Can the extinction of Melitaea britomartis in NW Italy be explained by unfavourable weather? An analysis by Optimal Interpolation

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Can the extinction of *Melitaea britomartis* in NW Italy be explained by unfavourable weather? An analysis by Optimal Interpolation.

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Abstract (150-250 words)

We investigated possible correlations between climate-related factors and butterfly range restrictions by selecting a study case represented by 4 populations of *Melitaea britomartis*, which become ‘simultaneously’ extinct in NW Italy in 1976-1977 without any observable habitat change. To overcome difficulties related to the analysis of past extinctions and hypothesise causal factors, we applied the Optimal Interpolation method, a statistical method used to create a gridded climatological analysis of temperature and precipitation data, to a historical dataset containing all available information on the Italian butterfly fauna. We tested two different hypotheses: i) the role of climate change, expressed as a general trend in temperature and precipitation data; ii) the role of extreme weather events, expressed as anomalous conditions during the years of extinctions. Our results show that long-term temperature and precipitation data do not present any clear trend at our study site, suggesting that they cannot be involved in the species’ extinction. On the opposite, 1976 and 1977 were climatologically critical for the study area. In particular, 1977 was characterized by the coldest summer in the entire historical dataset (1958-1977), with strong negative temperature anomalies. Moreover, both years experienced unusually many rainy days during spring and summer. The year 1977 in particular, was the wettest within the entire historical dataset. The years of *Melitaea britomartis* populations’ extinction were characterised by many more cold and rainy days than usual during the species’ flight period. These results allow us to hypothesize a strong component of unfavourable weather in driving populations’ extinction.

Key words: butterflies; weather variability; population decline; extinction

Introduction

Factors leading to populations’ extinctions are many since, even though habitat destruction is probably the most pervasive, a number of others may come into play, either separately or in multiple combinations. Among these factors, climate change is currently attracting the attention of many ecologists. Global warming is held responsible for changes observed in a number of butterfly species, in particular their uphill (Thomas et al. 2006, Wilson et al. 2007), or northwards range shifts (Parmesan et al. 1999, Pöyry et al. 2009), or some observed range contractions (Warren et al. 2001). Climate change has otherwise caused mismatches between the ecological requirements of herbivores and of their larval food-plants (Inouye 2000, Schweiger et al.

2008) and most projections based on bioclimatic envelope models have shown that, in the persistence of current scenarios, many butterfly populations are deemed to be at risk of future extinction, particularly in the South of Europe (Settele et al. 2008). Moreover, an increase in climate variability and consequently in the frequency of extreme weather events has been already recorded and a further amplification of such phenomena is strongly hypothesized (Easterling et al. 2000; Parmesan et al. 2000). Consequences on the biotic components, however, have been less explored (Parmesan et al. 2000).

Attributing extinctions to a single factor is generally difficult and little evidence of a direct relationship between climate change and local species loss is available (Franco et al. 2006; Cahill et al. 2012).

In this paper, we investigated possible correlations between climate-related factors and butterfly range restrictions by selecting a study case, represented by 4 populations of *Melitaea britomartis* which become 'simultaneously' extinct in NW Italy in 1976-1977, causing the species to altogether disappear from this general area without any observable habitat change. To overcome difficulties related to the analysis of past extinctions and to hypothesizing causal factors, we applied a statistical approach used to produce climatological gridded series to a historical dataset in which all the available information on the Italian butterfly fauna has been summarised (Balletto et al. 2007; Bonelli et al. 2011).

We tested two different hypotheses: i) the role of climate change, expressed as a general trend in temperature and precipitation data; ii) the role of extreme weather events, expressed as anomalous conditions during the years of extinctions.

Methods

The Study Case

Melitaea britomartis is an oligophagous butterfly (its main larval host plants are *Plantago lanceolata* and some species belonging to the genus *Veronica*). It is usually monovoltine, although some cases of partially bivoltine populations have been recorded in NW Italy. The flight period spans from May/June to late July/August. The species is restricted to an altitudinal range of ca. 300-900 m and is characterized by low dispersal ability (Balletto et al. 1985).

Melitaea britomartis is among the most seriously threatened butterflies of the Italian fauna (Balletto et al. 2005; Bonelli et al. 2011) and is declining all across Europe (van Swaay and Warren 1999; van Swaay et al. 2010). It is considered highly sensitive to human activities such as, in particular, overgrazing and/or changes in agricultural management (van Swaay and Warren 1999; Schmitt and Rakosy 2007).

