

Article

Climate Influence on the Adult *Phengaris alcon* Abundance in the Alvão Natural Park, Northern Portugal

Teresa R. Freitas ^{1,*} , Paula S. Oliveira ¹, André Fonseca ¹ , Nathalie Guimarães ¹ , Joaquim Jesus ^{1,2}  and João A. Santos ¹ 

¹ Centre for the Research and Technology of Agroenvironmental and Biological Sciences, CITAB, Inov4Agro, University of Trás-os-Montes e Alto Douro, UTAD, Quinta de Prados, 5000-801 Vila Real, Portugal; paula.s.oliveira@utad.pt (P.S.O.); andre.fonseca@utad.pt (A.F.); nsguimaraes@utad.pt (N.G.); jjesus@utad.pt (J.J.); jsantos@utad.pt (J.A.S.)

² Laboratory of Fluvial and Terrestrial Ecology, LEFT, University of Trás-os-Montes e Alto Douro, UTAD, Quinta de Prados, 5000-801 Vila Real, Portugal

* Correspondence: trfreitas@utad.pt

Abstract

Phengaris alcon is one of Europe's emblematic invertebrate species and is currently classified as Near Threatened on the IUCN Red List. In Portugal, this endangered species occurs mainly in Alvão Natural Park (ANP). This study investigated the effects of microclimatic conditions on the adult *P. alcon* capture records in the Libânia meadow of the ANP. Adult butterflies were monitored (Mark–release–recapture method) from 2006 to 2014 (except 2012). Microclimatic conditions were modelled (NicheMapR), generating values of precipitation (Prec), maximum (Tmax), minimum (Tmin) and mean temperature (Tmean), solar radiation (SR), relative humidity (RH), soil surface wetness (PCTWET), and wind speed (WS). Growing degree days (GDD), cumulative precipitation (Prec-cum), and seven-day means (d7) for all variables were calculated. Seven microclimatic variables showed strong associations with adult abundance. Higher values of Prec-cum, Tmin-d7 and Prec-d7 were negatively associated with abundance, whereas higher values of SR, RH-d7, Tmean-d7 and PCTWET-d7 were significantly associated with butterfly abundance. More than 50% of individuals were recorded within the following favourable climatic ranges: Prec-cum = 157.9–251.4 mm; SR = 6730.1–8220.4 W/m²; Tmin-d7 = 8.0–12.2 °C; RH-d7 = 71.2–86.7%; Prec-d7 = 0.0–0.8 mm; Tmean-d7 = 13.2–18.0 °C; and PCTWET-d7 = 60.8–92.0%. These findings provide quantitative microclimatic ranges that could guide habitat management and support the long-term persistence of *P. alcon* under future climate change.

Keywords: Alcon Blue; Mark–release–recapture; microclimate; NicheMapR; monitoring species; species conservation



Academic Editor: José Ramón Arévalo Sierra

Received: 26 May 2026

Revised: 22 July 2026

Accepted: 28 July 2026

Published: 3 August 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

The Alcon Blue, *Phengaris alcon* (Denis & Schiffermüller, 1775), is a monophagous and univoltine butterfly species [1] which has become a ‘flagship’ species for biodiversity conservation [2,3]. Owing to its distinctive biology, its remarkable life cycle has been featured in several high-profile television and streaming platforms [4–6]. In 2023, this species was classified as Near Threatened on the IUCN Red List of Threatened Species [2,7]. The persistence of *P. alcon* depends on the presence of both of its hosts: marsh gentian (*Gentiana pneumonanthe*) and ants of the genus *Myrmica* [8]. The species occurs in isolated

populations across Europe, including Portugal, Spain, France, Austria, the Netherlands, Belgium, Germany, Slovenia, Serbia, Croatia, Hungary, Romania, Ukraine, Moldova, Poland, Greece, Italy, and Denmark [2,9–12]. In Portugal, this endangered species [13] can occur in suitable meadows located in the north of the country, namely within the Alvão Natural Park (ANP) [14,15]. In this mountain region, the survival of the Alcon Blue critically depends on peatland habitats (i.e., moist heaths, meadows, and peat bogs), the continued presence of the marsh gentian and host ants of the genus *Myrmica* [9]. Furthermore, traditional grazing practices and hay harvesting play a vital role in maintaining plant species diversity and conservation [16]. Livestock management and ecosystem conditions in this area substantially influence its habitat suitability.

Between July and September, after breeding, the females (Figure 1A) lay the eggs on the *G. pneumonanthe* (Figure 1C) [12,17]. After hatching, phytophagous caterpillars (Figure 1D) feed in the flower's ovary for about two to three weeks [18,19]. After this period, the caterpillars leave the flowers and drop to the ground. At this point, this endophagous species uses chemical and acoustic mimicry to resemble *Myrmica* ants (i.e., *M. aloba*, *M. scabrinodis* and *M. sabuleti*) [15], allowing it to be adopted and carried to ant nests (Figure 1E), where it remains for approximately eleven months, until it reaches the chrysalis stage and leaves the nest as an imago [4,20,21]. This social parasitism provides both protection from predators and nutrition through trophallaxis [12,20].



Figure 1. *Phengaris alcon* phenological stages: (A) female; (B) male; (C) eggs in *Gentiana pneumonanthe*; (D) caterpillar; (E) caterpillar in the *Myrmica* nest.

Climatic conditions influence butterfly development, emergence, abundance, and activity. Warm temperatures and favourable moisture conditions often promote higher abundances, while low spring temperatures can delay adult emergence and flight periods [22,23]. Flight activity increases with higher temperatures, but decreases with stronger winds, increased cloud cover, or reduced solar radiation [23,24]. In the long term, increasing temperatures have led to earlier flight periods in many species [25]. In addition, the growing frequency of droughts or extreme precipitation can change habitat characteristics, further constraining species distributions and exacerbating extinction risk [2,12,26]. Furthermore, changes in temperature and precipitation patterns affect marsh gentian phenology, which in turn changes the timing of butterfly life-cycle stages, such as oviposition [27]. The activity, persistence, and abundance of host ants also depend on vegetation structure and microclimatic conditions [22,25,26,28].

In the ANP, the Alcon Blue has been characterised as a species with reduced dispersal capacity, which may result in a population decline due to the risk of interpopulation inbreeding [28]. Forest fires have occurred within the ANP, and studies indicate that these disturbances can cause habitat degradation, affect *Myrmica* ant colonies and host plants, as well as alter soil physicochemical properties [29,30]. Furthermore, the reduction in traditional grazing practices observed in ANP may promote shrub encroachment and reduce habitat structural heterogeneity, affecting the availability of suitable conditions for *P. alcon* and its host species [8,12,16,19].

An active conservation effort is needed to ensure the long-term survival of *P. alcon*. Due to its complex multitrophic interactions and its potential sensitivity to climatic changes

and management-driven alterations in microclimatic conditions, it is critical to understand how butterfly populations respond to environmental variability. Thus, the main objective of this study was to evaluate how microclimatic conditions influence the abundance of adult *P. alcon*. Specifically, we aimed to (i) relate capture number to microclimatic variables and (ii) identify the climatic variables' ranges most strongly associated with the abundance of adult butterflies. Understanding these relationships is fundamental for characterising the microclimatic conditions associated with adult *P. alcon* abundance. Identifying microclimatic ranges is expected to improve understanding of habitat requirements, provide a basis for comparative studies among populations and co-occurring species, as well as for conservation planning and habitat management.

2. Materials and Methods

2.1. Study Area Description

The ANP is located in northeastern Portugal (Figure 2A), covers 72.3 square kilometres, and ranges in altitude from 255 to 1319 m. It lies within the transition zone between the Euro-Siberian and Mediterranean phytoclimatic regions [31]. Its biodiversity is influenced by proximity to the Atlantic Ocean and Iberian continental influence, as well as by the subalpine climate at higher elevations. The vegetation is composed of a highly diverse ecological community of herbaceous species, including sedges (*Carex*), cross-leaved heath (*Erica tetralix*), Portuguese broom (*Genista falcata*), furze (*Ulex mino*) and marsh gentian (*G. pneumonanthe*) [31]. Libânia meadow (LI) (41°22'27.5" N, 7°48'27.5" W), located near the Lamas de Olo village, was selected as the study site due to the known presence of *P. alcon* (Figure 2B). This meadow, situated at an elevation of 965 m and covering an area of approximately 0.8 ha, provides a suitable ecosystem for the presence of *P. alcon*, *G. pneumonanthe* and *M. aloba*. This meadow is mainly characterised by a balanced vegetation cover composed of herbaceous and shrub layers, along with moderate livestock grazing (Figure 2C) [21]. The surrounding landscape is predominantly shaped by low scrub and granitic rocky outcrops, interspersed with a mosaic of coniferous forest, croplands (i.e., rye), and hygrophilous ericaceous shrub communities [32]. This area is bordered by forest land, stone hedges, roads and the Olo River [33]. The wider landscape also includes pedunculate oak (*Quercus robur*) and pyrenean oak (*Quercus pyrenaica*) species, providing good sunlight exposure, gentle slopes, and proximity to running water [34].

