



## Influence of extreme climatic effects on butterfly assemblages in a Mediterranean landscape, with new records of threatened and endemic species

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**Abstract.** Climate change is seriously threatening biodiversity and, especially, insects because their biological cycles are highly dependent on environmental conditions. We studied (1) how climate characterised by droughts and heatwaves affected the butterfly assemblage at four sampled sites in Campo de Montiel (central Spain) over three consecutive years; and (2) the differences in the assemblage abundance, species richness, density, and diversity among sites that represent a variety of land use/cover types. Sites were sampled with transects using the Butterfly Monitoring Scheme methodology (Pollard & Yates, 1993). A total of 8,275 butterflies and 69 species were sampled across sites and years. Sites were well sampled in the three years according to species richness estimators and accumulation curves. The relationship between the mean length of dry spells and butterfly abundance was negative and significant at all sites. However, heatwaves did not affect butterfly abundance and species richness. There were no significant differences in the ecological parameters studied among sites. Mediterranean forest transects tended to have higher values of ecological parameters than those dominated by more degraded vegetation, pine plantations and cropland intensification. Butterfly assemblage and diversity were positively related to the presence of semi-natural habitat with traditional agricultural and livestock uses. Our surveys recorded *Polyommatus celina* for the first time in Castilla-La Mancha. Two endangered and endemic species, *Polyommatus violetae* and *Kretania hesperica*, were recorded at the site with higher Mediterranean forest cover, which increases the conservation value of this site. Maintaining semi-natural habitats and traditional farming systems may allow butterfly assemblages to be more resilient to climate change.

### INTRODUCTION

Insects have developed a range of biological responses to climate change (Bartomeus et al., 2011; Wagner et al., 2021; Wilson & Fox, 2021). Recent climate change has documented shifts in the geographical distribution of species (Parmesan et al., 1999; Edwards et al., 2025), phenological advances (Parmesan & Yohe, 2003; Parmesan, 2007), local extinctions (Parmesan, 2006), declines in insect diversity and abundance (Van Dyck et al., 2015; Hallmann et al., 2017; Lister & Garcia, 2018; Forister et al., 2019; Van Klink et al., 2024; Edwards et al., 2025), and phenological mismatches related to interspecific relationships (Gordo & Sanz, 2005; Parmesan, 2007; Yang & Rudolf, 2010; Ovaskainen et al., 2013).

Butterflies (Lepidoptera, superfamily Papilionoidea) are among the best studied insect taxa in Europe, as they are included in a detailed dataset with information on species distribution and abundance (Van Swaay et al., 2025a). Their geographic distribution, abundance and richness have declined sharply in the last few decades (Thomas et al., 2004; Wilson et al., 2005; Romo et al., 2023; Shirey et al., 2024; Edwards et al., 2025). Butterflies are very sensitive to climate change (Parmesan et al., 1999; Radchuk et al., 2013) because they have a relatively short generation period and are ectothermic organisms, meaning that their population dynamics can respond to temperature changes more directly and rapidly and can be used as bioindicators for understanding ecosystem changes (Parmesan & Yohe, 2003; Cleary, 2004; Van Swaay & Warren, 2012).

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Climate change and extreme weather events threaten biodiversity (Ubach et al., 2022). Rising global temperatures have produced extreme weather events, such as heatwaves and droughts, which are increasingly frequent (Hansen et al., 2012; IPCC, 2014). This is expected to lead to significant changes in diversity patterns and ecosystem dynamics worldwide (Ummenhofer & Meehl, 2017). Temperature extremes have the potential to alter plant mortality, assemblage composition (Frank et al., 2015; Ummenhofer & Meehl, 2017), and primary productivity (Halsch et al., 2024). The butterfly life cycle involves caterpillars feeding on different parts of their host plants (García-Barros, et al., 2013) and the adults rely on nectar-rich flowers for food (Corbet, 2000; Baz, 2002). Drought causes a decline in nectar production in plants (e.g., Jaworski et al., 2022; Frigero et al., 2025) and could negatively affect butterfly abundance and survival. Johansson et al. (2022) observed that host plants were fewer and smaller after a drought episode. Thus, the distribution and abundance of plants in an ecosystem is closely associated with those of butterflies (Kitahara et al., 2008; Van Halder et al., 2008; Andreas & Mevi-Schütz, 2009). Ubach et al. (2022) found that declines in butterfly population density in the Mediterranean region were more frequent due to drought and extreme heat. During a recent heatwave period in the UK, it was shown that shaded areas provided shelter to the butterflies; however, they could be negatively affected if the heatwave period extended in time as they would be unable to fly, feed and mate (Hayes & Turner, 2023; Hayes et al., 2024). The temperature of heatwaves is known to affect the mortality of butterfly caterpillars when they exceed 37°C (Melone et al., 2024). Winter heatwaves with maximum temperatures of 20°C can have more devastating effects on survival than summer heatwaves (up to 41°C; Abarca et al., 2019). Heat and desiccation stress can decrease egg hatching (Klockmann & Fisher, 2017).

Ecological parameters such as butterfly diversity, abundance and species composition can reveal how they are affected by climate change (Habel et al., 2022; Forister et al., 2023). Few studies have addressed the effects of climate change-induced changes in butterfly communities in the Mediterranean basin (Peñuelas et al., 2002; Stefanescu et al., 2011; Ali et al., 2022). Furthermore, some evidence suggests that species composition in these communities has not reacted to global warming as rapidly as assumed (Stefanescu et al., 2011). This may be attributed to the relative resilience to climate change of Mediterranean butterfly communities.

