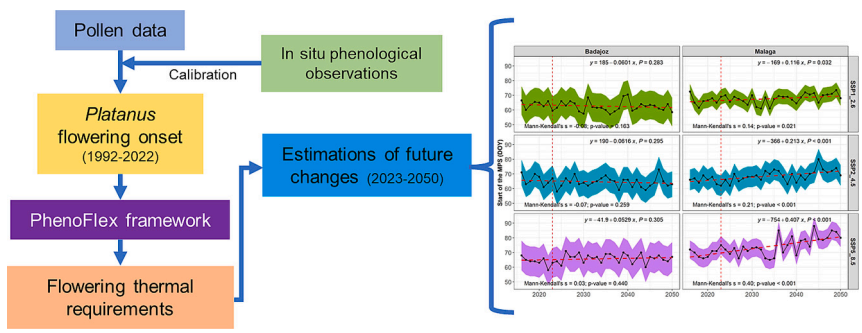
HIGHLIGHTS

- Each MPS definition had different accuracy to estimate the *Platanus* flowering onset.
- The PhenoFlex framework can be applied to forecast the flowering onset of *Platanus*.
- Errors of 3–4 days were reported when forecasting *Platanus* flowering dates.
- The global warming is producing a chilling-forcing compensation in *Platanus* flowering.
- For some regions this compensation will unbalance, delaying its flowering onset.

GRAPHICAL ABSTRACT



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ABSTRACT

Ornamental trees can reduce some of the negative impacts of urbanization on citizens but some species, such as *Platanus* spp., produce pollen with high allergenic potential. This can exacerbate the symptomatology in allergic patients, being a public health problem. Therefore, it would be relevant to determine the environmental conditions regulating the flowering onset of the *Platanus* species. The aims of this study were to use aerobiological records for modelling the thermal requirements of *Platanus* flowering and to make future projections based on the effects that climate change could have on it under several possible future scenarios. This study was conducted in Badajoz and Malaga, two Western Mediterranean cities with different climate conditions. In the first step, several main pollen season definitions were applied to the aerobiological data and their onset dates were compared with in situ phenological observations. The main pollen season definition that best fitted the *Platanus* flowering onset was based on the 4th derivative of a logistic function. This definition was used as a proxy to model the thermal requirements of the *Platanus* flowering onset by applying the PhenoFlex statistical framework. The errors

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obtained by this model during the external validation were 3.2 days on average, so it was fed with future temperature estimations to determine possible future trends. According to the different models, the flowering onset of *Platanus* in Badajoz will show heterogeneous responses in the short and medium term due to different balances in the chilling-forcing compensation, while it will clearly delay in Malaga due to a significant delay in the chilling requirement fulfilment. This may increase the chances of cross-reactivity episodes with other pollen types in the future, increasing its impact on public health.

1. Introduction

During the last decades, urbanization has become a general trend, increasing the size and population of cities worldwide (Schmidheiny and Suedekum, 2015; Wu et al., 2018). These changes are producing negative impacts on the life quality of citizens, some of which could be avoided with proper urban planning (Breuste et al., 2015). In this regard, the creation of urban and peri-urban green areas and the preservation of urban biodiversity are important for maintaining the well-being of citizens (Aerts et al., 2021; Carrus et al., 2015; Connop et al., 2016; Jonker et al., 2014; Latinopoulos et al., 2016; Lee et al., 2015). However, when designing and creating green areas, tree species are usually selected according to their adaptability, cost, aesthetic, availability, and the ecosystem services they provide, but little attention is usually put on their allergenic potential (Cariñanos et al., 2017). Some of the most frequent ornamental tree species in Europe, such as plane trees (*Platanus* spp. L.), produce high amounts of potentially allergenic pollen, which can trigger severe allergy symptoms in the sensitive population (Aerts et al., 2021; Damialis et al., 2011; Fernández-González et al., 2013).

Although *Platanus* pollen has a moderate allergenic capacity, the prevalence of allergy to this pollen is high in Western Mediterranean cities given that *Platanus* x *hispanica* Mill. ex Münchh, *Platanus orientalis* L. and *Platanus racemosa* Nutt. are among the most common ornamental shade trees in Europe (Bedeschi et al., 2007; Rocha-Afonso, 1990; Sánchez de Lorenzo and Cáceres, 2000). In addition, *Platanus* pollen grains contain the allergen Pla a 1, which remains in the atmosphere after the detection of this pollen type, prolonging the symptomatology in allergic patients (Fernández-González et al., 2013). As a result, this allergen has been included in the guidelines for the common standardized allergen battery tests to be used across Europe and high scientific interest has been put in this pollen type (Bousquet et al., 2012). Lara et al. (2020) and Maya-Manzano et al. (2017b) studied the impact of plane tree abundance on temporal and spatial variations of their pollen concentrations, highlighting the need to include this tree in urban green-space management plans to reduce the exposure to allergenic pollen grains and improve air quality. Other studies have mapped the pollen emission sources (Maya-Manzano et al., 2017a) and developed risk maps to propose the so-called "healthy itineraries" inside cities to avoid exposure to this pollen type (Pecero-Casimiro et al., 2019). Most of the negative health effects of *Platanus* airborne pollen could be avoided by monitoring the plane tree's flowering phenology and estimating its future trends to establish preventive measures (Lara et al., 2020).

Among other influent environmental cues, the temperatures are the main determinants of the seasonality and duration of the flowering period (Buonaiuto and Wolkovich, 2021; Fernandez et al., 2022; Wolkovich et al., 2022). Woody plant species in temperate areas have adapted to unfavourable winter conditions by inducing themselves into a resting state called dormancy. During dormancy, the plant inhibits its physiological activity (Kobayashi and Fuchigami, 1983; Perry, 1971). To break the dormancy and continue with the bud development, the plant must detect a series of relatively low temperatures known as chilling (Chuine et al., 2003; Geng et al., 2020). Then, the plant recovers its physiological activity in a phase called quiescence (Rensing and Samuels, 2004). To complete this phase, relatively warm temperatures are required, usually recognized as forcing (Chuine, 2000; Luedeling, 2012). At the end of this phase, the floral buds develop, and the flowering starts. Therefore, it is possible to model the flowering onset of plants for analysing their thermal requirements of chilling and forcing (Fraga et al., 2019; Picornell et al., 2023b; Rodríguez et al., 2019). For this, there are many thermal requirement models, some of them considering overlapping or even parallel chilling and forcing accumulation periods, while others considered them to be sequential. Luedeling et al. (2021) developed a thermal requirement framework that enables the simultaneous testing of both hypotheses. This model outperformed the traditional thermal accumulation models in fruit trees but, due to its novelty, it has not been applied yet to *Platanus* species.

Due to the influence of temperatures on phenology, global warming is affecting the flowering timing and intensity of many tree species in temperate climates, which will have effects on respiratory allergies and, indirectly, on the global economy (García-Mozo et al., 2015; Laskin et al., 2019; Ma et al., 2021; Picornell et al., 2023b; Zhang and Steiner, 2022; Zuberbier et al., 2014). In fact, *Platanus* spp. are already being affected by temperature changes in some Mediterranean cities (Tedeschini et al., 2006), and during the following decades, the temperatures are expected to continue rising, with a stronger trend in the case of the Mediterranean region (Giorgi and Lionello, 2008; IPCC, 2021).