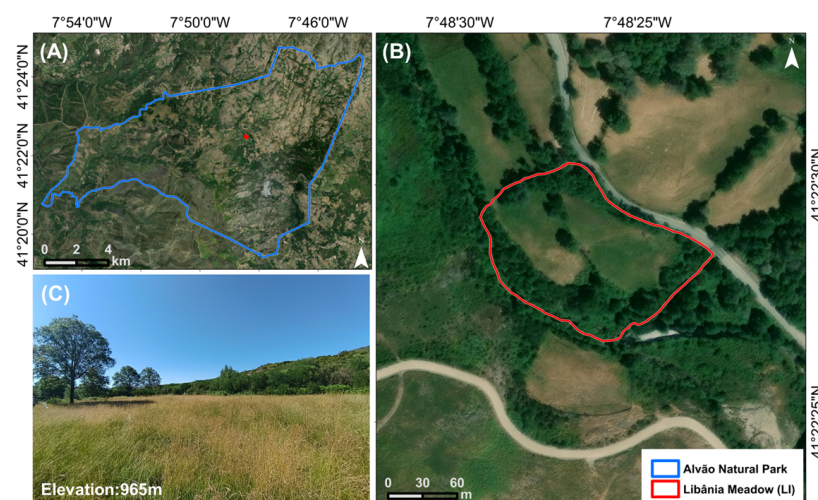


Figure 2. (A) Alvão Natural Park (ANP) and Libânia meadow (red dot) located in northeastern Portugal; Libânia (LI) meadow (B) location and (C) habitat context.

2.2. Mark–Release–Recapture (MRR)

To assess the daily abundance of active *P. alcon* adults in the LI meadow, field monitoring was conducted from 2006 to 2014, except in 2012, during the species' flight period, which extends from mid-July to mid-August. Abundance data were obtained from counts on fixed transect routes, conducted every second or third day between 09:00 and 13:00 h.

During each sampling session, butterflies were captured using entomological nets, individually marked on the underside of the hindwing with a fine-tipped permanent pen using site-specific code numbers, and immediately released at the capture location. For each capture, the individual identification code and date of capture were recorded. Recaptured individuals were also included in the daily counts, as the aim was to quantify the number of active butterflies recorded during each sampling day. With this methodology, it was possible to obtain the number of visible and active butterflies observed on each capture day [1,20].

2.3. Microclimate Modelling

The NicheMapR package (v3.3.3) [35] was used to model microclimate conditions and to generate daily climatic variables for the LI meadow. This package includes mechanistic model types: plant models, endotherm models [36], ectotherm models [37], and dynamic energy budget models [38]. It simulates climate conditions: daily total precipitation, daily maximum temperature, daily minimum temperature, daily mean temperature, daily total solar radiation, daily relative humidity, daily soil surface wetness and daily wind speed, based on several parameters: meteorological, terrain, vegetation, soil data, shading (including hill shade), slope, and aspect, which play a critical role in mimicking microclimate conditions with greater resolution and accuracy [31,38].

To run the microclimate simulations, MCERA5 [39] was used to obtain high-resolution climate forcing data for microclimate modelling. Combined with NicheMapR, MCERA5 allows ERA5 hourly data reanalysis (0.25° latitude $\times$ 0.25° longitude) [40] to be downscaled for local microclimate prediction. Additional packages were used to support data acquisition and processing: ECMWFR [41] to access climate datasets from Copernicus's Climate Data Store, LUBRDATE [42] to manage and format datetime information, DPLYR [43] to improve computational efficiency in data manipulation, and TIDYNC [44] to handle binary data formats such as NetCDF files [45].

A digital elevation model (DEM) was generated from the ELEVATR package [46]. This enables the incorporation of local orographic characteristics (i.e., latitude, slope, and aspect) along with climatic components (i.e., surface radiation, wind components, dew-point temperature, and cloud cover) to downscale ERA5 hourly data from a spatial resolution of approximately 28 km to approximately 10 m. The NicheMapR has taken one of the earliest mechanistic models [47], generalised it, and incorporated it into its features. All parameters were defined by integrating the meadow coordinates with the DEM, which provided the topographic variables required for climate downscaling. This methodology has been applied in a wide range of environments to ensure its applicability and effectiveness [31,48–51].

2.4. Climate Variables Selection

Based on the butterfly's life cycle, published articles, and the climatic characteristics of the study area [1,2,22,31,52], eight climatic variables were selected: maximum, minimum, and mean temperature, precipitation, solar radiation, relative humidity, soil surface wetness, and wind speed. After generating microclimatic data for each variable, the 24 h mean was calculated to obtain daily data, and grid-cell outputs within LI were spatially averaged to characterise the overall habitat microclimate.

Besides the climatic conditions observed on the capture day, additional variables were calculated to represent the climatic conditions over the capture day and the preceding six days (hereafter, d7). These seven days were defined based on mark–release–recapture data, which indicated that adult *P. alcon* individuals were recaptured within the population for up to six days following their first capture.

Using the mean temperature, daily growing degree days (GDD) were computed with a base temperature of 5 °C. This temperature is frequently used to predict the butterfly species' abundance and distribution [53]. From 1 April onward (mid-spring), the accumulated GDD was calculated, as well as the accumulated GDD from the previous six days and the capture day (d7). Based on the precipitation data, the cumulative precipitation from 1 April (Prec-cum) and the precipitation accumulated for d7 were also calculated. The 1st of April was chosen as the reference date because it represents the typical start of the growing season, when temperatures consistently exceed the base threshold, and precipitation generally begins to decline [1,23]. In total, 21 climatic variables were considered for analysis (Table 1).

Table 1. Climatic variables selected.

Climatic Variable	Acronym (Units)
Spatial daily mean of daily total precipitation	Prec (mm)
Spatial mean of the 7-day means of daily total precipitation	Prec-d7 (mm)
Spatial mean of daily maximum temperature	Tmax (°C)
Spatial mean of the 7-day means of daily maximum temperature	Tmax-d7 (°C)
Spatial mean of daily minimum temperature	Tmin (°C)
Spatial mean of the 7-day means of daily minimum temperature	Tmin-d7 (°C)
Spatial daily mean of mean temperature	Tmean (°C)
Spatial mean of the 7-day means of mean temperature	Tmean-d7 (°C)
Spatial mean of daily total solar radiation	SR (W/m ²)
Spatial mean of the 7-day means of daily total solar radiation	SR-d7 (W/m ²)
Spatial mean of daily relative humidity	RH (%)
Spatial mean of the 7-day means of daily relative humidity	RH-d7 (%)
Spatial mean of daily soil surface wetness	PCTWET (%)
Spatial mean of the 7-day means of daily soil surface wetness	PCTWET-d7 (%)
Spatial mean of daily wind speed	WS (m/s)
Spatial mean of the 7-day means of wind speed	WS-d7 (m/s)
Spatial mean of growing degree days	GDD (°C-days)
Spatial mean of accumulated growing degree days	GDD-cum (°C-days)
Spatial mean of the 7-day accumulated growing degree days	GDD-cum-d7 (°C-days)
Spatial mean of the accumulated daily total precipitation	Prec-cum (mm)
Spatial mean of the 7-day accumulated daily total precipitation	Prec-cum-d7 (mm)

2.5. Determination of the Influence of Climatic Variables

For each climatic variable, a climatological baseline was established using a 15-day moving average (Figure S1). This approach smooths short-term fluctuations and highlights the expected seasonal pattern of each variable throughout the year, a procedure commonly applied in time-series analyses [1]. The climatic value recorded on each capture day was then compared with the corresponding 15-day moving average and classified as either above or below the seasonal baseline. The number of butterfly captures associated with each condition was subsequently quantified, allowing the percentage of captures occurring under values above and below the moving average to be calculated for each variable.

To assess the potential influence of each climatic variable on butterfly abundance, the difference between the percentages of captures recorded above and below the 15-day moving average was calculated. Small differences indicate a relatively balanced distribution of captures between the two conditions and therefore a weaker association with butterfly

occurrence. Conversely, larger differences suggest that captures were concentrated under one condition, indicating a stronger association with the variable.

Based on the magnitude of this difference, variables were classified into two categories: Low Influence and High Influence. Variables with differences greater than 23 percentage points were classified as High Influence, whereas those below this threshold were classified as Low Influence. The threshold was defined empirically to maximise variability among the climatic variables retained in the analysis.

Additionally, when variables within the same climatic category yielded identical percentages, only one representative variable was retained to avoid redundancy.

2.6. Determination of Climatic Variable Ranges

After identifying the climatic variables most strongly associated with butterfly abundance, the climatic ranges corresponding to the highest proportion of captures were determined for each variable. Intervals containing more than 50% of all butterfly captures were identified (Table 2). Although adults were observed outside these ranges, the concentration of captures within these intervals suggests that they represent favourable climatic conditions for adult abundance.

Table 2. Climatic variables and respective ranges for more than 50% of captures.