The aim of this study is to assess whether butterfly assemblage structure changes in relation to extreme climatic events such as heatwaves and droughts in a mixed Mediterranean forest and farmland mosaic located in central Spain over three consecutive years (2021–2023). Specifically, we investigated (1) how well the butterfly assemblage has been recorded along the transects including the location of endemic, threatened, and rare species, and consequently how they are affected by impacts on habitat; and (2) whether the abundance and species richness of the butterfly assem-

blage have changed over the three-year period in response to climate. We expect that the results of this study will contribute to understanding the effects of climate change on biological communities and infer recommendations for butterfly conservation.

## MATERIAL AND METHODS

### Study area

The study area is in Campo de Montiel, Ciudad Real province (central Spain; Fig. S1). It is an area of high erosion dominated by calcareous soils, generally stony and sometimes clayey. Climate is Mediterranean continental, which is characterised by long cold winters and dry and hot summers. In 2021–2023, the period we studied, mean annual temperature ranged between 14.6 and 15.6°C and total annual precipitation between 297 and 436 mm.

Vegetation is sparse, with steppe landscapes dominating. The predominant vegetation includes thyme (*Thymus*), gorse (*Genista scorpius*) and broom (*Retama sphaerocarpa*), alternating with rainfed crops. The holm oak (*Quercus ilex* subsp. *ballota*) is the most characteristic tree in the region, and can be found isolated in cultivated areas, or forming small corpses that are quite abundant in some localities.

### Sampling design

Four sampling transects were chosen in the study area (Figs S2–S5):

#### Carrizosa

On the plain of the Cañamares river. This 1,141-m transect crosses an area dominated by clay and gypsum, and its most characteristic vegetation is dominated by holm oak and thyme with presence of gypsophilous species such as *Onobrychis humilis* subsp. *matritensis* and *Astragalus alopecuroides*. The transect was divided into three sections which were 299, 348 and 494 m long.

#### Lagunas de Ruidera

This 2,385-m transect is located between the Rey and La Colgada lagoons at the heart of the Lagunas de Ruidera Natural Park. The transect crosses a great variety of habitats, but the holm oak forest is always predominant. Other present vegetation types are dominated by poplar (*Populus*) plantations, common reed (*Phragmites australis*), broadleaf cattail (*Typha latifolia*) and roundhead bulrush (*Scirpoides holoschoenus*). The transect was divided into four sections which were 790, 391, 893 and 311 m long.

#### Casa de Cañas plantation

This 1,123-m transect is in Villanueva de los Infantes municipality. It is an area of agricultural use, with rainfed crops, where the natural vegetation is dominated by annual herbs. The transect was divided into four sections of which were 273, 310, 233 and 307 m long, one of which hosts a hedgerow plantation.

#### Vallehermoso reforestation

This 1,542-m transect is located between La Solana and Villanueva de los Infantes towns. Different habitats alternate along this transect, namely an area reforested with holm oak and broom, a mixed area with reforestation and natural regeneration scrubland, and natural regeneration scrubland dominated by holm oak and presence of lavender (*Lavandula latifolia*), broom and thyme. The transect is divided into four sections which were 267, 362, 189 and 724 m long.

The transect location and detail maps of the vegetation types they crossed were generated using Qgis v.3.22.6-Białowieża software (QGIS Association, 2021).

## Butterfly sampling

The transects were sampled in years from 2021 to 2023, with a total of 22 sampling visits (2021, six samples from March to August; 2022, nine samples from March to October; and 2023, seven samples from March to August; online Table S5).

The sampling method used was that of Pollard & Yates (1993), more specifically, the methodology described in the Butterfly Monitoring Scheme (BMS; Sevilleja et al., 2019); the collected records were integrated into the eBMS database (<https://butterfly-monitoring.net>).

Many butterflies were readily identified at the time they were encountered or by means of detailed photographs following the identification guides of Montagud & García Alamá (2010) and Tolman & Lewington (2002). However, many others were captured for their correct identification and released in the same spot once identified. Some specimens have also been preserved for genitalia assessment (Fernández-Rubio, 1976, 1977, 1981, 1982; García Barros et al., 2013). Finally, the Institute of Evolutionary Biology (CSIC-UPF) genetically determined specimens of *Polyommatus icarus/celina* and *Polyommatus violetae*. Nomenclature followed the BMS application (García Barros et al., 2013; Wiemers et al., 2018).

## Species richness estimators

Directly comparing species richness in samplings can be misleading because of different sampling efforts (Bautista-Hernández et al., 2013) and because richness increases non-linearly with the number of encountered individuals as some rare species may not be detected or some of the individuals counted may be vagrants. Therefore, observed richness is generally considered to be a biased underestimate of true richness (Colwell et al., 2013; Bautista-Hernández et al., 2013) and the obtained data during sampling needs to be assessed for adequacy. For this purpose, accumulation curves relating the number of recorded species versus sampling effort were constructed and several richness estimators were calculated using EstimateS software v. 9.1.0 (Colwell, 2013), namely ICE (Incidence coverage-based species richness estimator; Chazdon et al., 1998; Chao et al., 2000); ACE (Estimator of species richness based on cover and abundance; Chazdon et al., 1998; Chao et al., 2000); Chao 2 (Estimator based on species occurrence data; Chao, 1984, 1987; Alfaro & Pizarro-Araya, 2017), and Bootstrap (Estimator based on sample variability, which provides tighter results when rare species are present in communities; Smith & Van Belle, 1984; Pla & Matteucci, 2001; Bautista-Hernández et al., 2013).