In this changing scenario, monitoring the flowering trends would be crucial for public health, but in situ phenological databases are scarce. Airborne pollen concentrations have proven to be a suitable proxy of regional flowering, given that the start of the Main Pollen Season (MPS) is usually representative of the flowering onset (Frenguelli et al., 2010; Tormo-Molina et al., 2011), which is even more true for local-emission pollen sources, as in the case of trees belonging to *Platanus* spp. (Maya-Manzano et al., 2017a). As a result of this, the effects of climate change are frequently studied using aerobiological databases (García-Mozo et al., 2006; Gehrig and Clot, 2021; López-Orozco et al., 2021; Recio et al., 2018; Rojo et al., 2021).

This study had a twofold aim: I) to model the thermal requirements of *Platanus* flowering in the western Mediterranean using aerobiological data, and II) to make future projections under several climate change scenarios.

2. Material and methods

In this study, the flowering phenology of *Platanus* was monitored using aerobiological data in Badajoz and Malaga. The flowering onset of *Platanus* was defined by the start date of the MPS on both locations using several MPS definitions. To determine which MPS definition reflected the flowering onset with more precision, the aerobiological registers were compared with in situ phenological observations in Badajoz. The MPS definition that matched more accurately the in situ phenological observations was used to model the thermal requirements of *Platanus* in both locations. The resulting thermal requirement model was used to make future projections of the *Platanus* flowering in the short and medium term.

2.1. Sampling sites

The study was conducted in Badajoz (southwestern Spain; 152,933 inhabitants; 17.5 °C mean annual temperature, and 423.4 mm mean total annual precipitation for the study period) and Malaga (southern Spain; 571,026 inhabitants; 19.0 °C mean annual temperature, and 494.9 mm annual mean total precipitation) (National Institute of

Statistics, 2022) (Fig. 1). The former being an inland city with a marked continentality, while the second one is a coastal city with warm summers and mild winters. Despite such differences, both sampling locations have a Mediterranean macrobioclimate (Rivas-Martínez et al., 2017).

2.2. Aerobiological sampling and main pollen season definition

Pollen was captured by means of two Hirst-type volumetric pollen traps (Hirst, 1952) during the period 1994–2022 in Badajoz and 1992–2022 in Malaga (Fig. 1). In Badajoz, a Burkad seven-day spore trap was placed on the terrace of the building Tierra de Barros in the Agricultural Engineering School of the University of Extremadura (38°53′45.53" N, 6°58′08.84" W; 6 m a.g.l. and 184 m a.s.l.). In Malaga, a Lanzoni VPPS 2000 pollen trap was installed on the roof of the Faculty of Sciences building, at the University of Malaga (36°42′57.93" N, 4°28′22.00" W; 20 m a.g.l. and 62 m a.s.l.). Both devices produced directly comparable data and were adjusted to aspire a continuous flow of 10 l/min. Samples were prepared and counted following the recommended methodology of the Spanish Aerobiology Network (REA) and the European Aeroallergen Society (EAS) (Galán et al., 2007, 2014). Daily airborne pollen concentrations were expressed as pollen grains/m^3, and the few days with missing airborne pollen data were interpolated by applying the moving mean interpolation method. This method was previously reported as the interpolation method that usually obtains the lowest errors (Picornell et al., 2021).

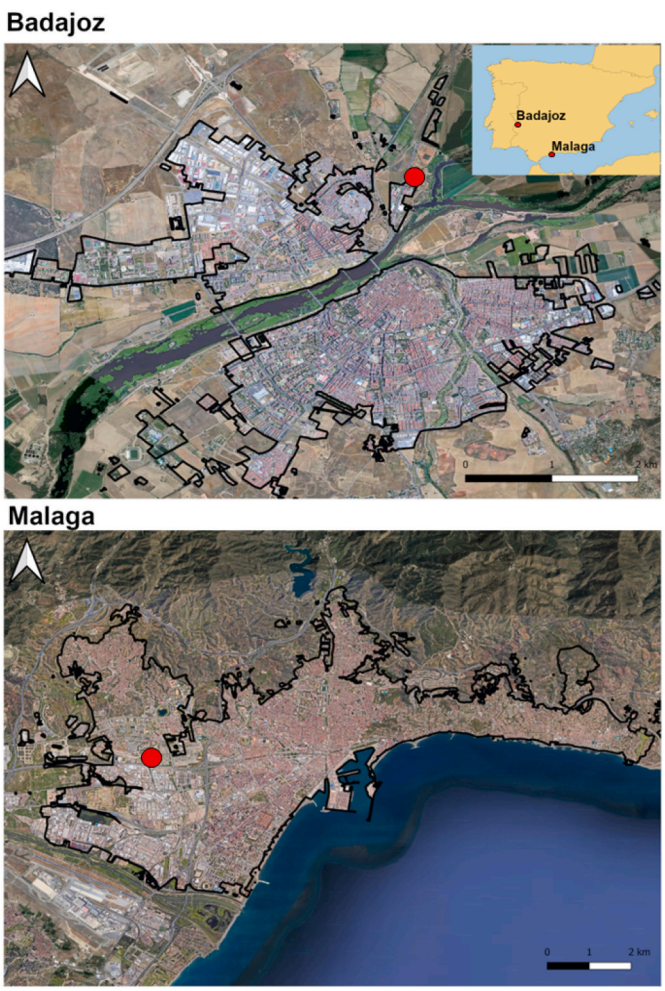

Fig. 1. Geographical location of the sampling sites. Background information extracted from the Institute of Statistics and Cartography of Andalusia (2011) and from the Geographical National Institute of Spain (IGN, 2023). Black lines indicate the boundaries of the cities. Red dots indicate the location of the two Hirst-type volumetric pollen traps. CRS: WGS 84. Satellite images extracted from Google and its data providers.

The different MPS definitions may provide considerable differences in their start dates and, thus, in the results. Despite that, the MPS methods selected for each study are not usually calibrated with in situ phenological observations (Gehrig and Clot, 2021; Jato et al., 2006). To avoid arbitrarily choosing the MPS definition in this study, several definitions were applied to the aerobiological records, and these estimated flowering dates were compared to in situ phenological observations. The accuracy of each MPS definition was calculated as the Mean Absolute Error (MAE) when compared to the in situ observations. The method with the lowest MAE was selected for estimating the flowering onset for the rest of the study. The considered MPS definitions during this calibration process were the clinical definition, percentages of the Annual Pollen Integral (APIn), moving mean definition, and adjustment of logistic regressions:

- *Clinical definition*. The start of the MPS was defined as the date whose previous week had, at least, 5 days with >5 pollen grains/m^3. In addition, the pollen integral of that week should have been higher than 100 pollen grains*day/m^3 (Pfaar et al., 2017).
- *Percentages of the APIn*. The start of the MPS was defined as the first date on which a certain percentage of the APIn was accumulated. The percentages applied to define the start of the MPS in this study were 2.5 % (95 % method for the whole MPS; Andersen, 1991) and 5 % (90 % method; Nilsson and Persson, 1981).
- *Moving mean definition*. A moving mean of 3 days was calculated for the daily pollen concentrations. The start of the MPS was defined as the first day in which the moving mean was higher or equal to 10 pollen grains/m^3 (Rojo et al., 2019).
- *Adjustment to logistic regressions*. The accumulated curve of daily pollen concentrations was fitted to a non-linear logistic regression model. Then, the start of the MPS was defined as the date on which the 4th, 5th or 6th derivative crossed the X-axis (Cunha et al., 2015). As an additional method, the start of the MPS was also defined as the first day on which the adjusted curve differed significantly from the lower asymptote of the function according to one-sided *t*-tests ($\alpha = 0.05$) (Ribeiro et al., 2007).