Climatic Variable	Range
Prec-cum (mm)	157.9–251.4 mm
SR (W/m ²)	6730.1–8220.4 W/m ²
Tmin-d7 (°C)	8.0–12.2 °C
RH-d7 (%)	71.2–86.7%
Prec-d7 (mm)	0.0–0.8 mm
Tmean-d7 (°C)	13.2–18.0 °C
PCTWET-d7 (%)	60.8–92.0%

3. Results

3.1. Butterfly Capture Records

The LI meadow shows considerable interannual variation in butterfly abundance throughout the eight monitored years (Figure 3). Monitoring was conducted over a total of 105 sampling days, distributed as follows: 11 days in 2006, 9 in 2007, 8 in 2008, 9 in 2009, 20 in 2010, 26 in 2011, 13 in 2013, and 9 in 2014. Consequently, sampling effort varied substantially among years, both in the number of sampling days and in the specific dates on which captures were conducted.

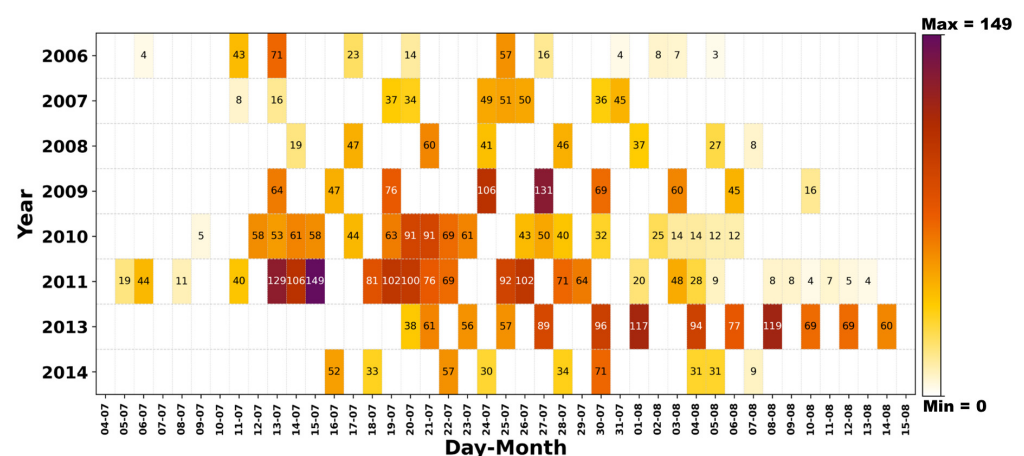


Figure 3. Heatmap of the daily distribution of total butterflies captured in Libânia meadow.

Annual capture numbers also varied markedly. The lowest number of individuals was recorded in 2006, with 250 captures, whereas the highest abundance was observed in 2011, when 1396 individuals were recorded.

The timing of peak adult activity differed among years. The earliest peak occurred in 2011, when the maximum daily abundance was recorded on 15 July (149 individuals). In contrast, the latest peak was observed in 2013, reaching a maximum of 119 individuals on 8 August. An intermediate pattern was recorded in 2009, when abundance peaked on 27 July with 131 individuals. Except for 2006, all monitored years showed a unimodal flight pattern, characterised by a single annual peak in adult abundance.

Throughout the study period, grazing management in the LI meadow remained relatively stable, with cattle activity being controlled and livestock numbers maintained at fixed levels.

3.2. Climate Context

The study area is located at an elevation of 965 m. In this region, the annual total precipitation is 1228 mm, and rainfall during the autumn, winter, and spring months ranges from 62 mm in September to 162 mm in October (Figure 4A,B). The wettest winter month, with a mean precipitation of 150 mm, receives three times more rainfall than the three driest summer months, which have a mean precipitation of 32 mm, with August being the driest month at only 19 mm. The winter months record the lowest temperatures (3.3–4.6 °C). In comparison, the remaining months have mean temperatures below 22 °C, with at least four months averaging above 10 °C, which clearly characterises the region as having a warm-summer Mediterranean climate (Csb). These climatic patterns reflect a typical upland Mediterranean environment, where cooler temperatures at higher altitudes combine with distinct seasonal contrasts in precipitation.

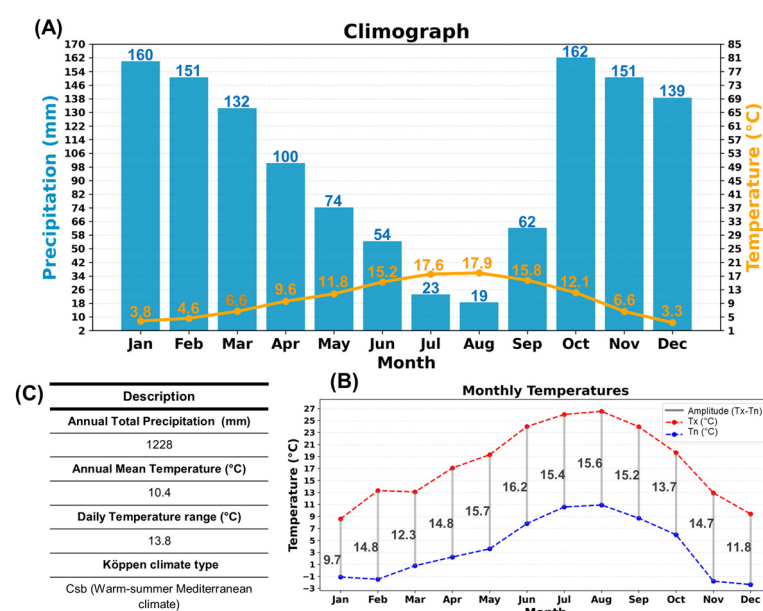


Figure 4. Study area (A) climograph, (B) climatic description and (C) monthly temperatures: maximum (Tx) and minimum (Tn), and amplitude range.

The highest temperatures occur between June and September (15.2–15.8 °C), and the mean annual temperature is 10.4 °C. Accordingly, the warmest month is August (17.9 °C), and the coldest is December (3.3 °C), while the annual thermal amplitude remains relatively stable, ranging between 9.4 and 15.7 °C (Figure 4C).

Although during winter and spring the butterfly is found on the ground with *M. aloba*, the climatic conditions of this rainy period directly affect the habitat and *G. pneumonanthe*, which is in its dormancy and growing seasons. When the butterfly becomes an adult in summer, it is already directly influenced by the climate, with higher temperatures and reduced rainfall. Moreover, these conditions trigger the flowering season of *G. pneumonanthe* and promote the activity of *M. aloba* and grazing [27,54].

3.3. Climate Variables Influence

Adult butterfly abundance is directly associated with the absence of precipitation on the day of capture (Prec) and accumulated precipitation (Prec-cum) (Figure 5A; Table S1). Based on Prec and Prec-cum, 94.2% and 81.3% of captures, respectively, occurred under rainfall levels below the 15-day moving average. As butterfly presence is clearly linked to the absence of precipitation on the day of capture, the variable Prec-cum was selected for further analysis, as it reflects the cumulative effect of precipitation since 1 April and accounts for a broader range of influencing factors.

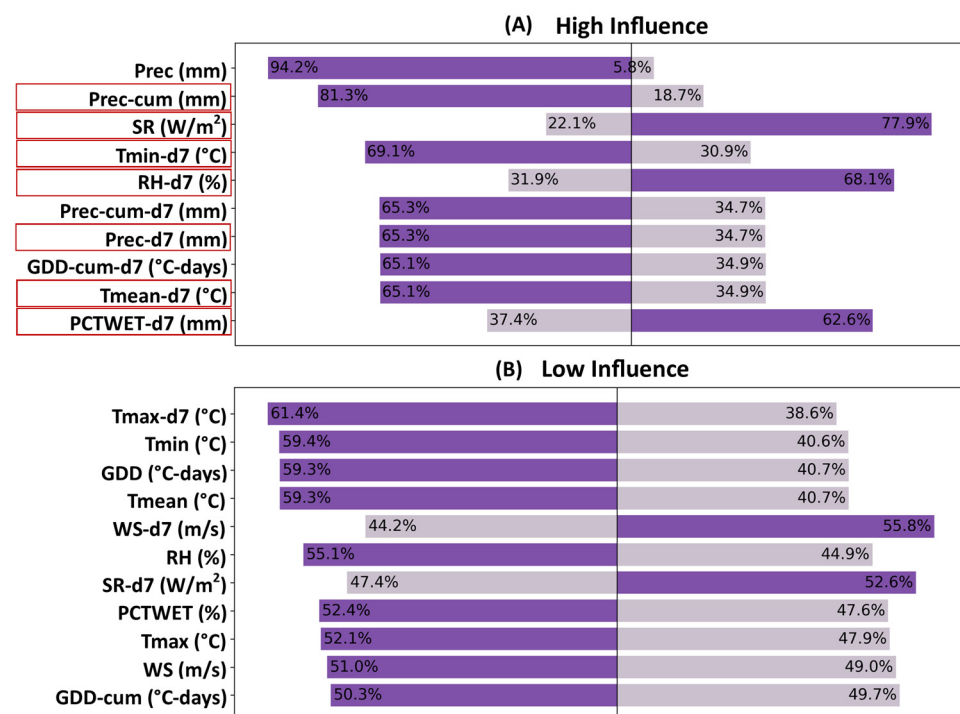


Figure 5. Classification of climatic variables according to influence on Alcon Blue individuals' abundance: (A) High Influence and (B) Low Influence. This classification is based on the days of capture and the total number of butterflies observed.