Once all the richness estimators were obtained, their average and standard deviation and the percentage of the number of species that were recorded with respect to what could be found (analysis of the estimators) were calculated to ascertain how well the transects were sampled. The observed species accumulation curves were plotted using Excel 2019 software (Microsoft Corporation, 2018).

## Statistical analysis

### Difference in ecological parameters between transects in relation to the butterflies sampled

A repeated measure (ANOVA) was carried out to determine whether there were significant differences in the studied ecological parameters (Abundance, Density, Richness and Ecological diversity) among transects across the three years of sampling; we used *ggpubr* (Kassambara, 2023), *stats* (R Core Team, 2021) and *tidyverse* (Wickham et al., 2019) of R software (R Core Team, 2021).

Abundance, density of specimens per area unit and visit, specific richness, and ecological diversity was calculated for each

transect and year. Richness is the sum of the species recorded each year. Abundance is the sum of individuals recorded each year. The density of individuals per area unit (hectare) was calculated using the formula:  $Density = ((abundance * 2000) / length) / number\ of\ visits$ . This formula adjusts the abundance to standardise the density per unit area and effort. On the other hand, ecological diversity was calculated using the Shannon-Wiener index with the formula  $H' = -\sum p_i \ln p_i$ , where  $p_i$  is the proportion (or relative abundance) of each species ( $p_i = n_i / N$ ,  $n_i$  is the number of individuals of species  $i$  and  $N$  is the total number of individuals;  $N$  is calculated by summing the individuals of all species; Shannon & Weaver, 1949).

### Effects of extreme climate events

The variables of the ecological parameters listed above were related to climatic variables using a generalised least square model (GLS).

The climatic variables used in the model were drought and heatwaves. We hypothesise that both variables will have an effect on the ecological parameters that define the butterfly assemblage. Drought was characterised with indices based on the number of consecutive dry days (CDD), where a dry day is defined as having less than 1 mm of precipitation (Klein Tank et al., 2009). Specifically, we calculated: (i) the maximum length of dry spells (maxNoprec), (ii) the mean length of dry spells (meanNoprec), and (iii) the number of dry spell events (nEventsNoprec). Heatwave events were defined as an episode of at least three consecutive days with maximum temperatures equal to or above 32°C (Meehl & Tebaldi, 2004). For heatwaves, we calculated the duration of the longest event (maxHeatwave), the mean duration of events (meanHeatwave), and the number of events (nEventsHeatwave). For the calculation of the length of dry spells and heatwaves, the daily climate data registered at the two closest meteorological stations were extrapolated to each transect by taking an average weighted by the inverse of the distance. The climate variables obtained are shown in Table S1.

There were highly correlated variables. To avoid collinearity and select a subset of meaningful explanatory variables (Araújo & Guisan, 2006), a multiple correlation model (Pearson's correlation coefficient  $\geq 0.7$ ) was used using IBM SPSS 27.0 software (IBM Corp. Released, 2020; Table S2). As a result of the multivariate correlation analysis, the drought variable meanNoprec (mean length of dry spells) and the heatwave variable maxHeatwave (duration of the longest heatwave) were selected as independent variables. Likewise, although all dependent variables had a significance level  $< 0.01$  and a Pearson correlation  $> 0.7$  among them, the richness and abundance variables were selected for statistical models (Table S3).

The normality test of the selected variables was carried out using the Shapiro-Wilks test (SPSS 27.0 software; IBM Corp. Released, 2020). The dependent variables, such as richness and abundance were fitted to the normality test, but the independent variables were transformed to be used in the Generalised least square (GLS) model (mean length of dry spells – meanNoprec by log transformation and maxHeatwave by Box-Cox transformation). The variables used in the regression models are shown in the Table S4. The model was performed following Zuur et al. (2009) and using the *nlme* R package (Pinheiro & Bates, 2000, 2023). To perform the GLS models, we correlated the response variables, on the one hand, abundance with the mean length of dry spells (meanNoprec) and the duration of the longest heatwave (maxHeatwave) and, on the other hand, richness with the mean length of dry spells and the duration of the longest heatwave. Site and Year were included as factors to avoid pseudoreplication in the analysis arising from having multiple measurements across years at the same sites.

**Table 1.** Abundance (number of individuals), density of individuals per area unit and visit, species richness and ecological diversity for each transect and year.

| Site                       | Year      | Abundance        | Density        | Richness     | Shannon-Wiener index |
|----------------------------|-----------|------------------|----------------|--------------|----------------------|
| Carrizosa                  | 2021      | 600              | 175.28         | 48           | 3.328                |
|                            | 2022      | 1278             | 248.9          | 56           | 3.562                |
|                            | 2023      | 895              | 224.11         | 53           | 3.578                |
|                            | Mean ± sd | 924.33 ± 339.95  | 216.09 ± 37.46 | 52.33 ± 4.04 | 3.49 ± 0.14          |
| Lagunas de Ruidera         | 2021      | 735              | 102.77         | 53           | 3.427                |
|                            | 2022      | 1715             | 159.9          | 56           | 3.55                 |
|                            | 2023      | 810              | 97.08          | 45           | 3.447                |
|                            | Mean ± sd | 1086.67 ± 545.44 | 119.92 ± 34.74 | 51.33 ± 5.69 | 3.47 ± 0.07          |
| Casa de Cañas plantation   | 2021      | 134              | 39.77          | 18           | 2.516                |
|                            | 2022      | 189              | 74.8           | 19           | 1.841                |
|                            | 2023      | 230              | 58.52          | 17           | 2.349                |
|                            | Mean ± sd | 184.33 ± 48.17   | 57.70 ± 17.53  | 18 ± 1       | 2.24 ± 0.35          |
| Vallehermoso reforestation | 2021      | 582              | 125.89         | 33           | 3.089                |
|                            | 2022      | 540              | 78.02          | 38           | 3.152                |
|                            | 2023      | 567              | 105.13         | 33           | 3.125                |
|                            | Mean ± sd | 563 ± 21.28      | 103.01 ± 24.01 | 34.67 ± 2.89 | 3.12 ± 0.03          |

