EU Grassland Butterfly Index 1991-2023

Technical report

Butterfly
CONSERVATION EUROPE

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Nature reserves with semi-natural grassland often are surrounded by large-scale intensive agriculture, but are important sites for the conservation of grassland butterflies.

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Executive Summary

1. Butterflies have been **systematically monitored** in Europe for several decades using standard protocols that are now adopted in over 30 countries. Butterflies are ideal biological indicators: they are well-documented, measurable, sensitive to environmental change, occur in a wide range of habitat types, represent many other insects, and are popular with the public because of their beauty.

***Cyaniris semiargus**, one of the butterflies of the GBI.*

2. Records from **over 6,000 standardised butterfly transects** are gathered into a central database as part of the European Butterfly Monitoring Scheme (eBMS) run by Butterfly Conservation Europe (BCE) and the UK Centre for Ecology and Hydrology (UKCEH). The database provides trends on individual species which can be combined to give trends for different habitats.

3. In this report **trends for 17 species have been used to generate an updated Grassland Butterfly Index (GBI) for 1991-2023**, using data from all 27 EU countries. The GBI is specifically mentioned in the EU Nature Restoration Regulation (NRR) in article 11 on the Restoration of Agricultural ecosystems as one of the possible indicators that should be measured until the satisfactory levels as set in accordance with Article 14(5) are reached. In practice, for those Member States choosing the GBI as an Indicator, under NNR Article 11, this means that 2025 will be the first year for this indicator.

4. **The EU Grassland Butterfly Index shows a decline of just over 50% since 1991**. In North-western Europe, the decline is primarily attributed to habitat loss resulting from the intensification of agricultural grasslands and nitrogen deposition in nature reserves. In Northern (Scandinavia, Finland and the Baltic states), Eastern and Southern Europe, the abandonment of grasslands is also a strong driver as shrubs and secondary forest encroachment result in less habitat for grassland butterflies. The decline observed over the last 33 years probably reveals only part of the historical decline in grassland butterflies, as many populations were extirpated from the landscape before 1990.

5. The **GBI is the Indicator on the EU Dashboard Target 5**, for evaluating progress with improving agroecosystems for biodiversity. It is also part of the EU Sustainable Indicator set, for evaluating the implementation of the Global Biodiversity Strategy.

6. This technical report provides an important message from scientists to policy makers - that **butterflies are still declining at an alarming rate across the EU and that urgent action is required** to protect and restore habitats to reverse this trend, not only for butterflies but also for other wild insect pollinators and their ecosystem services. The completion and appropriate management of the Natura 2000 network across Europe is a crucial step in helping grassland butterflies. Restoration and creation of landscapes with mosaics of habitats, both within and outside Natura 2000 areas, are essential to protect grassland butterflies in the EU.

7. We are grateful to all the many **thousands of volunteer butterfly recorders** who contribute their records to this important database, to the many BMS schemes, co-ordinators and funders who support the work, and to the EU for funding the EBMS through the EMBRACE project.

Chapter 1 / Introduction

There is mounting evidence of widespread declines in the diversity and abundance of insects across the globe (Sánchez-Bayo & Wyckhuys 2019, Seibold et al. 2019, van Klink et al. 2020, Wagner 2020). This gives a stark warning of the precarious state of biodiversity and demonstrates that addressing the gap in knowledge of the status of insects is vital (Cardoso et al. 2020, Samways et al. 2020). Insects are estimated to comprise more than half of all described species and are a dominant component of biodiversity in most ecosystems (Bar-On et al. 2018). Insects also play a crucial role in the functioning of ecosystems. They supply many ecosystem services such as pollination, biological control, soil fertility regulation and diverse cultural ecosystem services but also disservices such as damage to crops and spread of diseases to livestock and humans (Gutierrez-Arellano & Mulligan 2018, Noriega et al. 2018). There is a pressing need to assess the status of insects to set and evaluate conservation targets.