In Italy *Melitaea britomartis* is interestingly a hygrophilous species, restricted to the tall wet grasslands occurring in the northern fringes of the plains of the Po river valley, in the North of the country (Balletto et al. 2005), where it reaches its southern European boundary. Only 31 populations are known for having been historically present, scattered through a matrix of unsuitable, agricultural, or highly industrialized areas (Balletto et al. 2007). Of these populations, 24 are now extinct, in most cases without any apparent change in the immediate surrounding and any clear sign of habitat destruction (Bonelli et al. 2011). At present, only 7 populations are extant, all restricted to the North-eastern part of the peninsula (Balletto et al. 2007; Bonelli et al. 2011).

Butterfly Data

We obtained data on the former geographical distribution and population extinctions of *Melitaea britomartis* from a database that some of the authors had provided to the Italian Ministry for the Environment (Balletto et al. 2007; see also Bonelli et al. 2011) for the publication of the Atlas of the Italian Fauna (Ruffo and Stoch 2007). In this database, we deemed extinct any population that was published as such in the literature and whose status was never subsequently questioned. We also deemed extinct those butterfly ‘populations’ whose ‘locations’ were actively searched by several (5–10) professional or amateur lepidopterists on at least 3 (consecutive or not consecutive) years during the species’ flight season. Since their discovery, populations of *Melitaea britomartis* occurring in NW Italy attracted a lot of attention from lepidopterists and the historical record of their extinction is well documented (e.g. Verity 1917, 1950; Leigheb 1978).

Although there are rumours that one or two (unconfirmed) individuals may have been observed in the early 1980s, 4 populations went simultaneously extinct in 1976-1977. These populations were located in NW Italy, in the Piemonte region (Montalto Dora-Bienca, Turin) at a mean altitude of 350-400 m. They all occurred within the same climatological grid.

Habitats occupied by these populations were not subject to any clear alteration or destruction (no reforestation, or overgrazing, or changes in the water-table) during and before the time of extinction, always retaining dimension adequate to sustain viable populations of *Melitaea britomartis* (ca. 1 ha or more). We did not take into account any measure of habitat isolation.

The Methodological Approach

Optimal Interpolation

To investigate possible climate-related contributions to population extinctions we applied the Optimal Interpolation method (OI hereafter), a statistical method used to analyse temperature and precipitation data.

OI (Kalnay 2003) is a statistical method implemented in the Regional Meteorological Service (Piemonte, NW Italy) to create a gridded climatological analysis of temperature and precipitation, covering the period 1 Dec 1957 - 31 December 2009, on a 15 km resolution grid. The advantage of using gridded data instead of real weather station data is in the solution of problems generated by the non-continuous or sparse weather data obtained from independent networks working over different periods (Uboldi et al. 2008). OI, in fact, integrates and makes spatially explicit all the information obtained from weather stations, while maintaining as much as possible of their spatial homogeneity, and minimizing the punctual information loss typical of any spatial interpolation.

OI uses a statistical method to interpolate the weather station data, arbitrarily located on the area, on a regular and predefined three dimensional grid, based on a background field (BF). This allows linking different historical series. Temporal homogeneity of the signal was obtained through an appropriate and variable definition of the three dimensional interpolation coefficients, by compensating the variable density of the regional stations throughout the entire period of 52 years. The climatological variables taken into account for the OI analysis were maximum, minimum temperature (T_{max}, T_{min}) as well as precipitations data (Prec).

As far as temperatures are concerned, the background field used was the ERA 40 reanalysis archive (from 1957 to 2001), as well as the objective analysis from 2002 to 2009 produced by ECMWF (European Centre for Medium-range Weather Forecast (see Ciccarelli et al. 2008) while, for precipitation, the background field was calculated from observations using a detrending procedure (Uboldi et al. 2008). Before using ERA-40 on the regional area we checked that the main climatological signals (trends, etc.) were congruent with the signals resulting from a stations' subset working in the period 1950-2000 in the region of Piemonte. This method weights the contribution to the temperature for each grid point by the nearest observation data, through a set of parameters. A careful modulation of these parameters as a function of data density and the use of an external background field helps to achieve time homogeneity and spatial coherence over the final dataset.