## RESULTS

### Sampled butterflies

A total of 8,275 butterflies (*Papilionoidea* and *Hesperoidea*) were recorded in the four transects and three years, which were identified to the species level. They represented 69 different species of five families in total. According to their species richness, the transects were ranked Lagunas de Ruidera > Carrizosa > Vallehermoso reforestation > Casa de Cañas plantation (Table 1). Lagunas de Ruidera was also the transect with highest abundance. In terms of density of specimens per area unit and visit (individuals ha<sup>-1</sup> visit<sup>-1</sup>; Table 1), the highest and lowest values during the three years of sampling were recorded in Carrizosa and Casa de Cañas plantation, respectively. The ecological diversity measured by the Shannon-Wiener index was the highest in Carrizosa and Lagunas de Ruidera and the lowest in Casa de Cañas plantation (Table 1).

The repeated measures ANOVA resulted in non-significant differences ( $p > 0.05$ ) for abundance, species richness, density and ecological diversity among transects (Table 2).

Our surveys recorded *Polyommatus celina* for the first time in Castilla-La Mancha. The closest area to the one identified in this study with presence of this species is located at a ca. 60 km distance (Roger Vila, pers. comm.). This species was confirmed by genetic determination of a specimen captured by Juan José Lucas (Carrizosa, viii-10-2021, RVcoll21A629).

We also found two endemic and threatened species of the Iberian Peninsula in the Carrizosa site, namely *Kretania hesperica* (Rambur, 1839) and *Polyommatus violetae* (Gómez-Bustillo, Expósito & Martínez, 1979). *Polyommatus violetae* was identified and confirmed by genetic

**Table 2.** Result of repeated measures ANOVA. F-test, p-value and generalised effect size (ges) are shown.

|                  | Abundance | Density | Richness | Ecological diversity |
|------------------|-----------|---------|----------|----------------------|
| F <sub>2,6</sub> | 2.447     | 3.464   | 1.034    | 0.216                |
| p                | 0.167     | 0.1     | 0.411    | 0.812                |
| Ges              | 0.164     | 0.025   | 0.038    | 0.006                |

determination (three specimens: RVcoll21A630, RVcoll21A631 and RVcoll21A630, Carrizosa, viii-19-2021, Juan José Lucas).

### Richness estimators and accumulation curves

The richness estimators for the four transects are reported in Table 3.

The Lagunas de Ruidera and Carrizosa transects showed a high percentage of sampling reliability (98.29% and 98.06%, respectively), which indicates that they have been well sampled. The Vallehermoso reforestation transect also had a high percentage of sampling reliability (92.07%). The Casa de Cañas plantation transect was the least reliable one (88.83%).

The richness estimators showed the possibility of finding more species in the four transects (Table 3), namely 1–2 in Lagunas de Ruidera, 1 in Carrizosa, 3–6 in Vallehermoso reforestation and 1–5 in Casa de Cañas plantation. Accordingly, the Lagunas de Ruidera and Carrizosa transects have an accumulation curve that flattens towards the asymptote (Fig. S6). The Vallehermoso reforestation transect also exhibited a flattened curve, but the accumulation curve for the Casa de Cañas plantation transect did not approach the asymptote, indicating that more species could be recorded.

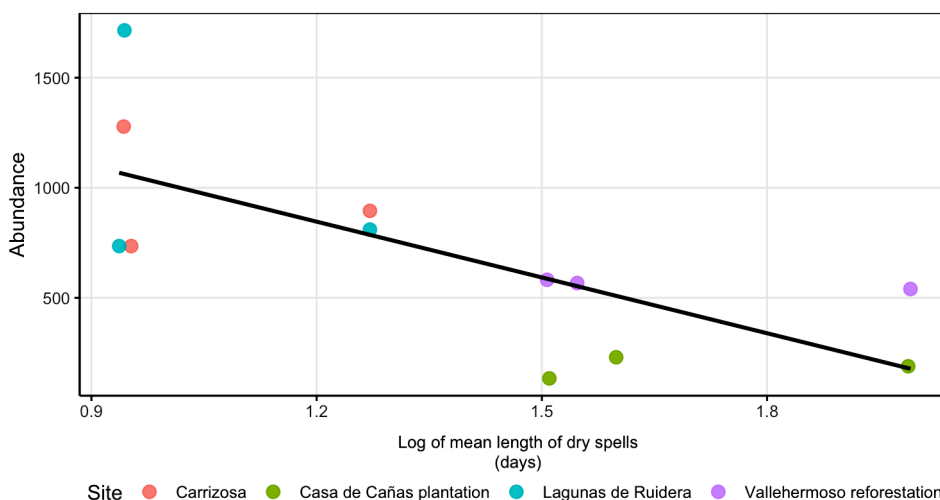
### Effects of extreme climate events on butterfly assemblage

The GLS models indicated that the mean length of dry spells, but not the heatwave variable, affected butterfly abundance (abundance decreased with increasing number of days without precipitation; Fig. 1); however, none of these two explanatory variables had a significant effect on butterfly richness (Model 1, Table 4). The mean length of dry spells correlated negatively with abundance ( $r = -0.967$ ,  $p = 0.0025$ ), but richness did not ( $r = -0.735$ ,  $p = 0.693$ ).