Trends in the flowering onset were analysed by linear regressions and Mann-Kendall tests. All the data was managed by using the AeRobiology package, implemented in the R software (R Core Team, 2021; Rojo et al., 2019).

2.3. In situ phenological sampling used to select the MPS definition

The flowering phenology of a total of 15 individuals (10 *Platanus x hispanica* and 5 *Platanus orientalis*) was studied in the city of Badajoz during the period 2016–2022 (excluding 2020 due to the pandemic breakdown). The location, number of individuals sampled per year and their flowering dates can be consulted in the supplementary material (figs. S1 and S2). The individuals were adult ornamental trees located in three areas of the city and were monitored every 3–4 days during late winter and early spring. The phenological stage was identified according to the BBCH code (Biologische Bundesanstalt, Bundessortenamt, Chemische Industrie) (Meier, 1997). This is an internationally recognized standard scale in the agricultural sector to classify plant growth phases (Meier, 2001). For each sampled tree, pollen release was mechanically tested in 10 branches at 1.5–2 m height. The flowering onset in each individual was defined as the day in which ≥10 % of the flowers were open and dispersing pollen (BF, BBCH 61), as applied in previous studies (Monroy-Colín et al., 2018, 2020). For each year, the flowering onset date of *Platanus* in Badajoz was defined as the day on which ≥20 % of the monitored individuals were flowering according to the previous criteria. These flowering onset dates were compared with the MPS start dates for the same years and location, as described in Section 2.2, to

determine the MPS definition that was more accurately reflecting the *Platanus* flowering onset.

2.4. Thermal requirements of Platanus

The PhenoFlex framework was used to model the thermal requirements of *Platanus* flowering using the MPS start as input (Luedeling et al., 2021). This framework utilises the Dynamic Model (DM; Erez et al., 1990) for the chilling estimation and the Growing-Degree-Hours (GDH; Anderson et al., 1986) for the forcing estimation. The PhenoFlex framework is implemented in the chillR R package, and it enables simultaneous testing for the parallel, overlapping and sequential hypotheses for the chilling and forcing accumulations (Luedeling et al., 2021).

The DM chilling sub-model assumes that a Precursor of the Dormancy Breaking factor (x) needs to be converted into a Dormancy Breaking factor (y). The x synthesis is reversible, and the rates of conversion and destruction of x are temperature-dependent. Proper chilling temperatures favour the x synthesis and accumulation, and this phenomenon is fitted by four parameters in the PhenoFlex model: A_0, A_1, E_0 and E_1 (Fishman et al., 1987; Luedeling et al., 2021; Picornell et al., 2023a). A_0 is the amplitude in the process of the x synthesis, and A_1 is the amplitude in the x destruction (both measured in h^{-1}). E_0 and E_1 are the time-independent activation energies of forming and destroying x, respectively (both expressed in K).

When the temperature conditions are favourable for the chilling accumulation, and x reaches a threshold of 1, it is converted into y through a sigmoidal function. This non-reversible function has two parameters to fit, i.e., T_f and S (Luedeling et al., 2021).

The GDH forcing sub-model presumes that a Bud Breaking Factor (z) must be accumulated to complete the forcing phase. The synthesis of z is temperature-dependent, and it is also conditioned by the availability of its precursor, the y factor. In this sub-model, 3 parameters are fitted, i.e., T_b, T_c and T_u. These parameters indicate the base, upper and optimal temperatures for the z synthesis, respectively (Luedeling et al., 2021).

There is a slope parameter, S_1, which determines the transition from y to z. Values of S_1 close to 1 indicate sequential chilling and forcing, while values near 0 indicate parallel phases. The fulfilment of the chilling and forcing thermal requirements triggers the flowering onset but, to do so, certain amounts of y and z need to be accumulated. These accumulation thresholds are y_c and z_c, respectively, and are fitted in the PhenoFlex framework.

Overall, 12 parameters were concurrently fitted in the PhenoFlex framework (i.e., A_0, A_1, E_0, E_1, S, T_f, S_1, T_b, T_c, T_u, y_c and z_c) by means of a GenSA algorithm that tried to minimize the RMSE that the model obtained when applied to the calibration dataset (Luedeling et al., 2021; Xiang et al., 2013). The maximum number of iterations was limited to 1000, and the algorithm stopped when no further improvement was detected during 250 consecutive iterations. To avoid statistical artefacts, the fitting domain was limited to biologically meaningful maximum and minimum values. Further details about the model parameters can be consulted in the original PhenoFlex framework publication (Luedeling et al., 2021). To ensure the fitting procedure, a bootstrapping analysis was performed. It repeated the fitting process 10 times, every single time altering the input dataset according to the errors obtained during the calibration. Then, the model's parameters are fitted again and the algorithm checks if they differ from their original fitted values. As the last step, it calculates the fitting standard errors for each parameter as described by Luedeling et al. (2021). This bootstrapping process is intended to check if small variations in the input data produce large variations in the values of the fitted parameters.

The temperature data used to fit the models were obtained from the European Climate Assessment & Dataset in a gridded format with 0.1 degree resolution (version 27.0e) (Cornes et al., 2018; Klein Tank et al., 2002). Daily temperature data were downscaled to hourly temperatures by means of nigh-time cooling logarithmic decay functions and considering the hours of sunrise and sunset (Almorox et al., 2005; Linvill, 1990; Spencer, 1971). The downscaling was performed using the chillR package (Luedeling, 2021). The model required an initial setting for the maximum period of thermal accumulation. As recommended by Luedeling et al. (2013), a partial least-squares regression analysis was performed to determine this period, and it was set from October to April.

The thermal requirements of certain species are expected to be similar despite being at different locations (Fernandez et al., 2022; Luedeling et al., 2013, 2021). Therefore, a single PhenoFlex model was fitted with data from both sampling locations. The model was trained with 75 % of the available data (i.e., 1994–2015 for Badajoz and 1992–2014 for Malaga as a single validation dataset), and externally validated with the remaining 25 % (i.e., 2016–2022 for Badajoz and 2015–2022 for Malaga). Data from Badajoz during 2016 were not considered due to a lack of pollen data next to the start of the *Platanus* flowering onset.

2.5. Future projections of Platanus flowering

The PhenoFlex model together with the fitted parameters were used to make future projections of the *Platanus* flowering onset under different climate change scenarios (Shared Socioeconomic Pathways or SSP) proposed by the Coupled Model Intercomparison Project Phase 6 (CMIP6). The scenarios considered were the SSP1 2.6, SSP2 4.5 and SSP5 8.5. The SSP1 2.6 was based on the assumption that substantial investments in health and education would be made, and the institutions would promote sustainable practices to obtain energy, which would favour a forcing pathway of 2.6 W/m^2. The SSP2 4.5 assumes similar circumstances to the previous one but with an intermediate efficiency in the climate policies and sustainable practices, favouring a forcing pathway of 4.5 W/m^2. The SSP5 8.5 scenario considers that the economy will continue relying on fossil energy, which would favour a forcing pathway of 8.5 W/m^2 (CMIP6, 2022; Eyring et al., 2016; O'Neill et al., 2016).

For each SSP, different working groups have developed temperature models to estimate future warming. In this study, those with complete registers of daily maximum and minimum temperatures were initially considered for each scenario. These temperature estimations were obtained from the Copernicus Climate Data Store (gridded data) with resolutions ranging from 1 to 2.5 latitude and longitude degrees (Copernicus Land Monitoring Service, 2022).