Daily total solar radiation (SR) was also strongly associated with butterfly abundance, with 77.9% of captures occurring under values above the moving average. In contrast, 69.1% of captures occurred when the Tmin-d7 was below the 15-day moving average. Considering the ecosystem of the study area, which is meadow habitats, the RH-d7 has 68.1% of captures occurring under values above the moving average.

The variables Prec-cum-d7 and Prec-d7 showed identical responses, with 65.3% of captures occurring under values below the moving average; therefore, only Prec-d7 was retained for performance. Likewise, Tmean-d7 and GDD-cum-d7 showed the same percentage response (65.1%), indicating that captures were more frequent under lower temperature conditions during the preceding seven days. PCTWET-d7 is associated with 62.6% of cap-

tures occurring under values above the moving average. Overall, climatic conditions during the six days preceding capture showed strong associations with butterfly abundance.

Lower-than-average values of Tmax-d7 (61.4%), Tmin (59.4%), GDD (59.3%), and Tmean (59.3%) were associated with higher capture frequencies (Figure 5B). Wind speed averaged over the previous seven days (WS-d7) was associated with 55.8% of captures occurring under values above the moving average, whereas wind speed on the capture day (WS) showed a weaker and opposite pattern (51.0%). Relative humidity on the capture day (RH) was associated with 55.1% of captures occurring under values below the moving average, while solar radiation averaged over the previous seven days (SR-d7) showed a weaker positive association (52.6%). Similar patterns were observed for PCTWET, Tmax, WS, and GDD-cum.

The climatic variables showing the strongest associations with adult abundance were: Prec-cum, SR, Tmin-d7, RH-d7, Prec-d7, Tmean-d7 and PCTWET-d7.

After identifying the climatic variables with the greatest effect on the number of individuals, these were analysed in greater detail. In Figure 6, in the left panels, the value of the climatic variable on the day of capture (▲) is shown, with the continuous line representing the 15-day moving average. In the right panels, the percentage of annual captures occurring above and below the climatological mean of the respective variable is shown.

According to the Prec-cum (Figure 6A,B), the years with the highest accumulated precipitation are 2007 (285.9–310.6 mm), 2008 (403.6–415.7 mm), and 2014 (283.2–314.4 mm). In these years, all captures occurred under Prec-cum values above the 15-day moving average. Conversely, the lowest accumulated precipitation values are recorded in 2011 (157.9–184.0 mm), a year that nevertheless exhibited one of the highest butterfly abundances. Similar Prec-cum ranges are observed in 2006 (160.5–172.4 mm) and 2013 (169.1–179.2 mm), despite the marked difference in the total number of butterflies recorded between these years. Across the entire study period, 81.3% of captures occurred under Prec-cum values below the 15-day moving average.

SR is consistently associated with higher capture frequencies (Figure 6C,D). In all years, more than 55% of captures occur under radiation values above the climatological mean. The year 2008 (5738.0–8016.1 W/m²) shows the lowest percentage of captures above the 15-day moving average. Lower radiation values were observed in 2011, when a value of 2628.4 W/m² was recorded on 5 July. The highest value was recorded in 2010, reaching 8220.4 W/m².

In 2006, the year with the lowest butterfly abundance, temperatures ranged between 10.8 and 17.4 °C (Figure 6E,F) and 98% of captures occurred above the 15-day moving average. In contrast, in 2009, one of the years with the highest abundances, lower temperatures were recorded (9.0–12.1 °C), with all captures occurring below the climatological mean. Intermediate values were observed in 2007, 2008, 2011 and 2013, with minimum temperatures ranging from 8.0 to 14.7 °C. The highest Tmin-d7 value recorded during the study period was 16.1 °C in 2010. These results indicate that this climatic variable plays a more important role than maximum temperature (Figure 5A,B) in butterfly abundance.

RH-d7 (Figure 6G,H) shows that the butterfly tends to appear when the relative humidity over the seven days exceeds 50%. In 2006, relative humidity ranged from 60.7 to 82.4%, and 62% of captures occurred below the 15-day moving average. By contrast, in 2009, when humidity values ranged from 75.4 to 86.7%, all captures occurred above the climatological mean. Overall, 68.1% of captures were recorded under relative humidity values above the moving average.

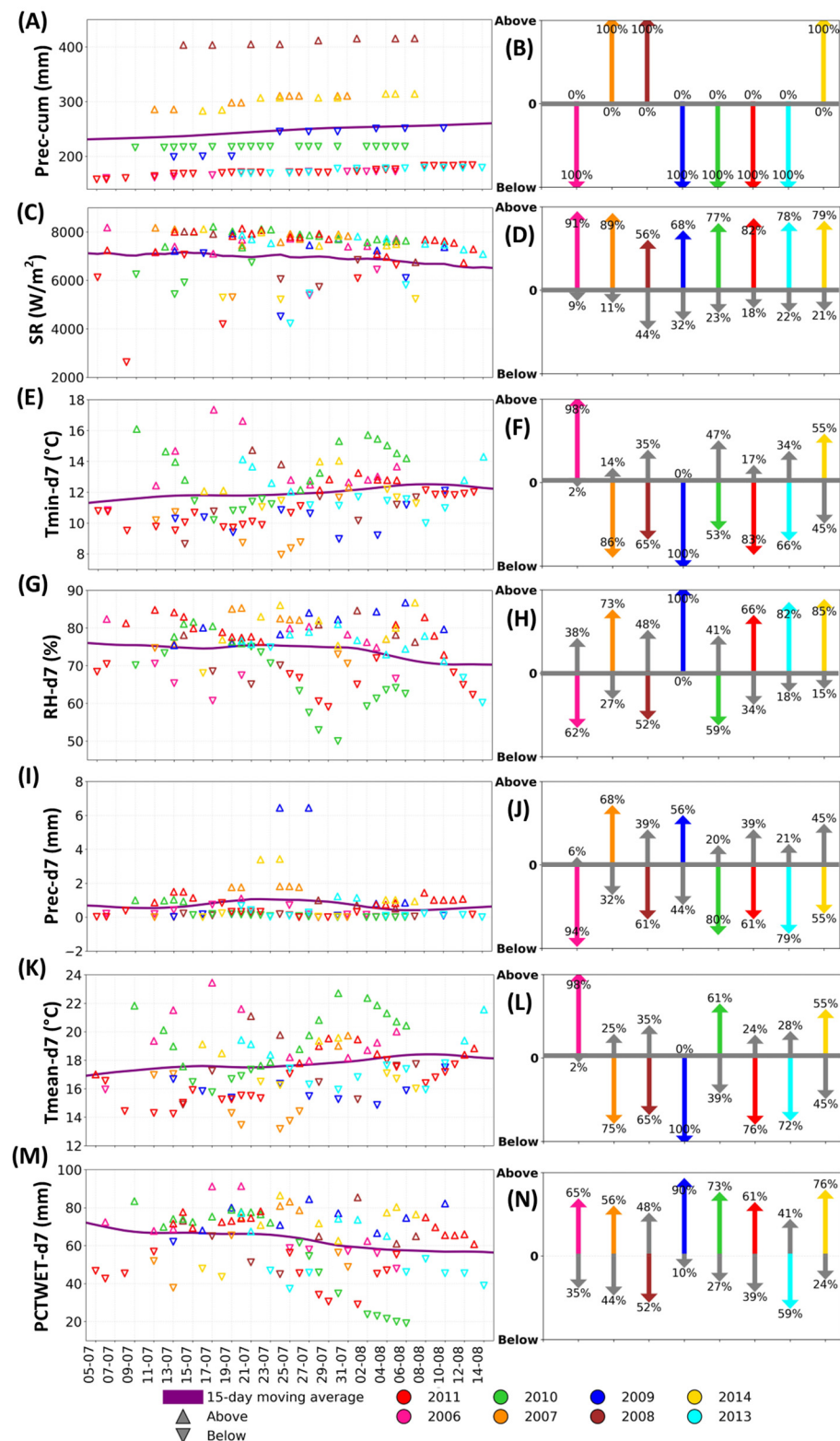


Figure 6. Representation of the values of each climate variable on the day of capture and the 15-day moving average (left panels) and captures the percentage that occurs with climate variables above or below the 15-day moving average (right panels): (A,B) Prec-cum (Spatial mean of the accumulated daily total precipitation); (C,D) SR (Spatial mean of daily total solar radiation); (E,F) Tmin-d7 (Spatial mean of the 7-day means of daily minimum temperature); (G,H) RH-d7 (Spatial mean of the 7-day means of daily relative humidity); (I,J) Prec-d7 (Spatial mean of the 7-day means of daily total precipitation); (K,L) Tmean-d7 (Spatial mean of the 7-day means of mean temperature); (M,N) PCTWET-d7 (Spatial mean of the 7-day means of daily soil surface wetness).