Given that heatwaves did not have a significant effect on GLS models, a second model that only included the relationship between the mean length of dry spells and abundance and richness was developed (Model 2, Table 4).

**Table 3.** Species richness estimators. The indices shown are ACE (Estimator of species richness based on cover and abundance), ICE (Incidence coverage-based species richness estimator), Chao 2 and Bootstrap. The mean and standard deviation of the species richness estimators and the percentage (%) reliability of the samples are shown.

| Transect                   | Registered species | ACE   | ICE   | Chao 2 | Bootstrap | Mean  | SD   | %     |
|----------------------------|--------------------|-------|-------|--------|-----------|-------|------|-------|
| Carrizosa                  | 59                 | 59.67 | 60.57 | 59.57  | 60.85     | 60.17 | 0.76 | 98.06 |
| Lagunas de Ruidera         | 61                 | 61    | 62.55 | 61.32  | 63.37     | 62.06 | 1.06 | 98.29 |
| Casa de Cañas plantation   | 25                 | 26.06 | 29.11 | 29.77  | 27.63     | 28.14 | 2.01 | 88.83 |
| Vallehermoso reforestation | 44                 | 50.22 | 47.92 | 45.79  | 47.23     | 47.79 | 2.33 | 92.07 |



**Fig. 1.** Generalised least squares model of butterfly abundance against the logarithm of the mean length of dry spells. Log of the mean length of dry spells and abundance data used in the GLS model are shown in Table S4.

**Table 4.** Coefficients of GLS models of butterfly abundance and richness with respect to the mean length of dry spells (logarithm of mean-Noprec) and heatwaves (maxHeatwave Box-Cox transformation) (Model 1) with respect to the logarithm of mean length of dry spells (Model 2). The data used to develop the models are shown in Table S4. Abbreviations: AIC – Akaike information criterion; BIC – Bayesian information criterion; logLik – maximum likelihood.

| Model    | Response variable | Coefficients              | Estimate | Std. Error | t-value | p-value |
|----------|-------------------|---------------------------|----------|------------|---------|---------|
| 1        | Abundance         | Intercept                 | 1897.36  | 310.57     | 6.1     | 0.0002  |
|          |                   | Mean length of dry spells | -1302.95 | 308.9      | -4.21   | 0.0022  |
|          |                   | Heatwave                  | 11.62    | 5.71       | 2.04    | 0.0722  |
|          |                   | Degrees of freedom        | 12       |            |         |         |
|          |                   | AIC                       | 148.46   |            |         |         |
|          |                   | BIC                       | 149.44   |            |         |         |
|          | Richness          | logLik                    | -69.23   |            |         |         |
|          |                   | Intercept                 | 48.33    | 12.31      | 3.93    | 0.0035  |
|          |                   | Mean length of dry spells | -10.23   | 9.85       | -1.04   | 0.33    |
|          |                   | Heatwave                  | 0.09     | 0.1        | 0.91    | 0.39    |
|          |                   | Degrees of freedom        | 12       |            |         |         |
|          |                   | AIC                       | 81.6     |            |         |         |
| 2        | Abundance         | BIC                       | 82.59    |            |         |         |
|          |                   | logLik                    | -35.8    |            |         |         |
|          |                   | Intercept                 | 1957.72  | 321.54     | 6.08    | 0.0001  |
|          |                   | Mean length of dry spells | -902.43  | 225.71     | -3.99   | 0.0025  |
|          |                   | Degrees of freedom        | 12       |            |         |         |
|          |                   | AIC                       | 155.31   |            |         |         |
|          | Richness          | BIC                       | 156.52   |            |         |         |
|          |                   | logLik                    | -73.65   |            |         |         |
|          |                   | Intercept                 | 42.51    | 11.47      | 3.7     | 0.004   |
|          |                   | Mean length of dry spells | -2.5     | 6.15       | -0.41   | 0.693   |
|          |                   | Degrees of freedom        | 12       |            |         |         |
|          |                   | AIC                       | 77.57    |            |         |         |
| Richness | BIC               | 78.78                     |          |            |         |         |
|          | logLik            | -34.78                    |          |            |         |         |

As Model 2 in Table 4 shows, the mean length of dry spells was significantly related to abundance ( $p = 0.0025$ ), but richness was not ( $p = 0.693$ ). Furthermore, the modeled correlation of abundance with the mean length of dry spells exhibited an R-value of  $-0.967$ .

## DISCUSSION

Butterfly assemblage structure may undergo rapid changes due to heatwaves or droughts (Habel et al., 2022; Forister et al., 2023), which are predicted to be particularly intense in the Mediterranean basin (IPCC, 2022), as described in the decline in butterfly population density due to drought and extreme heat (Ubach et al., 2022). Furthermore, these effects may have consequences for the conservation status of threatened species (Thomas et al., 2004; Wilson et al., 2005; Van Swaay et al., 2010). Here, we assessed whether butterfly assemblage structure changes in relation to extreme climatic events in a mixed Mediterranean forest and farmland mosaic over three consecutive years.

### Sampled butterflies

We did not find significant differences in abundance, species richness, density and ecological diversity among the four study sites. However, the highest values for these variables were in the Lagunas de Ruidera and Carrizosa sites, which are little altered by human intervention. The Lagunas de Ruidera site is within a Natural Park area and Carrizosa has a substantial cover of Mediterranean forest and shrubland together with traditional uses of agriculture and livestock, which benefit the conservation status of butterflies (Van Swaay et al., 2010; Munguira et al., 2017). On the other hand, the Vallehermoso reforestation and the Casa de Cañas plantation exhibited lower values of the studied ecological parameters. The tree plantations at Vallehermoso reforestation may explain these low values (Jiménez-Valverde et al., 2004; Van Halder et al., 2008; Van Swaay et al., 2010). Habitat loss and degradation due to agricultural intensification may explain the low values at Casa de Cañas plantation (Van Swaay et al., 2009; Wilson et al., 2015; Warren et al., 2021).