In the first step, the daily gridded data were downscaled to the sampling locations comparing the observed and gridded data for the study sites during the period 2016–2022 and establishing linear regression transformations. Then, the downscaled temperatures were included in the PhenoFlex model to estimate the flowering onset of *Platanus* in the study sites during the period 2016–2022. The obtained RMSE in these flowering onset dates was used to determine the accuracy of the climate models for each scenario. The first third of the most accurate climate models in each SSP was integrated into an ensemble climate model to make future projections (supplementary material, tables S1 and S2). The flowering date predicted by the ensemble model was the median of all the output dates of the individual models. The validation of the ensemble model was performed by comparing its estimated flowering onset dates for the period 2016–2022 with the observed ones. Further information about this methodology is provided in the supplementary material (supplementary material, tables S1 and S2) and can be consulted in Picornell et al. (2023a).

The ensemble climate model was used to develop phenological projections for the period 2023–2050. The future trends were estimated by fitting linear regressions and through Mann-Kendall trend tests. The temperatures of the individual models integrated into the ensemble were used also to calculate monthly temperatures and to analyse their future trends.

3. Results

3.1. Platanus seasonality and connection between aerobiological and in situ phenological records

Platanus airborne pollen is usually detected between February and April in Badajoz and Malaga, with the highest concentrations being detected in March (Fig. 2). The airborne pollen concentrations were much higher in Badajoz than in Malaga (supplementary material, Fig. S3), but the annual peak was usually detected before in this last location (Fig. 2).

The MPS definition method that obtained the lowest Mean Absolute Error (MAE) for estimating the flowering onset in Badajoz was the adjustment to logistic regressions and consideration of the 4th derivative (Fig. 3). The average error of this method was 5.67 days, ranging from 2.00 to 11.00 days depending on the year. Other methods such as the percentage definitions obtained similar MAEs (6.00–6.20 days), but the medians of their errors were higher. For some punctual years, the logistic with the 6th derivative and the moving mean definitions obtained the lowest errors (1 day), but their accuracy showed marked contrasts among years.

Therefore, as provided by its lowest average error, the definition based on the adjustment to logistic regressions and consideration of the 4th derivative was used as a proxy for the flowering onset of *Platanus* in the rest of the study.

According to this MPS definition, there was not any significant trend in the start date of the MPS in none of the sampling locations during the study period (Fig. 4).

3.2. PhenoFlex framework performance

The fitted PhenoFlex model obtained a RMSE of 4.56 days and a MAE of 3.76 days during its calibration. In the external validation, these errors were 4.37 days and 3.20 days, respectively (Fig. 5). In general, the errors in both the calibration and validation process were not substantially influenced by the sampling location or the MPS start timing (i.e., similar errors for Badajoz and Malaga, and similar errors for early and late flowering dates).

The fitted parameters of the model generally showed low variations during the bootstrap analysis (Table 1). The highest variations were detected for the S_1 parameter, which determines if the chilling and forcing accumulations are sequential, overlapping, or parallel. However, even if considering the possible variations in this parameter's value, it indicates partially overlapped chilling and forcing accumulations.

The transitional temperature of the chilling sigmoidal function (T_f) was fitted to 7.26 °C whereas the base (T_b), optimum (T_u) and maximum (T_c) temperatures for the forcing accumulation were 2.68 °C, 26.56 °C and 37.09 °C, respectively.

3.3. Future projections for Platanus flowering onset

The errors of the ensemble climate models during their external validation (2016–2022) were variable depending on the location and future scenario considered (supplementary material, Fig. S4), but in most cases were higher for Badajoz than for Malaga. The scenario with the lowest errors for Badajoz was the SSP2 4.5 (5.92 days) while for Malaga it was the SSSP1 2.6 (3.74 days).

According to all the ensemble climate models of the future

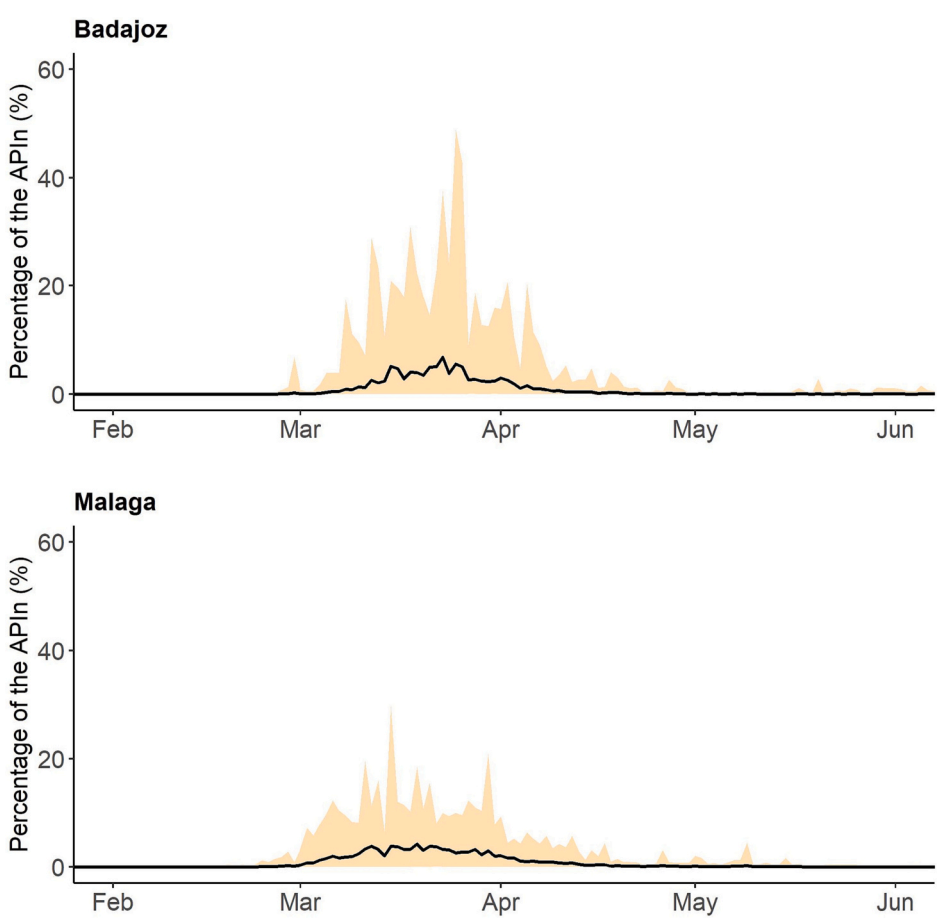

Fig. 2. Mean (black line) and maximum (orange area) daily airborne pollen percentages of the annual pollen integral (APIn) in Badajoz and Malaga during the study period.