More than half of the 501 European butterflies occur in grassland habitats (dry, alpine, subalpine, mesophilic and dry siliceous grasslands and steppes; van Swaay et al. 2006). As in many other regions, several butterfly species have declined dramatically in Europe (Warren et al. 2021). These declines are often linked to habitat loss and unsuitable environmental conditions due to land-use change, pollution and climate change (Van Swaay et al. 2010, Rashid et al. 2023).

In May 2020, the European Commission adopted the EU Biodiversity Strategy for 2030. It aims to ensure that Europe's biodiversity will be on the path to recovery by 2030 for the benefit of people, the planet, the climate and our economy, in line with the 2030 Agenda for Sustainable Development and with the objectives of the Paris Agreement on Climate Change. It addresses the five main drivers of biodiversity loss, sets out an enhanced governance framework to fill remaining gaps, ensures the full implementation of EU legislation, and pulls together all existing efforts. The strategy established the EU Nature Restoration Plan includes *"Bringing back nature to agricultural land"* and uses the Grassland Butterfly Index (GBI) as the policy indicator for Target 5 to reverse the decline of pollinators (see the EU Action Tracker).

The EU used the strategy as an example to help agree and adopt a transformative post-2020 global framework at the 15th Conference of the Parties to the Convention on Biological Diversity held in Montreal, Canada, in December 2022.

The Grassland Butterfly Index (GBI) is specifically mentioned in the EU Nature Restoration Regulation (NRR), which came into force on 18 August 2024. Article 11 on the Restoration of agricultural ecosystems lists the GBI as one of the possible indicators, which should be measured by Member States from 18 August 2024 until 31 December 2030, and every six years thereafter, until the satisfactory levels as set in accordance with Article 14(5) are reached. The methodology used by the Member States to calculate their national GBI should mirror the methodology used to produce the EU GBI (see NNR Article 20 and NNR Annex IV).

In practice, for those Member States choosing the GBI as an Indicator, under NNR Article 11, this means that 2025 will be the first year for this indicator. Article 4 on the Restoration of terrestrial, coastal and freshwater ecosystems requires Member States to achieve an increasing trend towards the sufficient quality and quantity of the habitats of the species listed in Annexes II, IV and V of the Habitats Directive, which includes a number of butterfly species.

Some of the EU biodiversity indicators provide specific measurements and trends on genetic, species and ecosystem/landscape diversity, but many have a more indirect link to biodiversity. Very few have been explicitly established to assess biodiversity. The status indicators on species only cover birds, bats and butterflies, since these are the only taxa/species groups for which reasonably harmonised European monitoring data are available (EEA, 2012). This technical report builds upon previous technical reports for the EU Grassland Butterfly Indicator (e.g., van Swaay et al. 2019).

Butterflies are ideal biological indicators: they are well-documented, measurable, sensitive to environmental change, respond rapidly, occur in a wide range of habitat types, represent many other insects, and are popular with the public because of their beauty (Erhardt & Thomas 1991). Field monitoring is essential to assess changes in their abundance. Indicators based on butterfly monitoring data are valuable to understand the state of the environment and help evaluate policy and implementation. Trained volunteers are a cost-effective way of gathering robust data on butterflies, more so when supported by informative materials and efficient online recording.

This technical report provides an important message from scientists to the policy makers - that butterflies are still declining at an alarming rate across the EU and that urgent action is required to protect and restore habitats to reverse this trend, not only for butterflies but also for other wild insect pollinators and their ecosystem services.

Phengaris arion ***is one of Europe's largest Blues. The larvae spend most of their lives in ants nests***

Chapter 2 / Butterfly Monitoring in Europe

Butterfly monitoring enjoys a growing popularity in Europe, mainly supported by Butterfly Conservation Europe (BCE) and its partners. While Butterfly Monitoring Schemes are present in a growing number of countries and new ones are being initiated in many places, long time series are currently only available for a limited number of countries. For the EU Grassland Butterfly Indicator (GBI) presented in this report, we used data from all 27 Member States of the European Union (Figure 1; see Annex II for the Europe-wide GBI).