The results obtained here are in agreement with those obtained in a study carried out in Cabañeros National Park (Ciudad Real, Spain) by Jiménez-Valverde et al. (2004), where transects through Mediterranean forest had a higher specific richness and composition than those more altered by humans. Furthermore, Van Halder et al. (2008) found that butterfly diversity and assemblage composition were closely related to the presence of semi-natural habitats with a suitable vegetation structure in a Mediterranean ecosystem like our Carrizosa site.

Records of the endemic butterflies *K. hesperica* and *P. violetae* highlight the importance of maintaining the habitat in Carrizosa with traditional agricultural and livestock uses (Munguira et al., 2015; Maes et al., 2019; Habel et al., 2022; Mora et al., 2022). *K. hesperica* is listed as ‘Near Threatened’ by the IUCN (Van Swaay et al., 2025b) and it is also included in the Regional Catalogue of Threatened Species of Castilla-La Mancha. This species is threatened by the lack of adequate grassland management, particu-

larly by agricultural intensification and by land abandonment and habitat loss, fragmentation and disturbances (Pérez Fernández, 2011; Verdú et al., 2011; Van Swaay et al., 2025b). For example, its habitat has been taken over by pistachio crops in other locations in Castilla-La Mancha, leading to the disappearance of its host plant, *Astragalus alopecuroides* (Arce, 2024). On the other hand, *Polyommatus violetae* is listed as a threatened species within the IUCN category ‘Endangered’. Its main threats are land abandonment and afforestation, although agricultural intensification, overgrazing by sheep and goats, forest fires, and urban and road development also pose risks in some areas (Munguira et al., 2015, 2017; Van Swaay et al., 2025c). Habitat loss and reduced quality have also led to increasing habitat fragmentation and isolation of its subpopulations (Van Swaay et al., 2025c). Therefore, maintaining the population of these two threatened butterflies in Carrizosa is important from a conservation perspective.

### Sampling reliability

Our richness estimators and accumulation curves showed that the samplings carried out here were reliable to inform the studied butterfly assemblages given that richness estimators and observed richness were close to or  $> 90\%$  (Table 1). Well sampled data are important for further statistical analysis (e.g. Jiménez-Valverde et al., 2004; Mora et al., 2022). The lowest value at Casa de Cañas plantation transect (88.83%) may be related to the high degradation by agricultural crops. Few additional sampled species are expected at the Lagunas de Ruidera and Carrizosa sites, the best sampled sites that also harbour the highest specific richness recorded in this study. However, it is expected that new species will be found at the Vallehermoso reforestation and the Casa de Cañas plantation. Given that hedgerows planted with many different native species occurred at this latter site, it is expected that butterfly species richness will increase over time; for instance, *Leptotes pirithous* (Linnaeus, 1767), *Pieris brassicae* (Linnaeus, 1758) or *Pyronia tithonus* (Linnaeus, 1758) that occur in other localities near the study area and may eventually colonize this site.

### Effects of extreme climate events

We found that butterfly abundance declined with longer dry spells (i.e., drought). This result concurs with those reported by Ubach et al. (2022), which suggest that the decline in butterfly population density has a correlation with drought in the Mediterranean basin. A drought also means less nectar production for pollinating insects such as butterflies (Phillips et al., 2018; Jaworski et al., 2022; Frigero et al., 2025) and smaller host plants (Johansson et al., 2022), i.e., butterflies have fewer host plants to develop their biological cycle and compete more intensively for nutritional resources. Balmaki et al. (2024) have found a decrease in pollinator abundance due to climate change. Another effect of climate change is the increasing frequency of drought events (IPCC, 2023), and our results hint that the abundance of the butterfly assemblage in Mediterranean ecosystems will decrease. Our work complements the necessity for further studies in Mediterranean ecosystems, such

as those of Ubach et al. (2022), to understand the effects of extreme climate events in the Mediterranean region.

We found that butterfly abundance was not related to heatwaves. Likewise, specific richness was not related to the mean length of dry spells and heatwaves. These findings might be explained by the tolerance and resilience of butterflies in Mediterranean climate ecosystems to high temperatures and a fluctuant precipitation regime (Zografou et al., 2014). For instance, butterflies can take shelter under the foliage during heatwaves (Hayes et al., 2024). This response is opposite to that of mountain butterflies, which have disappeared or strongly declined in low mountain areas concomitantly with increases in species more tolerant to warmer and drier climates (Bonelli et al., 2022). The Carrizosa and Lagunas de Ruidera sites, which are well preserved, are expected to buffer warm temperatures for butterflies better than the Casa de Cañas plantation, the site least covered by vegetation and most vulnerable to heatwaves. A few more years of establishment of the recently planted hedgerows at Casa de Cañas plantation are necessary to know if this restoration action impacts the abundance of the butterfly assemblage and favours the colonisation of nearby areas. In short, maintaining an adequate vegetation structure without habitat alteration can enable butterfly communities to cope with the predicted climate change (Zografou et al., 2014; Mingarro et al., 2021).