In formula, the computed OI analysis field is:

$$x^a=x^b+K(y^o-y^b)$$

where x stands for a variable on a grid and y for a variable on a station point. The superscripts a, b and o stand for analysis, background and observation. In particular y^o represents the measured values on a station point, y^b the corresponding values from the background.

The gain matrix K is obtained by minimizing the analysis of error variance:

$$K=G(S+O)^{-1}$$

where G is the covariance matrix between the background error field on a grid point and the same error on a station point. S is the covariance matrix of the background error field of a couple of station points and O is the covariance matrix of the observations.

Statistical Analysis

To analyse the time series obtained from OI we used a technique known as Seasonal-Trend decomposition procedure (STL), based on LOESS smoother (Cleveland et al. 1990; Hastie and Tibshirani 1990). It represents a filtering procedure for decomposing a time series into three components, i.e. i) seasonal - the periodic component present in our signal, ii) trend - over the years, and iii) residuals - the remaining unexplained components (Cleveland et al. 1990). Secondly, looking for tendencies that might reflect patterns of coherent changes in temperature or precipitation, we estimated linear trends in deseasonalised values through the years and determined their significance by *F*-test. We executed this analysis for all the time series (1958-2009) and for the time-period finishing with the year of *Melitaea britomartis* extinctions (1958-1977).

To investigate other possible weather-related mechanisms, which may have played a role in the extinction, we focused on data relating to the extinction period itself. We averaged daily values for the summer months (June-July-August, JJA hereafter), corresponding to the *Melitaea britomartis* flight period, to obtain seasonal values for each year. Next, we analysed JJA temperatures and precipitations in the study area and in the whole region of Piemonte during the years 1976 and 1977 and focused our attention on the possible occurrence of significant anomalies. Anomalies were defined as differences between values observed during the year of interest with the climatological mean evaluated for the reference period of 1961-1990.

Results

During the entire time frame for which detailed climatological records were available (1958-2009), both the minimum and maximum deseasonalized temperatures showed positive trends (T_{min}, +0.03°C per year, r^2= 0.11, F=74.0, df= 1, 623, p<0.0001; T_{max}, +0.06°C per year, r^2=0.22, F=175, df= 1, 623, p<0.0001).

Focusing on the first climatological period, however, we observed a different trend. Indeed, limiting the time frame until the *Melitaea britomartis* extinction period (1976-1977) we observed that in the area of interest, the deseasonalized data showed negative average trends (T_{min}, r^2=0.06, F=14, df= 1, 238, p=0.0002; T_{max}, r^2=0.005, F=1.3, df= 1, 238, p=0.255) rather more pronounced for minimum temperatures (-0.02°C per year for T_{max} versus -0.06°C for T_{min}). These negative trends, however, did not sufficiently explain the variability present in the data, thereby suggesting that if climate had an impact on the species' extinction, the main driving factor was not to be found in the long-term temperature trend.

A more in-depth analysis showed that the years 1976 and 1977 were climatologically critical for the study area.

In particular, the lowest maximum temperatures for the whole 1958-1977 period were observed in 1977, especially during the spring and summer season (Fig. 1). Looking at the raw daily data, another strong negative anomaly was observed for the year 1977, when T_{max} never exceeded the threshold of 26.4 °C, thereby resulting in the coldest summer in the entire OI dataset (Fig. 1).

This anomaly was not just peculiar to the study area, since it was observed over the whole region of Piemonte, where the year 1977 experienced the coldest summer within the whole historical dataset (1958-1977), when compared to the whole reference climatological period (1961-1990), for both minimum and maximum temperatures (Fig. 2).

Concerning precipitation in the study area, we did not find any statistically significant trend, either all through the 1958-2009 period, or within the reduced time frame.

Restricting the analysis to the year characterized by the extinction of *Melitaea britomartis*, however, we observed that July 1976 was the year with the highest number of rainy days in the entire dataset, while the summer seasons of 1976 and 1977 came second in this respect (Tab. 1).

The amount of precipitation during the summer of 1976 was not particularly anomalous, since the mean summer precipitation was on average within the climatological mean, although rains were distributed over more days (Fig. 3a). In contrast, the summer of 1977 was particularly wet, scoring the highest precipitation anomaly and thereby resulting in the wettest year within the entire period 1958-2009 (Fig. 3b). We obtained very similar results for the whole region of Piemonte.