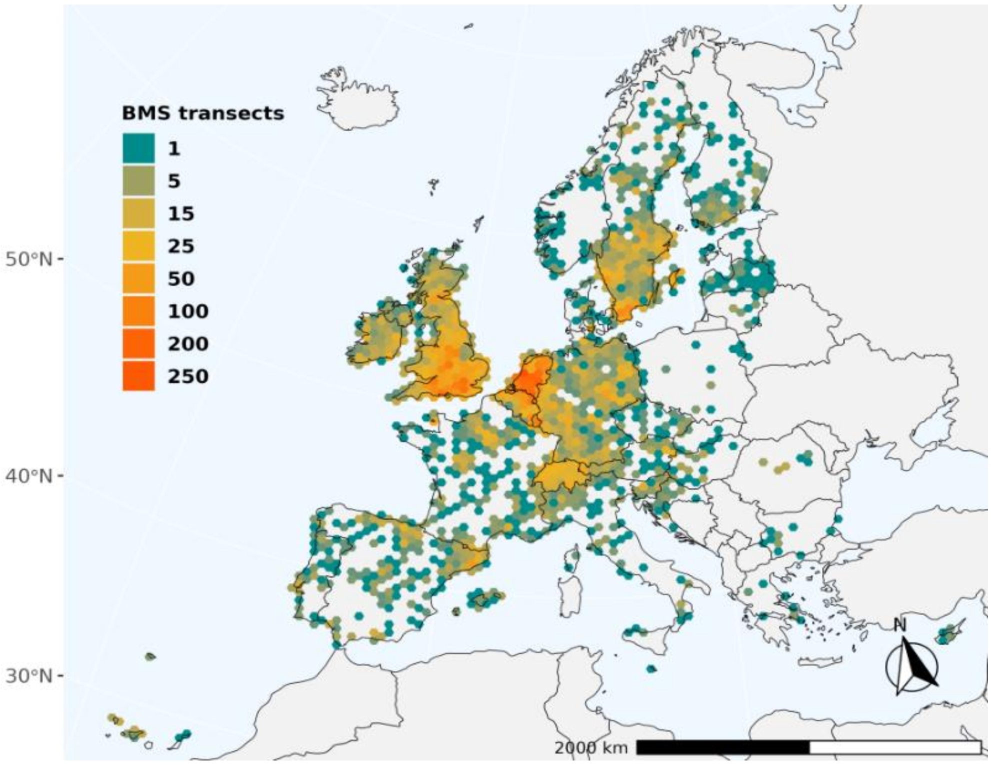


Figure 1: Density of Butterfly Monitoring sites.

The indicator uses data up to and including the 2023 field season. The method for calculating indicators has been improved and enhanced. During 2023, almost 3,800 standardised butterfly transects distributed across 30 monitoring schemes in all EU27 Member States have been counted (Figure 2). Since 1990, more than 8,900 separate transects have contributed to the EU27 GBI indicator. Outside the EU, almost 6,250 additional transects have been counted in Europe, mainly in the United Kingdom, Switzerland and Norway.