We conclude that (1) the samplings carried out in this study were reliable to inform the butterfly assemblages; (2) butterfly abundance declined with longer dry spells but it was not related to heatwaves; (3) maintaining semi-natural habitats with Mediterranean forest cover and traditional farming systems may allow butterfly assemblages to be more resilient to climate change, particularly to drought periods; and (4) a new species was identified in Castilla-La Mancha region and two endemic species of conservation importance have been located in the study area. We expect that the results provided by this study will assist conservation efforts of butterflies in continental Mediterranean environments.

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**Table S1.** Variables characterizing dry spells and heatwaves. Dry spell indices are based on consecutive dry days (CDD), where a dry day is defined as having less than 1 mm of precipitation: maxNoprec (maximum length of dry spells); meanNoprec (mean length of dry spells); nEventsNoprec (number of dry spell events). Heatwave indices, defined as episodes of at least three consecutive days with maximum temperature  $\geq 32^\circ\text{C}$ , are: maxHeatwave (duration of the longest heatwave); meanHeatwave (mean duration of heatwaves); nEventsHeatwave (number of heatwave events).

| Site                       | Year | Max Noprec | Mean Noprec | nEvents Noprec | Max Heatwave | Mean Heatwave | nEvents Heatwave |
|----------------------------|------|------------|-------------|----------------|--------------|---------------|------------------|
| Carrizosa                  | 2021 | 62         | 8.97        | 33             | 17           | 7.83          | 6                |
|                            | 2022 | 89         | 8.77        | 35             | 46           | 18.25         | 4                |
|                            | 2023 | 168        | 18.65       | 17             | 65           | 65            | 1                |
| Lagunas de Ruidera         | 2021 | 62         | 8.65        | 34             | 17           | 8             | 6                |
|                            | 2022 | 89         | 8.8         | 35             | 46           | 15.4          | 5                |
|                            | 2023 | 168        | 18.65       | 17             | 66           | 66            | 1                |
| Casa de Cañas plantation   | 2021 | 252        | 32.33       | 9              | 17           | 6.63          | 8                |
|                            | 2022 | 248        | 97.33       | 3              | 78           | 78            | 1                |
|                            | 2023 | 198        | 39.75       | 8              | 68           | 68            | 1                |
| Vallehermoso reforestation | 2021 | 249        | 32.11       | 9              | 17           | 7.86          | 7                |
|                            | 2022 | 250        | 98          | 3              | 80           | 80            | 1                |
|                            | 2023 | 198        | 35.22       | 9              | 69           | 69            | 1                |

**Table S2.** Multiple correlations among the independent variables. Results in bold show correlation  $> 0.7$ .

|                 | Max Noprec    | Mean Noprec   | nEvents Noprec | Max Heatwave | Mean Heatwave | nEvents Heatwave |
|-----------------|---------------|---------------|----------------|--------------|---------------|------------------|
| maxNoprec       | 1             | <b>0.735</b>  | <b>-0.964</b>  | 0.374        | 0.489         | -0.25            |
| meanNoprec      | <b>0.735</b>  | 1             | <b>-0.782</b>  | 0.593        | 0.65          | -0.461           |
| nEventsNoprec   | <b>-0.964</b> | <b>-0.782</b> | 1              | -0.498       | -0.647        | 0.421            |
| maxHeatwave     | 0.374         | 0.593         | -0.498         | 1            | <b>0.953</b>  | <b>-0.96</b>     |
| meanHeatwave    | 0.489         | 0.65          | -0.647         | <b>0.953</b> | 1             | <b>-0.957</b>    |
| nEventsHeatwave | -0.25         | -0.461        | 0.421          | <b>-0.96</b> | <b>-0.957</b> | 1                |

**Table S3.** Multiple correlations among the dependent variables. Results in bold show correlation > 0.7.

|                      | Abundance    | Density      | Richness     | Ecological diversity |
|----------------------|--------------|--------------|--------------|----------------------|
| Abundance            | 1            | <b>0.71</b>  | <b>0.852</b> | <b>0.773</b>         |
| Density              | <b>0.71</b>  | 1            | <b>0.785</b> | 0.686                |
| Richness             | <b>0.852</b> | <b>0.785</b> | 1            | <b>0.92</b>          |
| Ecological diversity | <b>0.773</b> | 0.686        | <b>0.92</b>  | 1                    |

**Table S4.** Variables for the four transects in each year sampled: abundance, richness, mean length of dry spells (meanNoprec) (Logarithm of meanNoprec) and heatwave (maxHeatwave Box-Cox transformation) values.

| Site                       | Year | Abundance | Richness | Log meanNoprec | maxHeatwave Box-Cox |
|----------------------------|------|-----------|----------|----------------|---------------------|
| Carrizosa                  | 2021 | 735       | 48       | 0.953          | 28.02               |
|                            | 2022 | 1278      | 56       | 0.943          | 46.15               |
|                            | 2023 | 895       | 53       | 1.271          | 54.22               |
| Lagunas de Ruidera         | 2021 | 735       | 53       | 0.937          | 28.02               |
|                            | 2022 | 1715      | 56       | 0.944          | 46.15               |
|                            | 2023 | 810       | 45       | 1.271          | 59.87               |
| Casa de Cañas plantation   | 2021 | 134       | 18       | 1.510          | 28.02               |
|                            | 2022 | 189       | 19       | 1.988          | 84.27               |
|                            | 2023 | 230       | 17       | 1.599          | 66.11               |
| Vallehermoso reforestation | 2021 | 582       | 33       | 1.507          | 28.02               |
|                            | 2022 | 540       | 38       | 1.991          | 84.27               |
|                            | 2023 | 567       | 33       | 1.547          | 73.62               |