The Prec-d7 further highlighted the importance of moisture conditions (Figure 6I,J). Except for 2007 (0–1.8 mm) and 2009 (0–6.5 mm), values are predominantly below the 15-day moving average in all years. In 2009, only two sampling days recorded precipitation totals exceeding 6 mm during the previous seven days.

The Tmean-d7 (Figure 6K,L) exhibits a percentage pattern similar to Tmin-d7, except in 2010, when it presents a higher percentage (61%) of captures at mean temperatures above the 15-day moving average. The year 2006 stands out for recording capture days with temperatures as high as 23.4 °C. However, the highest overall proportion of butterflies is observed at around 18.4 °C, as in 2009, which was one of the years with the greatest number of butterflies recorded.

PCTWET-d7 shows greater variability among years and less distinct patterns than the other climatic variables (Figure 6M,N). Values are predominantly above the 15-day moving average. However, in 2008 (45.0–85.4%) and 2013 (37.3–77.1%), the majority of observations occurred below the climatological mean, accounting for 52% and 59% of captures, respectively. The highest soil moisture value recorded during the study period was 91.3% in 2006, whereas the lowest was 19.1% in 2010.

3.4. Climate Range Determination

The climatic ranges associated with the highest frequency of adult captures were determined from the variables identified as having the strongest associations with butterfly abundance (Figure 7; Table S2). Although captures also occurred outside these intervals, the selected ranges contained the majority of observations.

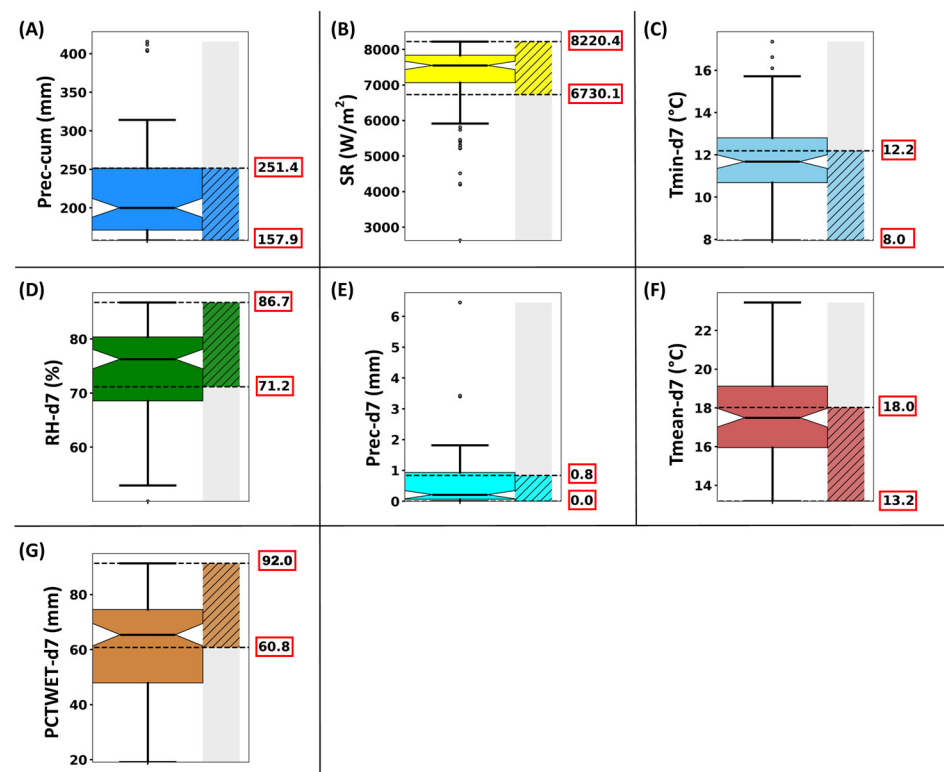


Figure 7. Boxplots of the climatic variables' distribution on the butterfly capture days, with the respective limits defined based on the predominant percentage defined with High Effect classification: (A) Prec-cum (Spatial mean of the accumulated daily total precipitation); (B) SR (Spatial mean of daily total solar radiation); (C) Tmin-d7 (Spatial mean of the 7-day means of daily minimum temperature); (D) RH-d7 (Spatial mean of the 7-day means of daily relative humidity); (E) Prec-d7 (Spatial mean of the 7-day means of daily total precipitation); (F) Tmean-d7 (Spatial mean of the 7-day means of mean temperature); (G) PCTWET-d7 (Spatial mean of the 7-day means of daily soil surface wetness).

Prec-cum (Figure 7A) ranges from 157.9 to 415.7 mm, with a median of 200.1 mm, Q1 171.2 mm, and Q3 251.4 mm. Approximately 81% of captures occurred within the range 157.9–251.4 mm, whereas observations associated with precipitation above 251.4 mm were less frequent. Outliers (>400 mm) correspond to exceptionally wet days and do not represent abundance conditions, indicating that the species is associated with humid but not excessively rainy periods.

SR (Figure 7B) varies between 2628.4 and 8220.4 W/m², with a median of 7550.8 W/m², Q1 7066.1 W/m², and Q3 7836.5 W/m². Most captures were recorded under radiation values between 6730.1 and 8220.4 W m^{−2}. Tmin-d7 (Figure 7C), representing nocturnal conditions preceding daytime sampling, ranged from 8.0 to 17.4 °C, with a median of 11.7 °C (Q1 = 10.7 °C; Q3 = 12.8 °C). Temperatures above 17.4 °C are residual, which suggests that moderate nocturnal temperatures provide suitable conditions for subsequent daytime abundance.

Relative humidity averaged over the previous seven days (RH-d7; Figure 7D) varied between 52.9 and 86.7%, with a median of 76.3%. Most captures (68.1%) occurred under relative humidity values between 71.2 and 86.7%. Seven-day mean precipitation (Prec-d7; Figure 7E) ranged from 0 to 6.45 mm, with a median of 0.21 mm. Approximately 65% of captures occurred under precipitation values between 0 and 0.8 mm, indicating occasional heavier rainfall that did not affect overall butterfly abundance.

Tmean-d7 (Figure 7F) ranged from 13.2 to 23.4 °C, with a median of 17.5 °C (Q1 15.95 °C, Q3 19.13 °C). Over 65% of individuals were observed in the 13.2–18.0 °C range. This distribution shows no outliers, indicating stable and optimal thermal conditions during capture days. PCTWET-d7 (Figure 7G) showed an association with soil moisture (19.1–92.0%), with Q1 at 47.9% and Q3 at 74.6%. Most captures (≈63%) occurred between 60.8 and 92.0%, and no extreme values were observed outside this range, highlighting the species' association with humid microclimates.

4. Discussion

The structural complexity of meadow habitats directly influences the climatic variables that can enhance or limit *P. alcon*, as well as its host species, *G. pneumonanthe* and *Myrmica* ants (*M. aloba* in ANP) [55,56]. In the present study, refs. [23,27,52], the climatic variables Prec-cum, SR, Tmin-d7, RH-d7, Prec-d7, Tmean-d7, and PCTWET-d7 showed a strong influence on the observed adult abundance of the Alcon Blue in Libânia meadow.

It became evident that the occurrence of the Prec variable is not favourable to butterfly activity [22,23]. However, Prec-cum (157.9–251.4 mm) and Prec-d7 (less than 3.4 mm) were positively associated with adult abundance. This pattern suggests that *P. alcon* depends on humid habitats that support both *G. pneumonanthe* [27] and *Myrmica* ants, while requiring dry conditions for flight activity, mating, and oviposition. RH-d7 showed optimal values between 71.2% and 86.7%. Similarly, [55] identified humidity values between 84% and 92% as favourable for butterfly reproduction. Temperature also played a key role, influencing activity, distribution, oviposition, mating, and larval development [55]. Lower values of Tmin-d7 (8.0–12.2 °C) and Tmean-d7 (13.2–18.0 °C) proved to be essential for the species' presence. Tmin-d7 showed a stronger association with observed adult abundance than Tmax variables. This finding suggests that nocturnal thermal conditions may play a particularly important role in determining suitable microclimatic conditions for adult activity and occurrence during the flight period.

Regarding SR, optimal values ranged between 6730 W/m² and 8220 W/m², with minimum values reaching 4819 W/m². These results are consistent with [55], who emphasised that cloud cover can limit butterfly flight, as can wind speed. SR was positively associated with the number of active adults recorded during sampling events, likely reflecting

increased adult activity under favourable thermal and light conditions, which may enhance feeding, mating, and oviposition. Concerning PCTWET-d7, excessively wet conditions reduce the density of host plants and ant nests, consequently decreasing the presence of the Alcon Blue [8], which contrasts with the high percentages obtained in the present study (60.8–92.0%). This apparent discrepancy may be related to the particular characteristics of the mountain peatland habitats of ANP, where high drainage capacity and heterogeneous topography can maintain humid microclimatic conditions without generating prolonged waterlogging. The stronger association of seven-day climatic variables with adult abundance indicates that abundance is related not only to weather conditions during sampling but also to cumulative microclimatic conditions in the preceding days [1,20,26].