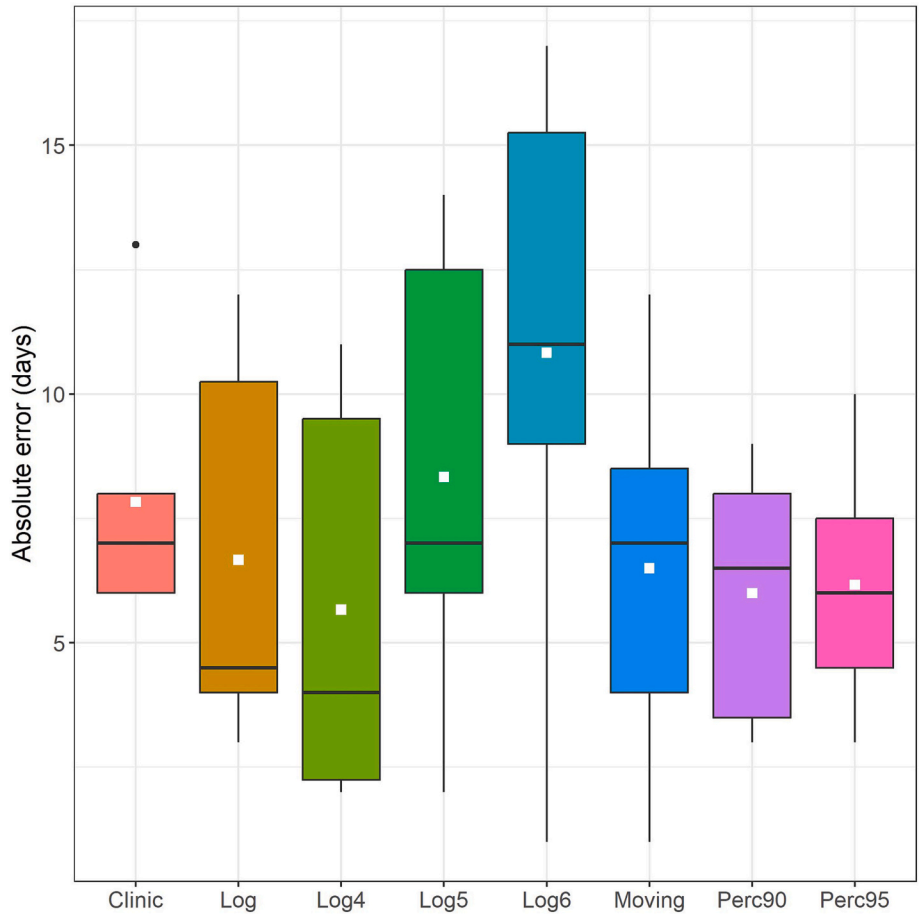

Fig. 3. Absolute errors of each MPS definition method for estimating the flowering onset when compared to in situ phenological records in Badajoz during 2016–2022. The white squared dots indicate the Mean Absolute Errors while the black lines indicate the medians of the errors. *Clinic*, clinical definition method; *Log*, adjustment to logistic regression method and one-sided *t*-tests; *Log4,* adjustment to logistic regression method and 4th derivative; *Log5*, adjustment to logistic regression method and 5th derivative; *Log6,* adjustment to logistic regression method and 6th derivative; *Moving*, moving mean definition method; *Perc90*, definition according to 90 % of the APIn; *Perc95*, definition according to 95 % of the APIn.

temperature scenarios, the flowering onset of *Platanus* will be delayed in Malaga. On the contrary, the forecasts in Badajoz are diverse (Fig. 6). Under the assumptions of the SSP1 2.6 scenario, the flowering will not significantly change in Badajoz, while in the SSP2 4.5 scenario the flowering will advance and, in the SSP5 8.5, it will be delayed.

These trends will be produced by changes in the chilling and forcing accumulation dynamics according to the ensemble climate models (Fig. 7). In Badajoz, the end of the chilling phase will not be affected in the short or medium term by the increase in temperatures according to all the scenarios. However, in the case of the SSP5 8.5 scenario, the start of the chilling period will be delayed due to the higher temperatures detected during this period (supplementary material, Fig. S5). The forcing will reduce its duration under the assumptions of the SSP5 8.5 scenario.

In Malaga, the fulfilment of the chilling requirements will be significantly delayed under the assumptions of all the climate scenarios. In contrast, the duration of the forcing period will remain almost constant (Fig. 7).

4. Discussion

4.1. *Platanus seasonality, current trends, and model performance*

Badajoz and Malaga presented a similar seasonality in the *Platanus* airborne pollen than reported in other parts of the south and centre of the Iberian Peninsula (Alcázar et al., 2004; Cariñanos et al., 2020; Lara et al., 2019). This suggests that the phenological seasonality of the sampling locations is representative of the general regional pattern.

The higher pollen concentrations detected in Badajoz compared to Malaga can be explained by a higher abundance of ornamental plane trees in Badajoz and their distribution within the city (~2600 trees in Badajoz vs. ~1700 trees in Malaga). It has been previously reported that the distribution of ornamental trees within a city can affect the pollen concentrations detected (Maya-Manzano et al., 2017a; Pecero-Casimiro et al., 2019; Ruiz-Mata et al., 2023). However, the seasonality of the pollen concentrations is usually shared among the different sampling points (Rojo et al., 2020; Ruiz-Mata et al., 2023). Therefore, the differences in the abundance and distribution of the plane trees in the studied locations are not expected to have played a significant role in the results of this study.

The advance in the peak detection of Malaga when compared to Badajoz can be explained by the warmer temperatures detected in the first location (19 °C of annual mean temperature vs. 17.2 °C in Badajoz), which can produce an earlier flowering peak (Lara et al., 2020; Pecero-Casimiro et al., 2019).

To date, very few studies have compared different methods for defining the MPS (Bastl et al., 2018; Gehrig and Clot, 2021; Jato et al., 2006; Pfaar et al., 2017), and none of them compared their similarity with in situ phenological observations. However, the proper choice of method is a crucial part of aerobiological studies given that the MPS definition can significantly affect the results (Gehrig and Clot, 2021; Jato et al., 2006). In this study, the number of sampled trees used for

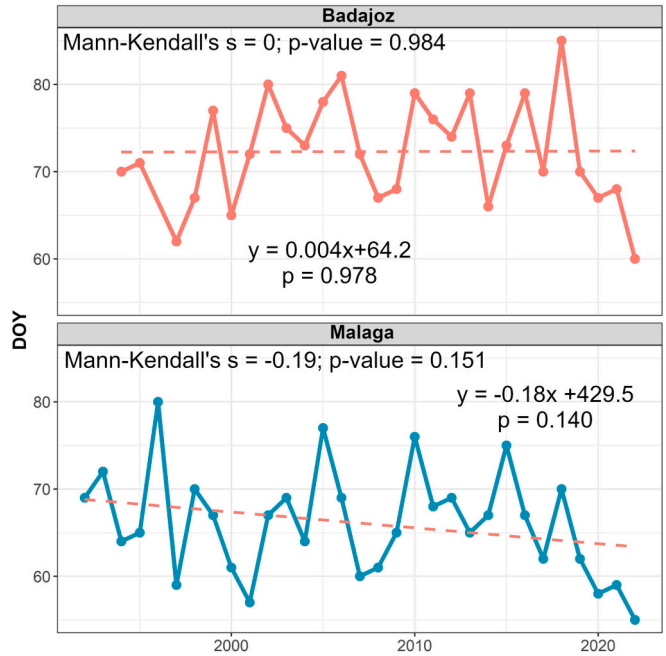

Fig. 4. Trends in the start date of the main pollen season in Badajoz and Malaga during the study period.

defining the flowering onset of *Platanus* was relatively small (15 individuals) and all of them were located within Badajoz. Some authors, such as Miller-Rushing et al. (2008), have suggested that the size of the sampled population can alter the determination of the flowering onset for a given species. However, Miller-Rushing et al. conducted their study with natural populations of plants in mountainous regions, and there were some sampling locations in which these differences were not significant. Wild populations are expected to have higher genetic diversity and heterogeneity of functional traits than ornamental individuals within a reduced flat area. Moreover, the tree populations used for

Table 1
PhenoFlex fitted parameters and their bootstrapping standard errors. *SE*, standard error; *Min.*, the lower limit of the parameter value during parametrization; *Max.*, the higher limit of the parameter value during parametrization.