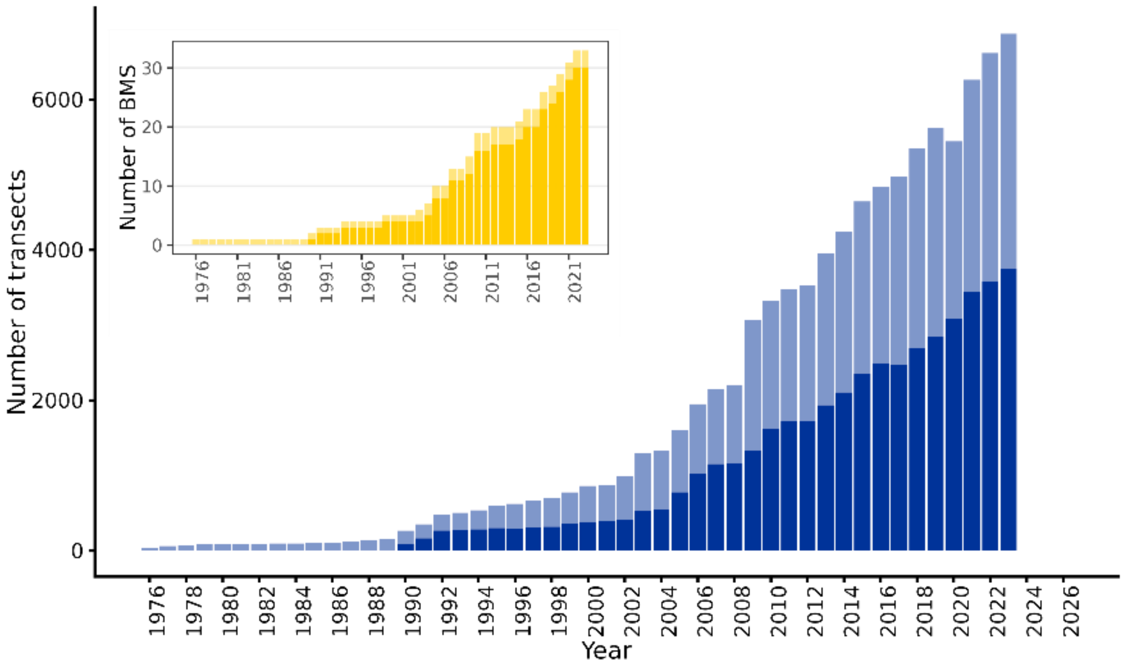


Figure 2: Number of butterfly monitoring transects (blue) and number of Butterfly Monitoring Schemes (yellow) in Europe. Dark colored=EU27, light colored=rest of Europe.

Chapter 3 / From butterfly counts to indicators

Butterflies can be found all over Europe and are one of the best-known groups of insects. Although popular, until recently little was known about their density and trends. In this chapter, we will describe how counts are made and how they can be used to detect trends and to build indicators.

Fieldwork

The butterfly indicators are based on the fieldwork of thousands of trained volunteers and professional recorders, who have counted butterflies on more than 15,000 transects scattered widely across Europe. These counts are made under standardised conditions, providing high-quality data that are suitable to assess species status and trends. National coordinators collect the data and perform the first quality control.

Fieldwork on steep calcareous grasslands can be challenging.

All schemes apply the method initially developed for the UK Butterfly Monitoring Scheme (Pollard & Yates, 1993). The counts are conducted along fixed transects of 0.2 to 3 kilometres in length, divided into smaller sections for recording. The fieldworkers record all butterflies observed 2.5 metres to their right, 2.5 metres to their left, 5 metres ahead of them, and 5 metres above them (Van Swaay *et al*. 2008). Butterfly counts are conducted between March-April to September-October, depending on the region. In some places (e.g., Andalucia, Canary Islands), monitoring is conducted all year round, although it sometimes pauses in July-August due to the hot and dry summer. Visits are only conducted when weather conditions meet specific criteria. The recommended number of visits varies from every week, e.g., in the UK, Catalonia and the Netherlands, to 3-5 visits annually in France. In Austria (Tirol) and Switzerland, the BMS employs a stratified sampling design, where a portion (25% and 20% respectively) of the sites is monitored annually, allowing for coverage of all sites every four or five years. This protocol enables representative and high-frequency monitoring in areas where access presents specific challenges (alpine sites).

European Butterfly Monitoring Scheme database

The European Butterfly Monitoring Scheme (eBMS) database collates standardised butterfly counts recorded along Pollard walks repeated in time (since 1976 in the UK). Since 1990, volunteers and professionals have recorded nearly 58 million butterflies identified at the species level in the eBMS database. These counts have been recorded over more than 1,25 million monitoring events (e.g., BMS transect visits). In terms of sampling effort, these visits took place in over 15,000 transects (Figure 1), distributed across 36 monitoring schemes and 31 countries (Figure 2), with 9,100 monitoring sites located in EU27 Member States.