This detailed microclimatic characterisation defines quantitative microclimatic ranges associated with adult *P. alcon* abundance, providing reference values for assessing current habitat requirements and supporting future evaluations of habitat conditions under climate change. Climate projections indicate that mountain peatlands are among the most endangered ecosystems in Mediterranean regions, where up to 60% of mountain species are projected to disappear by 2085 [31]. Iberian Peninsula will experience a 74% decline in climatically suitable habitats for gentian species by 2060, thereby compromising butterfly survival [25,27]. By 2050, losses of 40% of suitable climatic niches are expected due to desynchronisation between host plant flowering and habitat suitability, while an average temperature increase of 4.1 °C by 2100 is projected to reduce the distribution area of *P. alcon* by approximately 74%, particularly affecting Central European populations [2,57]. Habitat fragmentation is also associated with the abandonment of traditional land-use practices, fire, agricultural intensification, urbanisation, and tourism development [3,16,19,20,24,31]. In Belgium, Spain, Denmark, the Netherlands, and Slovenia, butterfly diversity has been severely decreased [2,16,19,57–59].

Within the context of projected climate change, habitat conditions in the ANP may shift beyond the microclimatic ranges associated with adult *P. alcon*, highlighting the need for targeted conservation measures. This may include low-intensity grazing, hay cutting to prevent shrub encroachment and preserve structural heterogeneity [16,59], together with controlled burning and peatland restoration. Additional measures include maintaining a balance of herbaceous and shrub layers to ensure the presence of *Myrmica* nests [8], re-wetting degraded heathlands, and (re)introduction of *G. pneumonanthe* or butterfly larvae near host ant nests. Where the ecological requirements of the species are met, including the presence of host plant (*G. pneumonanthe*) and *Myrmica* ants, suitable habitat could be expanded towards higher elevations and wetter areas [4,15,18,34,60]. Furthermore, these microclimatic ranges can be used to identify suitable habitat patches, optimise monitoring during the flight period, and support the long-term evaluation of habitat conditions under environmental change [60]. Integrating these findings into the “Plano de Cogestão do Parque Natural do Alvão” and monitoring programmes, including “Operação Biodiversidade do Sítio Alvão/Marão” and “To Protect is to Know”, could support evidence-based conservation planning and adaptive management in the ANP [61–63].

Although the current study provides insights into the microclimatic conditions associated with adult *P. alcon* abundance in Libânia meadow, future studies should incorporate population estimates as a complementary approach. The development of integrated indices that combine demographic, microclimatic variation, and habitat-related information, including reproductive behaviour, fine-scale measurements of vegetation structure, host species availability, and interactions, could improve understanding of the mechanisms influencing population dynamics and the identification of potential thermal refugia.

5. Conclusions

The *P. alcon* presence, its host plant *G. pneumonanthe*, and ants of the genus *Myrmica* are clearly influenced by microclimatic conditions. The present study demonstrated that adult *P. alcon* abundance is associated with a combination of moderate accumulated precipitation, high relative humidity, low to moderate temperatures, and adequate solar radiation. Adult activity was favoured by dry weather conditions on the day of observation, whereas habitat suitability was associated with humid conditions maintained over longer periods. Furthermore, climatic conditions during the six days preceding capture showed stronger associations with butterfly abundance than instantaneous daily conditions, highlighting the importance of cumulative microclimatic effects. Among the variables analysed, minimum temperature, relative humidity, and accumulated precipitation were identified as the climatic factors most strongly associated with adult abundance, emphasising the dependence of this species on stable and humid mountain meadow environments.

Given the climate change scenarios, characterised by rising temperatures and decreasing precipitation, a substantial reduction in suitable habitats is anticipated, as well as an increased risk of phenological desynchronisation between butterflies and their hosts. Such changes compromise population viability and long-term persistence. These impacts may be intensified by anthropogenic factors, including the abandonment of traditional management practices and habitat fragmentation, which directly affect the structure and species of meadows.

The quantitative microclimatic ranges identified in this study can support *P. alcon* conservation in the ANP by informing habitat management in Libânia meadow, identifying habitats with suitable microclimatic conditions for the butterfly, its host plant (*G. pneumonanthe*), and *Myrmica* ants, and providing reference values for future evaluations of habitat conditions under climate change. These microclimatic ranges can be integrated into the monitoring programmes within the ANP and in similar meadow habitats to support the conservation of these habitats and their associated species.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/ecologies7030076/s1>, Figure S1. Climatology mean and 15-day moving average of climatic variables: (A) Prec (mm); (B) Prec-d7 (mm); (C) Tmax (°C); (D) Tmax-d7 (°C); (E) Tmin (°C); (F) Tmin-d7 (°C); (g) Tmean (°C); (H) Tmean-d7 (°C); (I) SR (W/m²); (J) SR-d7 (W/m²); (K) RH (%); (L) RH-d7 (%); (M) PCTWET (%); (N) PCTWET-d7 (%); (o) WS (m/s); (P) WS-d7 (m/s); (Q) GDD (°C); (R) GDD-cum (°C); (S) GDD-cum-d7 (°C); (T) Prec-cum (mm); (U) Prec-cum-d7 (mm) of the Libânia meadow; Table S1. Contingency table based on a comparison between capture days (considering the total number of moths captured each day) and the 15-day moving average for each climate variable, in the Libânia (LI) meadow; Table S2. Descriptive statistics of the selected microclimatic variables: Prec-cum (Spatial mean of the accumulated daily total precipitation), SR (Spatial mean of daily total solar radiation), Tmin-d7 (Spatial mean of the 7-day means of daily minimum temperature), RH-d7 (Spatial mean of the 7-day means of daily relative humidity), Prec-d7 (Spatial mean of the 7-day means of daily total precipitation), Tmean-d7 (Spatial mean of the 7-day means of mean temperature), PCTWET-d7 (Spatial mean of the 7-day means of daily soil surface wetness), according with Figure 7.

Author Contributions: Conceptualisation, T.R.F., P.S.O. and J.A.S.; Methodology, T.R.F., P.S.O., A.F., N.G., J.J. and J.A.S.; Software, T.R.F., A.F. and N.G.; Validation, T.R.F. and J.A.S.; Formal Analysis, T.R.F., A.F., N.G. and J.A.S.; Investigation, T.R.F.; Resources, T.R.F., P.S.O. and A.F.; Data Curation, T.R.F., P.S.O. and A.F.; Writing—Original Draft Preparation, T.R.F.; Writing—Review and Editing, T.R.F., P.S.O., A.F., N.G., J.J. and J.A.S.; Visualisation, T.R.F.; Supervision, J.J. and J.A.S.; Project Administration, J.J. and J.A.S.; Funding Acquisition, J.J. and J.A.S. All authors have read and agreed to the published version of the manuscript.

Funding: This work is supported by National Funds by FCT—Portuguese Foundation for Science and Technology, under the projects UID/04033/2025: Centre for the Research and Technology of Agro-Environmental and Biological Sciences (<https://doi.org/10.54499/UID/04033/2025>) and LA/P/0126/2020 (<https://doi.org/10.54499/LA/P/0126/2020>). Teresa R. Freitas acknowledges the financial support of FCT through the Individual Scientific Employment Stimulus contract 2024.09620.CEECIND.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analysed in this study. Data sharing is not applicable to this article.

Acknowledgments: The authors acknowledge the project ReFOOD4North—Rebuilding FOODshed for a Sustainable Future in the North Region, operation n.º NORTE2030-FEDER-02654300, financed by European Regional Development Fund (ERDF) through the Northern Regional Programme 2021-2027 [NORTE2030] and the project STrengthS4WineChaiN Project (NORTE2030-FEDER-01786100) and was co-financed by the European Regional Development Fund (ERDF) under the Northern Regional Programme 2021-2027 [NORTE2030]. The authors also thank the funding from the Portuguese Government through the ON.2/QREN PROGRAMM and the project PROTEGER E CONHECER, by the European Union Funds (FEDER/COMPETE—Operational Competitiveness Programme).