These observations, therefore, matched the information obtained from temperature analysis and suggested that the summer seasons of 1976 and 1977 were characterized by many anomalously cloudy and rainy days.

Discussion

Weather Variability vs. Climate Change

Our results show that long-term temperature and precipitation data did not follow any clear trend at our study site, suggesting that these factors cannot be involved in the species' extinction. In contrast, 1976 and 1977, i.e. the years characterised by the disappearance of *Melitaea britomartis*, were climatologically critical for the study area. In particular, 1977 was the coldest summer in the entire historical dataset (1958-1977), with strong negative temperature anomalies. Moreover, both years were characterised by high numbers of rainy days during spring and summer. The year 1977 was in particular the wettest within the entire historical dataset.

Consequently, the years of *Melitaea britomartis* populations' extinction experienced unusually many cold and rainy days during the species' flight period. These results allow us to hypothesize a strong component of unfavourable weather in driving populations extinctions.

Population extinctions related to severe weather events have been previously observed in some butterfly species. Indeed, short-term responses to strongly unfavourable conditions may happen quite often in butterflies, sometimes with dramatic consequences for individual populations. Emblematic is the case of *Euphydryas editha*, in which multiple population extinctions were driven by three subsequent extreme weather events, involving low winter snowpack and unusually cold spring and summer temperatures (Parmesan et al. 2000). Ehrlich et al. (1972) described the catastrophic effects of a summer snowfall accompanied by hard frosts on a lycaenid butterfly species (*Glaucopsyche lygdamus*) at a high-altitude site. The loss of host plants and direct effects on the butterfly resulted in some local extinctions of the species, which only recolonised the area after about 10 years. A combination of unfavourable weather, in this case expressed as a heat wave, doubled by habitat fragmentation, was involved also in the extinctions of some populations of *Cupido minimus* in Central Europe (Piessens et al. 2009).

In the case of *Melitaea britomartis* we cannot directly assess the proximate causes of its extinctions, because of the nature of our data (i.e. a historical dataset), but a direct effect of unfavourable weather can be hypothesized. Many consecutive cold and rainy days could have had an impact on the butterfly behaviour, strongly reducing the time available for flying, as well as by directly reducing the probability of individuals' survival. Indeed, it is well-known that butterflies, being poikilothermic organisms, need favourable weather conditions to thermoregulate, to fly and to carry out all normal activities necessary for their trophic and reproductive life (feeding, mating, ovipositing). At the same time, many rainy days and low solar radiation, depending on cloudy conditions, will have strong negative effects on the survival and the development of the eggs and first instar larvae (Zalucki et al. 2002).

Methodological Considerations

In this paper, we explored the hypothesis of climate variation *versus* weather anomalies as possible causes for the simultaneous extinction of 4 populations of a single endangered butterfly, *Melitaea britomartis*.

As concerns climate- and weather-related effects on individual populations, butterflies are among the best-studied organisms (e.g. Dennis 1993; Hellman 2001). Yet, most of the currently available information on climate-driven impacts derives from systematically collected data, which, for the moment, are only available for some countries (e.g. Franco et al. 2006; Pöyry et al. 2009; Stefanescu et al. 2011; WallisDeVries et al. 2011), or to some better known butterfly species (e.g. Parmesan 2006).

In this framework, unstandardized, historical databases represent a valuable tool to explore present and future vulnerability in under-sampled geographical areas and for the less well-known species (e.g. Tingley and Beissinger 2009; Bonelli et al. 2011). Our database (i.e. CkMap, Balletto et al. 2007) represents an important source because it is periodically updated and integrates data from bibliographic references, museum specimens and validated field observations. It covers a geographic area, the Italian peninsula and the politically Italian islands, where at the moment no systematic butterfly survey has been carried out, but where butterfly diversity reaches very high levels (Balletto et al. 2007).

Moreover, the method applied in our work represents an interesting tool to overcome the gap between ecological data and climatic series. The main problems arising from climatological series are in their spatial resolution and temporal non-homogeneity. We resolved both problems by gridding weather and climate data by Optimal Interpolation (Kalnay 2003). Such an approach results, in some cases, in providing better data than station-based meteorological observations, which frequently suffer temporal non-homogeneity (Abatzoglou 2013). The spatial resolution of our gridded meteorological data (15 km), is relatively high and was decided on the base of the spatial density of weather station in the territory under analysis. At present, gridded surfaces of even higher resolution are freely available, but they generally do not describe temporal variation in selected parameters, only quantifying current climate conditions as 50 years averaged data. This is the case, for instance for the widely used WordClim database (Hijmans et al. 2005).