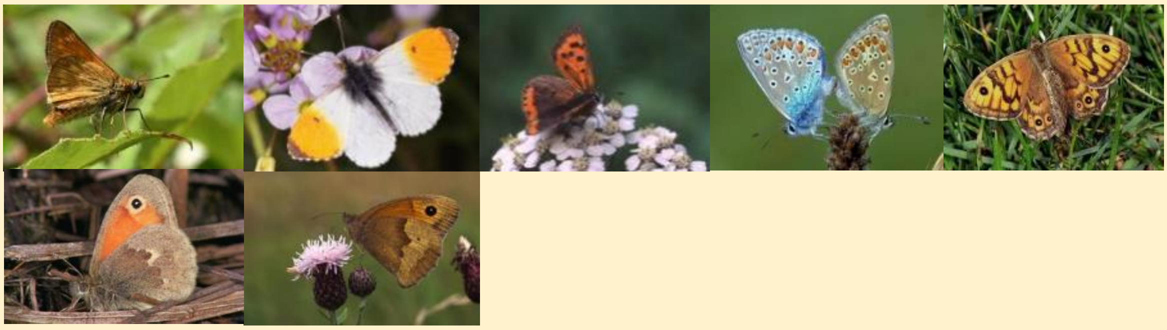
The eBMS database is updated annually, with each update released as a major version (e.g., v6.0). Subsequent corrections, additions, and bug fixes are identified and released as minor version updates (e.g., v6.1). Source data files are sent by national Butterfly Monitoring Schemes and processed programmatically to ensure adequate standardisation and formatting of the data before being integrated into the eBMS database.

Transect selection

To allow for robust and unbiased inference of temporal population trends at the national or regional scale, transects should ideally be selected in a grid, random, or stratified random manner (Sutherland, 2006). Several recent schemes, e.g. in Switzerland and parts of Austria (Tyrol), France and Luxembourg (Mestdagh *et al.* 2024), have been designed in this way (Henry *et al.* 2008). If a scheme aims to monitor rare or policy-relevant species, coordinators and observers will tend to locate transects in areas where these species are found, which may lead to an overrepresentation of special and protected areas. In most schemes, transect locations have been freely chosen by observers, which in some cases has led to an over-representation of protected areas in natural areas and an under-representation of the wider countryside and urban areas (Pollard & Yates, 1993). However, this is not the case in all countries (e.g., Germany, Kühn *et al.* 2008), and several schemes have addressed this problem by establishing new sites in rural (e.g., WCBS), urban (e.g., uBMS), and other underrepresented areas, or correct for this bias by weighting (Netherlands).

Calculating the EU27 Grassland Butterfly Indicator (GBI)

Butterfly trends can be calculated at various scales by integrating observations from specific habitats, individual monitoring schemes (BMS), or larger regions by aggregating data from multiple schemes. For the EU Grassland Butterfly Indicator (GBI), we combined annual abundance indices collected at the scheme level and aggregated data across the European Union Member States to estimate annual indices and trends for the EU-27 for each of the selected 17 grassland butterfly species (Box 1). These indices are then combined to produce a time series of multi-species indices, informing the EU Grassland Butterfly Indicator. For full details on the method, see Annex I.



Widespread species: *Ochlodes sylvanus, Anthocharis cardamines, Lycaena phlaeas, Polyommatus icarus, Lasiommata megera, Coenonympha pamphilus and Maniola jurtina*

Specialist species: *Erynnis tages, Thymelicus acteon, Spialia sertorius, Cupido minimus, Phengaris arion, Phengaris nausithous, Lysandra bellargus, Cyaniris semiargus, Lysandra coridon and Euphydryas aurinia*

Box 1. Seventeen butterflies were used to build the European Grassland Butterfly Indicator, comprising seven widespread and ten specialist species.

Phenology and Site indices

Time series of individual butterfly counts are recorded at regular intervals (e.g., weekly, fortnightly, monthly) over the extent of the adult activity season (i.e. flying imago). These time series often have missing counts due to unsuitable weather conditions or the unavailability of the recorder. Because the number of adult butterflies flying every week is strongly determined by species' seasonal patterns (phenology), it is essential to account for these patterns and correct for missing observations when estimating the annual abundance of a given species at a given site. This correction is achieved by calculating and imputing expected counts for weeks with missing counts, allowing us to estimate standardised annual abundance indices.