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ANP Alvão Natural Park
LI Libânia meadow

References

1. Cerrato, C.; Lai, V.; Balletto, E.; Bonelli, S. Direct and Indirect Effects of Weather Variability in a Specialist Butterfly. *Ecol. Entomol.* **2016**, *41*, 263–275. [[CrossRef](#)]
2. Maes, D.; Pardon, W.; Palmans, G.; Van Dyck, H. The Last of the Maculineans: Can We Save the Emblematic Alcon Blue Butterfly Phengaris Alcon under Climate Change When Its Habitat Continues to Deteriorate? *J. Insect Conserv.* **2024**, *28*, 1037–1049. [[CrossRef](#)]
3. Nowicki, P.; Pepkowska, A.; Kudlek, J.; Skórka, P.; Witek, M.; Settele, J.; Woyciechowski, M. From Metapopulation Theory to Conservation Recommendations: Lessons from Spatial Occurrence and Abundance Patterns of Maculinea Butterflies. *Biol. Conserv.* **2007**, *140*, 119–129. [[CrossRef](#)]
4. Tartally, A.; Somogyi, A.Á.; Révész, T.; Nash, D.R. Host Ant Change of a Socially Parasitic Butterfly (Phengaris Alcon) through Host Nest Take-Over. *Insects* **2020**, *11*, 556. [[CrossRef](#)] [[PubMed](#)]
5. Geraldés, H. Guia Ilustrado Para Saber o Que Comem Estas 10 Borboletas. Available online: <https://wilder.pt/naturalistas/guia-ilustrado-para-saber-o-que-comem-estas-10-borboletas> (accessed on 8 January 2026).
6. Quinta, L. A Borboleta Da Serra Do Alvão Que Parece Retirada de Uma Fábula. Available online: https://www.nationalgeographic.pt/meio-ambiente/a-borboleta-da-serra-do-alvao-que-parece-retirada-uma-fabula_1245 (accessed on 23 June 2025).
7. IUCN Phengaris Alcon; Van Swaay, C.; Ellis, S.; Warren, M. *IUCN Red List of Threatened Species*; IUCN: Gland, Switzerland, 2023.
8. Soares, P.O.; Crespi, A.L.; Rodrigues, M.C.; Arnaldo, P.S. The Habitat Vegetational Structure and the Success of the Blue Alcon, Maculinea Alcon (Denis & Schiffermüller). *Plant Biosyst.* **2012**, *146*, 1–6. [[CrossRef](#)]
9. Arnaldo, P.S.; Da Conceição Rodrigues, M.; Fonseca, T.F. Europe's Threatened Species: The Case of Endangered Phengaris (Maculinea) Butterflies (Lepidoptera, Lycaenidae). In *Endangered Species: Habitat, Protection and Ecological Significance*; Lucas-Borja, M.E., Ed.; Nova Science Publishers, Inc.: New York, NY, USA, 2012; pp. 143–153.
10. Gbif Phengaris Alcon. Available online: https://www.gbif.org/occurrence/charts?country=BE&country=FR&country=NL&country=AT&country=ES&country=DE&taxon_key=7459402 (accessed on 25 November 2025).
11. iNaturalist Borboleta-azul-das-turfeiras (Phengaris Alcon). Available online: <https://www.inaturalist.org/taxa/426193-Phengaris-alcon> (accessed on 9 January 2026).

12. WallisDeVries, M.F.; Bokelaar, J.; Kok, A.; Limpens, J.; Luijten, S.; Oostermeijer, J.G.B.; van Marrewijk, R.C.H.; van Stipdonk, A.H.; Vicente, I.; Vogel, C.; et al. Alcon Blues: Recent Shifts in Limiting Habitat Factors Challenge the Persistence of an Endangered Butterfly. *J. Insect Conserv.* **2024**, *28*, 993–1006. [\[CrossRef\]](#)
13. Boieiro, M.; Ceia, H.; Caramujo, M.J.; Cardoso, P.; Garcia Pereira, P.; Pires, D.; Reis, J. *Livro Vermelho Dos Invertebrados de Portugal Continental*; FCIências.ID e ICNF I.P.: Lisboa, Portugal, 2023.
14. Arnaldo, P.; Oliveira, I.; Santos, J.; Leite, S. Climate Change and Forest Plagues: The Case of the Pine Processionary Moth in Northeastern Portugal. *Investig. Agrar. Sist. Recur. For.* **2011**, *20*, 508–515. [\[CrossRef\]](#)
15. Tartally, A.; Rodrigues, M.C.; Brakels, P.; Arnaldo, P.S. Myrmica Aloba (Hymenoptera: Formicidae) Hosts Isolated Populations of a Hoverfly, a Butterfly and an Ichneumon Species in NE-Portugal. *J. Insect Conserv.* **2013**, *17*, 851–855. [\[CrossRef\]](#)
16. Tartally, A.; Nash, D.R.; Varga, Z.; Lengyel, S. Changes in Host Ant Communities of Alcon Blue Butterflies in Abandoned Mountain Hay Meadows. *Insect Conserv. Divers.* **2019**, *12*, 492–500. [\[CrossRef\]](#)
17. Arnaldo, P.S.; Gonzalez, D.; Oliveira, I.; van Langevelde, F.; Wynhoff, I. Influence of Host Plant Phenology and Oviposition Date on the Oviposition Pattern and Offspring Performance of the Butterfly Phengaris Alcon. *J. Insect Conserv.* **2014**, *18*, 1115–1122. [\[CrossRef\]](#)
18. Sielezniew, I.; Sielezniew, M. Efficiency of Emergency Conservation Methods: A Case Study of the Alcon Blue Butterfly (Phengaris Alcon) and Its Specific Parasitoid. *J. Insect Conserv.* **2024**, *28*, 263–268. [\[CrossRef\]](#)
19. Kljun, I.; Zagoršek, T.; Rome, T.; Lončar, T.; Ramšak, B. Estimation of Current Population Status of the Alcon Large Blue Phengaris Alcon (Denis & Schiffermüller, 1775) (Lepidoptera: Lycaenidae) in Bela Krajina (SE Slovenia) Based on Egg Counts. *Nat. Slov.* **2016**, *18*, 5–15. [\[CrossRef\]](#)
20. Dziekanska, I.; Nowicki, P.; Piroznikow, E.; Sielezniew, M. A Unique Population in a Unique Area: The Alcon Blue Butterfly and Its Specific Parasitoid in the Białowieża Forest. *Insects* **2020**, *11*, 687. [\[CrossRef\]](#) [\[PubMed\]](#)
21. Arnaldo, P.; Wynhoff, I.; Soares, P.; da Conceição Rodrigues, M.; Aranha, J.; Csosz, S.; Maravalhas, E.; Tartally, A. Maculinea Alcon Exploits Myrmica Aloba in Portugal: Unusual Host Ant Species of a Myrmecophilous Butterfly in a Peripheral Region. *J. Insect Conserv.* **2011**, *15*, 465–467. [\[CrossRef\]](#)
22. Roy, D.B.; Rothery, P.; Moss, D.; Pollard, E.; Thomas, J.A. Butterfly Numbers and Weather: Predicting Historical Trends in Abundance and the Future Effects of Climate Change. *J. Anim. Ecol.* **2001**, *70*, 201–217. [\[CrossRef\]](#)
23. Kral-O'Brien, K.C.; Harmon, J.P.; Antonsen, A.K. Snapshot Observations Demonstrate Within- and across-Year Weather Related Changes in Butterfly Behavior. *Clim. Change Ecol.* **2021**, *1*, 100004. [\[CrossRef\]](#)
24. Barnes, K.W.; Toso, L.B.; Niemuth, N.D. Dakota Skipper Distribution Model for North Dakota, South Dakota, and Minnesota Aids Conservation Planning under Changing Climate Scenarios. *Front. Ecol. Evol.* **2024**, *12*, 1304748. [\[CrossRef\]](#)
25. Goded, M.; Ursul, G.; Baz, A.; Wilson, R.J. Changes to Butterfly Phenology versus Elevation Range after Four Decades of Warming in the Mountains of Central Spain. *J. Insect Conserv.* **2024**, *28*, 935–949. [\[CrossRef\]](#)
26. Cormont, A.; Wiegner Wamelink, G.W.; Jochem, R.; WallisDeVries, M.F.; Wegman, R.M.A. Host Plant-Mediated Effects of Climate Change on the Occurrence of the Alcon Blue Butterfly (Phengaris Alcon). *Ecol. Model.* **2013**, *250*, 329–337. [\[CrossRef\]](#)
27. Freitas, T.R.; Martins, S.; Jesus, J.; Campos, J.; Fernandes, A.; Menz, C.; Maravalhas, E.; Fraga, H.; Santos, J.A. Bio-Ecological Indicators for Gentiana Pneumonanthe L. Climatic Suitability in the Iberian Peninsula. *Plants* **2025**, *14*, 2857. [\[CrossRef\]](#) [\[PubMed\]](#)
28. Saccheri, I.; Kuussaari, M.; Kankare, M.; Vikman, P.; Fortelius, W.; Hanski, I. Inbreeding and Extinction in a butterfly Metapopulation. *Nature* **1998**, *392*, 491–494. [\[CrossRef\]](#)
29. Pereira, D. Governo Vai Adquirir Dois Kits de Combate a Fogos Para Aviação C-130. 3000 Hectares de Área Ardida No Alvão. Available online: <https://www.dn.pt/sociedade/dominado-inc%C3%AAndio-em-vila-real> (accessed on 7 July 2026).
30. Sequeira, A.C.; Nunes, L.; Rego, F.C.; Andrés, C.; Oviedo, B. *Atividade: 1.15 Identificação de Parâmetros de Comportamento Do Fogo Em Florestas Complexas Úteis Para o Planeamento*; ISA: Lisbon, Portugal, 2022.
31. Fonseca, A.; Santos, J.; Pádua, L.; Santos, M. Unveiling the Future of Relict Mediterranean Mountain Peatlands by Integrating the Potential Response of Ecological Indicators with Environmental Suitability Assessments. *Ecol. Indic.* **2023**, *157*, 111206. [\[CrossRef\]](#)
32. ICNF Parque Natural Do Alvão. Available online: <https://www.icnf.pt/conservacao/napareasprotegidas/parquesnaturais/pnalvao> (accessed on 8 January 2026).
33. Natural.PT Parque Natural Do Alvão. Available online: <https://natural.pt/protected-areas/parque-natural-alvao?locale=pt> (accessed on 8 January 2026).
34. Da Conceição, M.; Rodrigues, C.; Arnaldo, P.M.S.O.; Aranha, J. Contribution to the characterization of Gentiana pneumonanthe L. and Maculinea alcon L. forest landscapes and global change-new frontiers in management, conservation and restoration. In Proceedings of the IUFRO Landscape Ecology Working Group International Conference; Forest Landscapes and Global Change-New Frontiers in Management, Conservation and Restoration, Bragança, Portugal, 21 September 2010.
35. Kearney, M.R.; Porter, W.P. NicheMapR—an R Package for Biophysical Modelling: The Microclimate Model. *Ecography* **2017**, *40*, 664–674. [\[CrossRef\]](#)