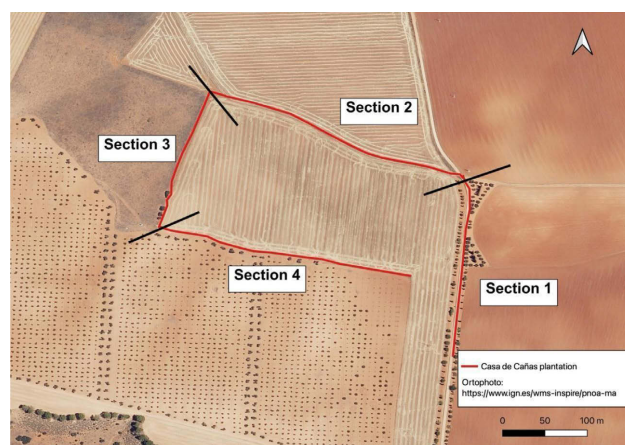
Online supplementary file: S1 (<http://www.eje.cz/2026/012/S01.pdf>). Table S5. Species and number of individuals recorded at the four sampling sites over three consecutive years.



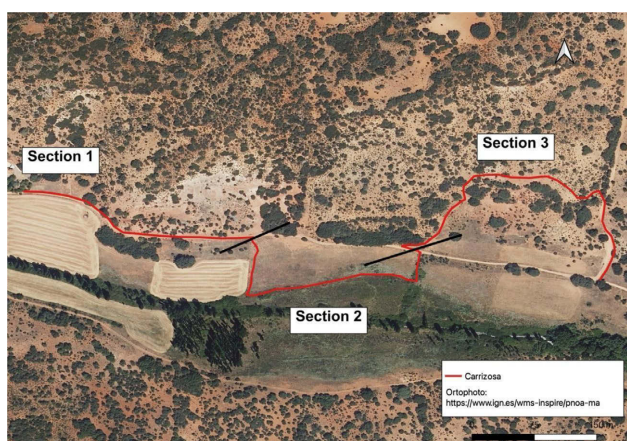
**Fig. S3.** Transect of Lagunas de Ruidera.



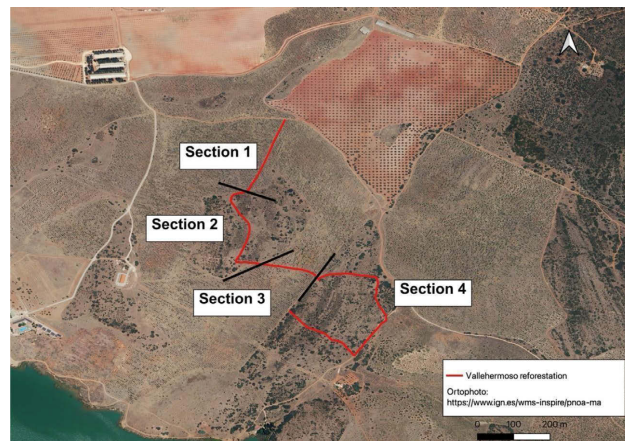
**Fig. S1.** Location of the study area and the four surveyed transects.



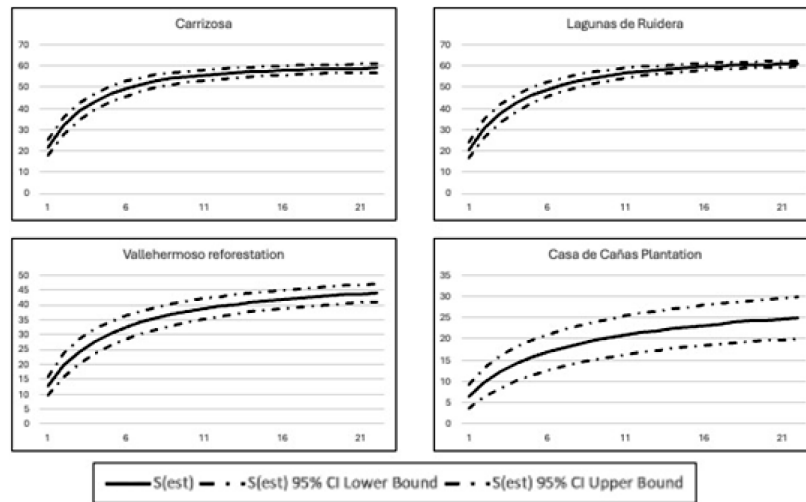
**Fig. S4.** Transect of Casa de Cañas plantation.



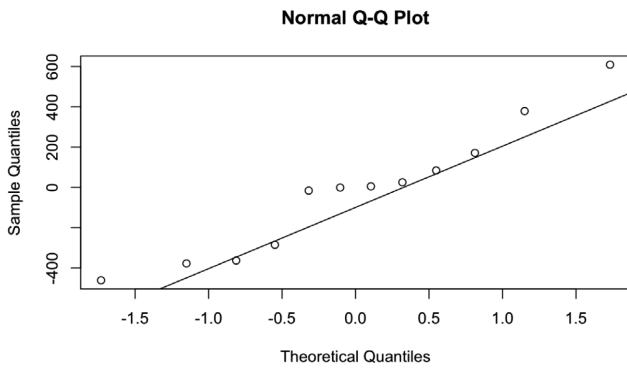
**Fig. S2.** Transect of Carrizosa.



**Fig. S5.** Transect of Vallehermoso reforestation.



**Fig. S6.** Species accumulation curves of the different sampling transects. S(est) is the number of recorded species. Lower and upper limits are shown with a 95% confidence interval.



**Fig. S7.** Residual vs. fitted values. Model diagnosis of the relationship between abundance and the mean length of dry spells (mean-Noprec) using site and year as factors.