Parameter	Fitted value ± SE	Min.	Max.
y_c	44.14 ± 0	35	75
z_c (h)	480.77 ± 0	300	1000
S_1	0.22 ± 0.29	0.1	1.0
T_u (°C)	26.56 ± 0.03	0	30
E_0 (K)	3143.81 ± 0	3000	4000
E_1 (K)	9698.82 ± 0	9000	10,000
A_0 (h^{-1})	6536.87 ± 12.93	6000	7000
A_1 (h^{-1})	5.94E13 ± 7.16E7	5.00E13	6.00E13
T_f (°C)	7.26 ± 2.50	0	10
T_c (°C)	37.09 ± 3.83	0	40
T_b (°C)	2.68 ± 0	0	15
S (K^{-1})	5.29 ± 13.73	0.05	50

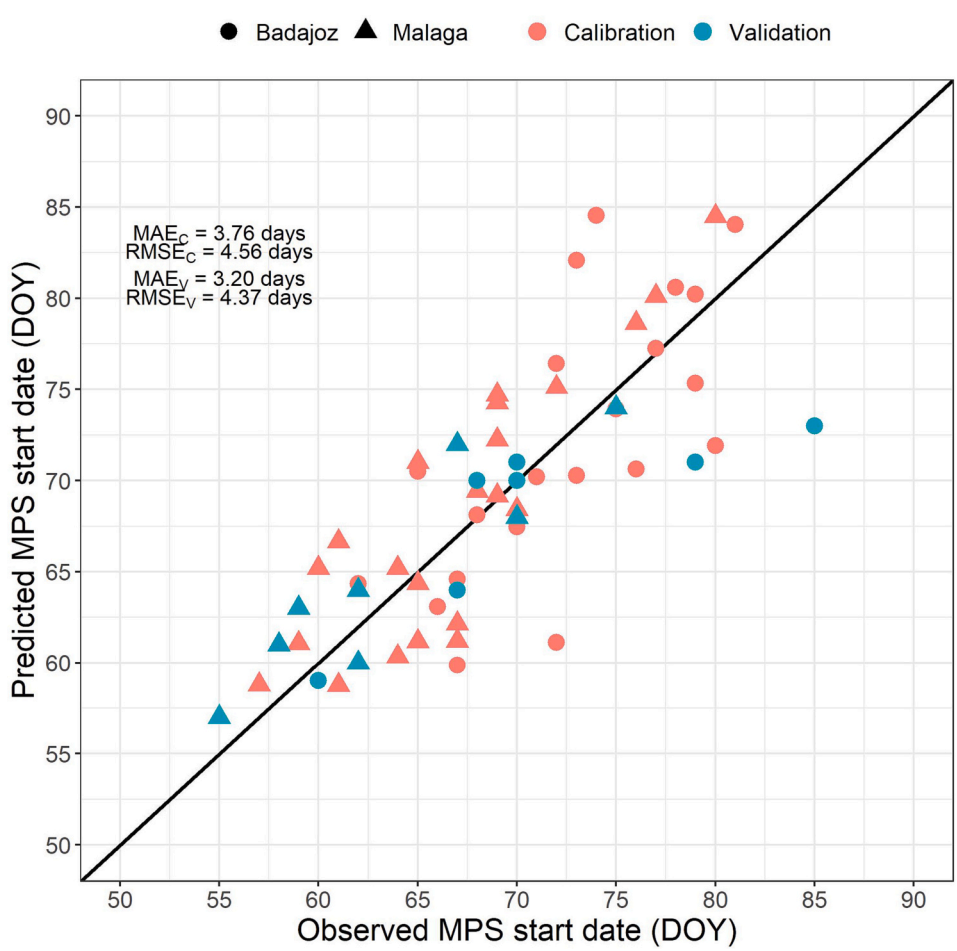

Fig. 5. Comparison between the observed flowering dates of *Platanus* and those predicted by the PhenoFlex model during calibration and validation. The hypothetical perfect performance of the model is indicated with a black line. *DOY*, day of the year; *MAEc*, calibration mean absolute error; *RMSEc*, calibration root mean squared error; *MAEv*, validation mean absolute error; *RMSEv*, validation root mean squared error; *MPS*, main pollen season.

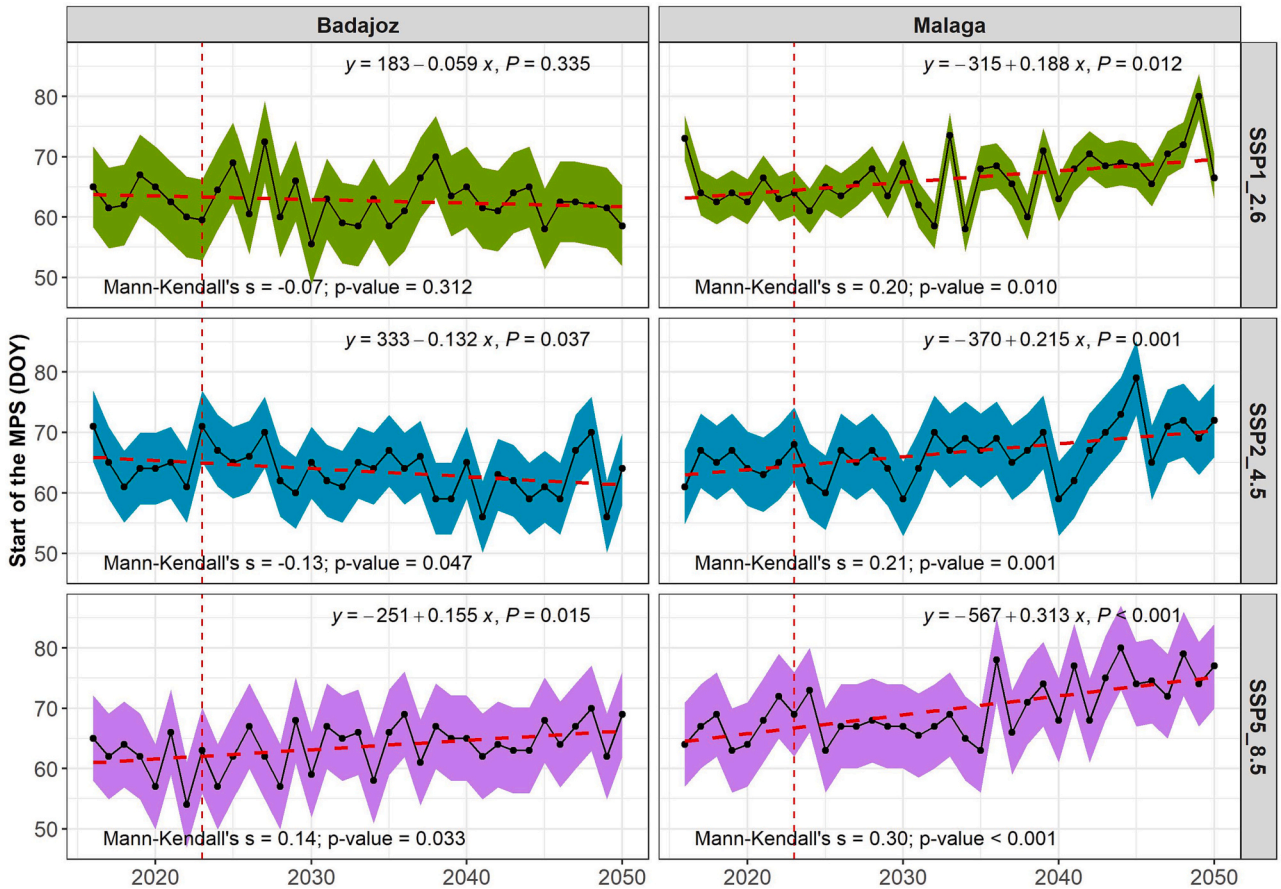

Fig. 6. Future projections of the *Platanus* MPS start date in Badajoz and Malaga according to the ensemble climate models of each scenario considered. The black line indicates the flowering onset date of the ensemble model while the coloured ribbons indicate the range of possible errors according to their validation RMSE. The vertical dashed line marks the current year (2023). *SSP1_2.6*: Shared Socioeconomic Pathway 1 with forcing pathway of 2.6 W/m^2; *SSP2_4.5*: Shared Socioeconomic Pathway 2 with forcing pathway of 4.5 W/m^2; *SSP5_8.5*: Shared Socioeconomic Pathway 5 with forcing pathway of 8.5 W/m^2; *DOY,* day of the year.