Consequently, due to its general validity and easy applicability, the approach that we followed in this paper may be applied to further investigate changes in butterfly species and communities.

Conclusions

The application of Optimal Interpolation on a temporal series of temperature and precipitation data allowed us to speculate about the hypothetical causes of the regional extinction of *Melitaea britomartis*.

Obviously enough, even if the population extinctions under study happened in areas not interested by any other kind of habitat alteration, it may be difficult to believe that unfavourable weather events taken alone are the exclusive cause of this dramatic decline. These populations were surely able to withstand much harsher climate and whether conditions over the last Centuries. So, why did they become extinct only in 1976-1977? Indeed, when population size becomes small, species are more prone to experience extinction events (e.g. Pimm et al. 1988; Piessens et al. 2009). Reduced population size is often accompanied by reduced mean genetic variability and by a consequently lower capability to adapt to new conditions (Hanski 1999; Parmesan et al. 2000; Opdam and Wascher 2004). Moreover, re-colonisation probability is highly reduced in isolated fragments (Hanksi 1999). Small fragments of suitable habitat inside a vast hostile matrix represents a good description of the lowland areas in N Italy, where many butterfly populations are now confined, where they experience reduced possibility to "escape" unfavourable events.

Our analysis of *Melitaea britomartis* population extinctions demonstrate that current ecological systems are characterised by low resistance and resilience to any kind of disturbance, or even to anomalous weather events (e.g. Parmesan et al. 2000; Opdam and Wascher 2004; Piessens et al. 2009). Moreover, climatic forecasts based on future scenarios suggest an increase in the occurrence of extreme events during the second half of the 21st century (Easterling et al. 2000; Trenberth et al. 2007), not only in term of heat waves, but also as an increase in intense precipitation events.

This underscores an urgent conservation problem for many butterfly populations, in particular for the hygrophilous species. Most of them are now surviving in conditions similar to those experienced by *Melitaea britomartis* before extinction events. They are locked inside few habitat patches and consequently, even if their present survival does not seem to be at risk, their long-term permanence may be threatened by their very low capacity to respond to any unforeseen catastrophic event.

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Captions

Fig.1. Seasonal maximum temperature (averaged among JJA-June, July, August). Temperature (°C) is on the y axis, while years of the full OI dataset are represented on the x axis. The dashed line include seasonal maximum temperature values observed for the years 1975, 1976 and 1977.

Fig. 2. a) Left: seasonal 1977 JJA (June-July-August) T_{max} anomalies over the whole region. Colours indicate positive (red) or negative (blue) anomalies with intensity proportional to the difference from the climatological mean; Right, historical T_{max} distribution and location of the JJA data of 1977 season inside it. The blue vertical line represents 1977 JJA T_{max} mean value, the pink dashed line represents the climatological mean (T=20.73°C) and the green dashed lines show the 90 and 95% confidence intervals of the climatological mean. The JJA of 1977, with a seasonal mean of 19°C, was the coldest year in the whole dataset. b) Same representation as before, of the T_{min} data. The climatological mean is 12.5°C and JJA of 1977 was the coldest year with a value of 10.8°C.

Fig. 3. a) Left: JJA (June-July-August) seasonal precipitation anomalies observed in 1976 over the whole region. Colours indicate positive (blue) or negative (red) anomalies with intensity proportional to the difference from the climatological mean. Right, position of the 1976 JJA precipitation data within the historical distribution. The blue vertical line represents 1976 JJA cumulative value (mm) of precipitation, the orange dashed line represents the climatological mean (245.4 mm), the red dashed line shows the median (234.8 mm), while the green lines respectively mark the 10th and 90th percentiles. b) Same representation as before as concerns the precipitation data for 1977 JJA. 1977 was the wettest year of the full dataset (410.8 mm).

Tab. 1. Total number of rainy days observed in the study area during June-July-August for the years of interest, and parameters describing the historical distribution of this variable (the 10th percentile, median, 90th percentile) are shown.