36. Kearney, M.R.; Briscoe, N.J.; Mathewson, P.D.; Porter, W.P. NicheMapR—an R Package for Biophysical Modelling: The Endotherm Model. *Ecography* **2021**, *44*, 1595–1605. [CrossRef]
37. Kearney, M. *Introduction to the NicheMapR Ectotherm Model 2022*; Wiley: Hoboken, NJ, USA, 2022.
38. Kearney, M.R.; Porter, W.P. NicheMapR—an R Package for Biophysical Modelling: The Ectotherm and Dynamic Energy Budget Models. *Ecography* **2020**, *43*, 85–96. [CrossRef]
39. Klings, D.H.; Duffy, J.P.; Kearney, M.R.; Maclean, I.M.D. Driving Microclimate Models with ERA5 Global Gridded Climate Data. *Methods Ecol. Evol.* **2022**, *13*, 1402–1411. [CrossRef]
40. Hersbach, H.; Bell, B.; Berrisford, P.; Biavati, G.; Horányi, A.; Muñoz Sabater, J.; Nicolas, J.; Peubey, C.; Radu, R.; Rozum, I.; et al. ERA5 Hourly Data on Single Levels from 1940 to Present. *Copernic. Clim. Change Serv. (C3s) Clim. Data Store (Cds)* **2023**, *10*, 24381. Available online: <https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview> (accessed on 26 November 2025).
41. Hufkens, K.; Stauffer, R.; Campitelli, E. The Ecmwfr Package: An Interface to ECMWF API Endpoints 2019. Available online: <https://bluegreen-labs.github.io/ecmwfr> (accessed on 26 November 2025).
42. Spinu, V.; Grolemond, G.; Wickham, H.; Lyttle, I.; Constigan, I.; Law, J.; Lee, C.H. Lubridate: Make Dealing with Dates a Little Easier 2018. *J. Stat. Softw.* **2011**, *40*, 3.
43. Wickham, H.; François, R.; Henry, L.; Müller, K.; Vaughan, D. *Dplyr: A Grammar of Data Manipulation*; CRAN: Contributed Packages; CRAN: Vienna, Austria, 2018.
44. Sumner, M. *Tidync: A Tidy Approach to “NetCDF” Data Exploration and Extraction*; CRAN: Contributed Packages; CRAN: Vienna, Austria, 2021.
45. Rew, R.; Davis, G. NetCDF: An Interface for Scientific Data Access. *IEEE Comput. Graph. Appl.* **1990**, *10*, 76–82. [CrossRef]
46. Hollister, R.M. The Project: Theoretical Framework and Global Institutional Experience. In *University Social Responsibility and Quality of Life: A Global Survey of Concepts and Experiences*; Springer: Singapore, 2017; pp. 3–9.
47. Porter, W.P.; Mitchell, J.W.; Beckman, W.A.; DeWitt, C.B. Behavioral Implications of Mechanistic Ecology. *Oecologia* **1973**, *13*, 1–54. [CrossRef] [PubMed]
48. Caldwell, A.J.; Hons, B. *Can Snow Skinks Survive Climate Change?* University of Tasmania Australia: Tasmania, Australia, 2016.
49. Enriquez-Urzelai, U.; Tingley, R.; Kearney, M.R.; Sacco, M.; Palacio, A.S.; Tejedo, M.; Nicieza, A.G. The Roles of Acclimation and Behaviour in Buffering Climate Change Impacts along Elevational Gradients. *J. Anim. Ecol.* **2020**, *89*, 1722–1734. [CrossRef] [PubMed]
50. Fonseca, A.; Cruz, J.; Fraga, H.; Andrade, C.; Valente, J.; Alves, F.; Neto, A.C.; Flores, R.; Santos, J.A. Vineyard Microclimatic Zoning as a Tool to Promote Sustainable Viticulture under Climate Change. *Sustainability* **2024**, *16*, 3477. [CrossRef]
51. Fonseca, A.; Cruz, J.; Fraga, H.; Andrade, C.; Valente, J.; Alves, F.; Neto, C.; Flores, R.; Santos, J.A. Enhancing Climate Change Impact Assessment in Viticulture by Resolving Microclimates. *Eur. J. Agron.* **2025**, *170*, 127740. [CrossRef]
52. Evans, L.C.; Sibly, R.M.; Thorbek, P.; Sims, I.; Oliver, T.H.; Walters, R.J. Integrating the Influence of Weather into Mechanistic Models of Butterfly Movement. *Mov. Ecol.* **2019**, *7*, 24. [CrossRef] [PubMed]
53. Hellegers, M.; van Swaay, C.A.M.; van Hinsberg, A.; Huijbregts, M.A.J.; Schipper, A.M. Modulating Effects of Landscape Characteristics on Responses to Warming Differ Among Butterfly Species. *Front. Ecol. Evol.* **2022**, *10*, 873366. [CrossRef]
54. Biologyinsights. What Time of Year Do Ants Come Out? Available online: <https://biologyinsights.com/what-time-of-year-do-ants-come-out/> (accessed on 6 January 2026).
55. Mahata, A.; Panda, R.M.; Dash, P.; Naik, A.; Naik, A.K.; Palita, S.K. Microclimate and Vegetation Structure Significantly Affect Butterfly Assemblages in a Tropical Dry Forest. *Climate* **2023**, *11*, 220. [CrossRef]
56. Milling, C.R.; Rachlow, J.L.; Olsoy, P.J.; Chappell, M.A.; Johnson, T.R.; Forbey, J.S.; Shipley, L.A.; Thornton, D.H. Habitat Structure Modifies Microclimate: An Approach for Mapping Fine-Scale Thermal Refuge. *Methods Ecol. Evol.* **2018**, *9*, 1648–1657. [CrossRef]
57. Redeia. The Alcon Blue Butterfly, an Endangered Species in Catalonia, Has Been Spotted below Electricity Transmission Lines. Available online: <https://www.redeia.com/en/press-office/news/press-release/2024/10/the-alcon-blue-butterfly-endangered-species-in-catalonia-has-been-spotted-below-electricity-transmission-lines> (accessed on 7 July 2026).
58. Boe, A.M.B.; Simonsen, T.J.; Colding-Jørgensen, C.T.; Folman, P.H.; Jensen, T.T.; Spencer, K.J.; Thomsen, P.F.; Nash, D.R. Spatial and Temporal Patterns of Genetic Diversity and Structure in Danish Populations of the Alcon Blue Butterfly *Phengaris Alcon* (Denis & Schiffermüller). *Diversity* **2022**, *14*, 1098. [CrossRef]
59. Maes, D.; Vanreusel, W.; Talloen, W.; Van Dyck, H. Functional Conservation Units for the Endangered Alcon Blue Butterfly *Maculinea Alcon* in Belgium (Lepidoptera: Lycaenidae). *Biol. Conserv.* **2004**, *120*, 229–241. [CrossRef]
60. Radchuk, V.; WallisDeVries, M.F.; Schtickzelle, N. Spatially and Financially Explicit Population Viability Analysis of *Maculinea Alcon* in the Netherlands. *PLoS ONE* **2012**, *7*, e38684. [CrossRef] [PubMed]
61. ICNF. *Plano de Gestão Do Parque Natural Do Alvão (2023–2027)*; ICNF: Vila Real, Portugal, 2023.

62. ICNF. *Plano de Gestão Da ZEC Alvão/ Marão*—PTCON0003; ICNF: Vila Real, Portugal, 2019.
63. ICNF. Rede Natura 2000. Available online: <https://www.icnf.pt/conservacao/redenatura2000> (accessed on 23 May 2025).

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.