assessing the phenology of plane trees in our study were evenly distributed within the city of Badajoz (Fig. S1) and showed certain heterogeneity in their flowering dates (Fig. S2), so we expect them to be representative of the general phenology in Badajoz. Nevertheless, this part of the study was a supplementary analysis to increase the objectivity in the election of a MPS definition in this particular case, but more data would be required to obtain a general conclusion about the optimum MPS definition to match the flowering onset in this species.

In this study, we have not found any significant trend in the flowering onset of *Platanus* in any of the sampling locations. Supporting our results, a previous study analysed the available data from all the pollen sampling locations in Andalusia (southern Spain) and did not find any significant trend for the start date of the MPS (Alcázar et al., 2011). In contrast, another study carried out in Italy and northern Spain found significant trends in this parameter, i.e. negative trends in the former and positives in the latter (Tedeschini et al., 2006). These differences with our results can be explained by the different analysed periods (1982–2003 vs. 1992–2023) and geographical location (higher latitudes) (Fu et al., 2016; Picornell et al., 2023b). All these results suggest that there is not a unique response of the *Platanus* reproductive timing to global warming, but responses to climate change conditioned by the temperatures of a certain location or period.

The PhenoFlex framework was recently developed and, thus, few studies have applied it, and none of them dealt with *Platanus* species. However, the errors obtained were similar to those obtained in other studies when modelling other temperate trees in Europe using in situ phenological observations (Fernandez et al., 2022; Luedeling et al., 2021). Slightly lower errors were reported by a previous aerobiological study of *Olea*, but it used less data for validation (Picornell et al., 2023a).

These models are usually applied to individual species or cultivars. In this case, we are modelling a hybrid (*Platanus x hispanica*) and one of its parental species (*Platanus orientalis)* together given that it is not possible to distinguish between the pollen of both taxa. However, some authors have suggested that these taxa belong to a single species and that the hybrids are different morphotypes of *Platanus orientalis* (López-González, 2001). Without the intention of initiating a systematic discussion, both taxa are closely related. This would justify the inclusion of both taxa in the same model, but other cases should be independently assessed.

Regarding the fitted values of the model's parameters, the value for the upper temperature of the forcing function (T_c) is not frequently reached in the sampling areas and is near the limits of the fitting algorithm. This suggests that there is not an upper-temperature threshold with biological relevance for the forcing accumulation, as previously reported in other Mediterranean locations and taxa (Picornell et al., 2023a).

One of the main limitations of the PhenoFlex framework is its high number of parameters (12), that make it necessary to dispose of a relatively high number of observations to avoid overfitting. The database size we used for this study (44 observations for calibration and 14 for validation) is similar to others used for similar studies, including those by the original developers of the framework (Fernandez et al., 2022; Luedeling et al., 2021). Within our validation dataset we covered a wide range of MPS start dates, including observations out of the range in which the model was trained (i.e., the earliest and latest dates observed; Fig. 5). In addition, the bootstrapping analysis reported

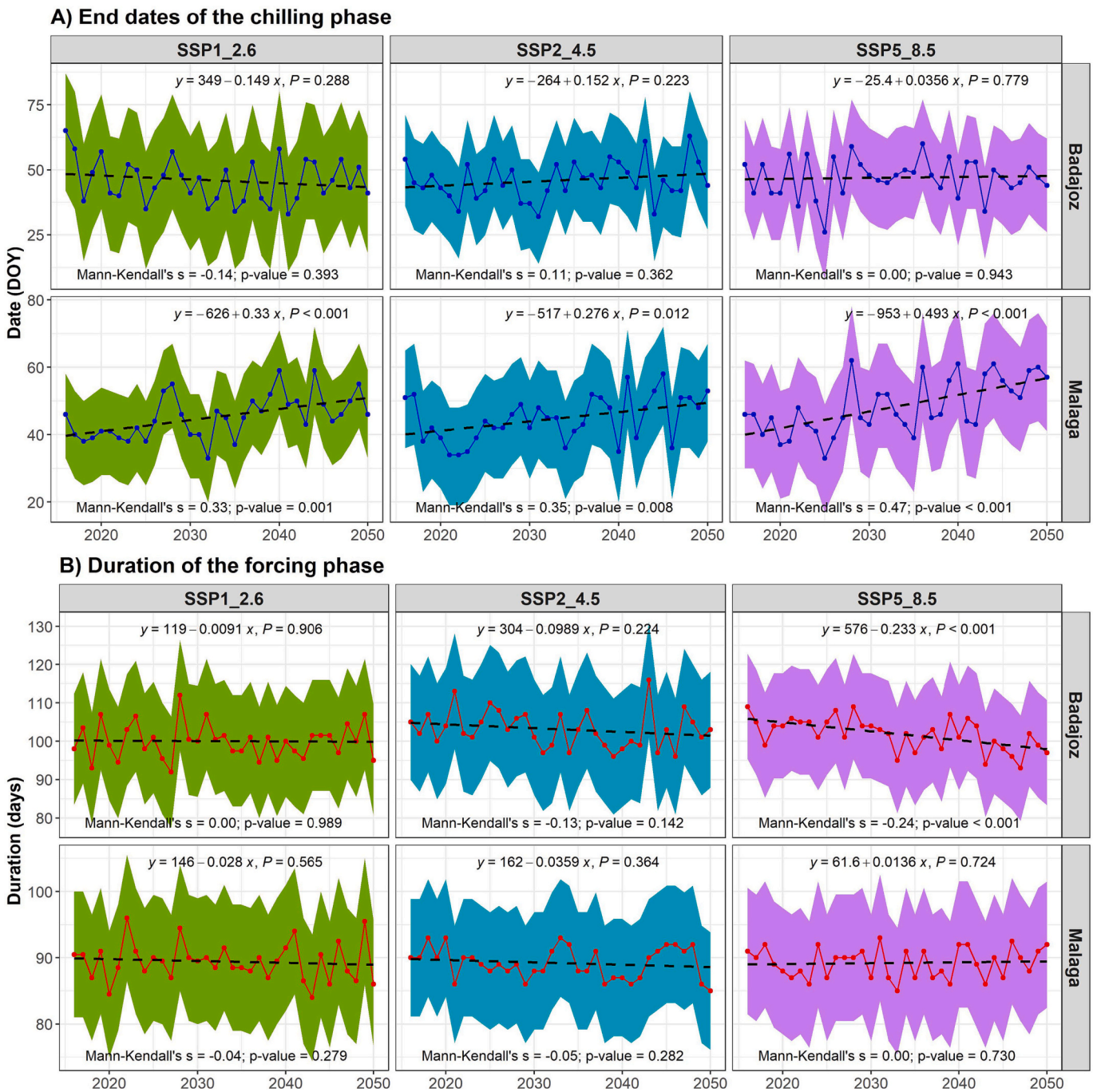

Fig. 7. Future projections of the end date of the chilling accumulation (A) and the duration of the forcing phase (B) in Badajoz and Malaga under the assumptions of the different future scenarios considered. The coloured ribbons indicate the range of possible errors according to the RMSE obtained by them during its validation. *SSP1_2.6*: Shared Socioeconomic Pathway 1 with forcing pathway of 2.6 W/m^2; *SSP2_4.5*: Shared Socioeconomic Pathway 2 with forcing pathway of 4.5 W/m^2; *SSP5_8.5*: Shared Socioeconomic Pathway 5 with forcing pathway of 8.5 W/m^2.

consistent fitting in the parameters (Table 1), which reduces the risk of having found a local minimum for them. Therefore, we expect the risk of overfitting to be low.

In this study we assumed that the thermal requirements of *Platanus* are the same regardless of the location where the individuals grow, so it would be possible to model its thermal requirements using data from different sampling locations. Under these assumptions, the differences in phenology among distant sites would be explained by differences in the local temperatures. The low errors obtained during the validation of the PhenoFlex model and the fact that errors for Badajoz and Malaga had similar ranges support these assumptions. However, in this study, we are modelling an ornamental taxa, which is less likely to show geographical adaptations in the thermal requirements of their populations. In addition, it is possible that the temperature differences between both sampling sites are not enough to trigger a selective process in this character. Therefore, future research should explore the effect of the geographical scale in the dataset when fitting a thermal requirement model.

4.2. Future projections under the different climate change scenarios

In the external validation of the ensemble climate models, the climate scenarios with more similarities to the current climatic

conditions obtained the lowest errors, but they are not necessarily the most probable future scenarios. The emission patterns can change in the short or medium term, affecting the reproductive phenology of *Platanus* with different intensities. Therefore, all the scenarios should be equally considered.

In Badajoz, the winter temperatures are not expected to increase significantly during the following decades and there is not a clear pattern for the spring temperatures under the assumptions of the SSP1 2.6 scenario (supplementary material, Fig. S6). This may explain the lack of trends for the end of the chilling period and the duration of the forcing phase in this scenario. Under the assumptions of the SSP2 4.5 scenario, neither the end date of the chilling period nor the duration of the forcing period will significantly change (Fig. 7), but the temperature increase would favour an earlier fulfillment of the forcing requirements, favouring a slight advance in the flowering onset of *Platanus* (Fig. 6). On the contrary, the forcing period is expected to significantly decrease its duration in the SSP5 8.5 scenario (Fig. 7), but this will be compensated by a significant delay in the chilling period start due to higher temperatures during the winter months (supplementary material, figs. S5 & S6). In the PhenoFlex framework, the forcing accumulation is dependent on the availability of the Dormancy Breaking factor produced during the chilling phase. Therefore, the delay in the chilling start results in a delay in the forcing start and compensates for the shortening of the forcing period. This chilling-forcing compensation results in a delay in the flowering onset according to the SSP5 8.5 scenario (Fig. 6). Previous studies reported this chilling-forcing compensation in other trees in nearby areas (Picornell et al., 2023a) and central Europe (Wang et al., 2022). However, in their cases, it resulted in a lack of significant trends due to similar trends in these opposite changes.

In Malaga, we observed a similar situation than in the SSP5 8.5 scenario in Badajoz. The delay in the chilling fulfilment entails the lengthening (or lack of shortening) of the forcing phase due to the overlap in the chilling and forcing phases in all the considered future scenarios. However, in the case of Malaga, the chilling fulfilment is considerably delayed and, overall, the period required to fulfil the thermal requirements of *Platanus* will be more extended than in Badajoz. This will be responsible for the later flowering onset of *Platanus* in Malaga according to all the forecasted climate scenarios (Fig. 6). Delays in flowering provoked by too-early heat periods during the chilling time were also reported by other authors (Anzanello et al., 2014; Wang et al., 2020).

As the results suggest, the effects of climate change on flowering phenology are not straightforward in all scenarios and geographical areas. Temperature increases do not always imply earlier flowering onset dates (Beil et al., 2021; Tedeschini et al., 2006; Velasco-Jiménez et al., 2020). Indeed, some recent studies dealing with phenological responses to climate change point towards a heterogeneous response of temperate trees to global warming (Menzel et al., 2020; Park et al., 2023; Zhang and Steiner, 2022). In our results, we have observed a gradient of responses to climate change, i.e., from no changes in the flowering onset to slight advances and marked delays. This heterogeneity of responses was caused by different degrees in the chillin-forcing compensation. If the trends in the chilling are more pronounced than those expected for the forcing period, it would result in a flowering delay but, if the opposite, it would result in a flowering advance. The chilling-forcing balance will experience further changes in the long term, given that more notable changes in the chilling accumulation of temperate trees are projected from 2071 in the Iberian Peninsula (Rodríguez et al., 2019). In addition, other variables can play more important roles in phenology when abrupt changes in temperatures are produced (Wolkovich et al., 2022).

The projected delay in the flowering onset of *Platanus* may increase the overlapping between *Platanus* MPS and the MPS from other spring allergy-relevant pollen types. Some of them, such as Amaranthaceae, *Plantago* or *Olea*, are currently partially overlapped but, if the responses to climate change are not synchronised among them, the delay in the *Platanus* flowering could favour cross-reactivity episodes in the allergic population (Fernández-González et al., 2013). Previous research has reported cross-reactivity with other pollen taxa such as Poaceae (measured in *Lolium*) and *Olea* (Asturias et al., 2002). Therefore, the phenological models developed in this study can prove utility for the allergic population in the short or medium term.

5. Conclusions

The MPS definition based on the 4th derivative of a logistic function obtained the highest accuracy matching the flowering onset of *Platanus* with the available data. The average error was 5.67 days, supporting its use as a proxy of in situ flowering phenology.

The PhenoFlex fitted model can be used to forecast the beginning of the *Platanus* pollen season with an average accuracy of 3.20 days (MAE), proving high applicability to alert the allergic population in order to avoid pollen exposure and take preventive measures.

According to the three future scenarios considered, the flowering onset of *Platanus* in Badajoz will not show a clear pattern in the short and medium term due to heterogeneous balances in the chilling-forcing compensation, while it will be delayed in Malaga due to a significant delay in the chilling requirement fulfilment. This delay could increase the overlapping between the *Platanus* pollen season and other potentially allergenic pollen types, increasing the chances of cross-reactivity episodes in the allergic population. In these future scenarios, the fitted PhenoFlex could enhance its utility for allergy alert systems.

CRediT authorship contribution statement

Conceptualization: A.P., J.M.M-M, S·F-R.
Methodology: A.P., J.M.M-M, M.F-R, S·F-R.
Software, validation and formal analysis: A.P., J.M.M-M.
Investigation and data curation: A.P., J.M.M-M., M.F-R., J.J.H-B, R. P.C., R.R-M, E.G-M., M.R.
Writing original draft: A.P., J.M.M-M, M.F-R, S·F-R.
Reviewing and editing the manuscript: all authors.
Visualization: A.P., J.M.M-M.
Supervision: S·F-R, M.M.T., M.R.
Project administration: S·F-R, M.M.T.
Funding acquisition and resources: S·F-R, M.M.T.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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ECA&D project (https://www.ecad.eu).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.167800.

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