To predict expected weekly counts, we first estimated the standardised flight curve by fitting a generalised additive model (GAM) to the weekly counts recorded at the different sites (Dennis *et al.* 2013, 2016), using sites and monitoring week as predictors. To account for regional and annual differences in species phenology, we estimated flight curves for each year and bioclimatic region (Schmucki *et al.* 2016). Therefore, we divided our European dataset into 15 geographical windows (Table S1), within which we estimated annual flight curves for each of the 17 species and environmental zones (Metzger 2018). From these models, we derived regional annual flight curves standardised to 1 (area under the curve = 1) and estimated the expected values for each week and location during the monitoring season. These weekly estimates were then used to correct for missing values in the weekly time series. The corrected time series (observed and imputed weekly counts) were used to calculate the annual abundance index for each site and monitoring season. The standardised abundance indices correspond to the expected total number of butterflies observed at a given site.

Collated abundance index

For each monitoring scheme (BMS), we estimated the annual abundance by calculating annual collated indices from the local abundance indices. The collated index indicates the total number of adult butterflies of a given species that are expected to be reported on a 1 km transect. Except for three rare species for which few data were available, we calculated the annual collated abundance index for each species and monitoring scheme (BMS) for which at least three years of data were available in the BMS. For three rare species (*P. arion, P. nausithous, S. sertorius),* we estimated the collated index directly at the EU27 scale by using all available site indices without first collating at the BMS level.

To calculate the collated index, we fitted a generalised linear model (GLM) for each BMS with site and year as predictors. In this model, we accounted for different transect lengths by including relative length as an offset. Using this model, we were able to estimate standardised collated indices based on the average abundance estimated for a standardised 1 km transect. This model also includes a weighting factor that is proportional to the proportion of the flight period monitored. This weight accounts for relative sampling effort and reduces the influence of sites with potentially less reliable annual abundance indices due to reduced monitoring effort (i.e. fewer visits). To avoid unreliable estimates, we also excluded all abundance indices that were three times higher than the mean absolute deviation from the median and thus identified as extreme and unreliable estimates within a scheme.

Multi-schemes (EU27) species abundance index

To estimate species abundance in the 27 EU Member States, we calculated a multi-scheme abundance index, using the weighted geometric mean calculated across schemes (BMS). First, we converted the collated abundance indices to a logarithmic scale (base 10). On this scale, we set the first year of each time series to a value of two (2), which corresponds to an abundance of 100 on the exponential scale (i.e. 102 = 100). The logarithmic scale allows us to align time series of different lengths and facilitates the interpretation of the relative rate of change. When calculating the abundance of EU27 species, the geometric mean was weighted by the proportion of the species' range monitored by each scheme (BMS). Using the latest IUCN distribution map (www.iucnredlist.org), we calculated the weighting based on the overlap between the convex hull (area) of the monitoring site and the range of the species.

Since the first year of the time series is set to 100, the weighted geometric mean (Grassland Butterfly Index - GBI) calculated across BMS is also 100 in the first year. The GBI of all subsequent years is therefore considered relative to the initial value of 100. For time series from BMS's that started after the first year of the GBI (i.e. 1991), the new series is rescaled by setting the first year to the value of the multi-scheme species abundance index calculated from the already active BMS. For example, if a scheme starts five years after the first year of the multi-schemes index, the new scheme's time series will be set to the multi-schemes index value calculated in year five from the already contributing schemes. In this way, we can align the new time series with the older ones without distorting the time series of the multi-scheme species abundance index. If values were missing in the series after the first year, we used the value of the last non-missing year to fill the time series. In this way, the imputed values are informed by the scheme without influencing the multi-scheme trend in either direction for the years for which data are not available.

Multi-species trend and the EU27 Grassland Butterfly Indicators

The EU Grassland Butterfly Indicator (GBI) is the trend of the combined index calculated for the 17 grassland species across the 27 EU Member States (Figure 3). Following the same approach as for the multi-scheme index, we aggregated the annual multi-scheme index for the 17 grassland butterfly species by calculating the geometric mean across all species, giving equal weight to each species and setting the first year to 100. For species with shorter time series, we rescaled the time series by setting the first year to the value of the geometric mean calculated for that year. By calculating the geometric mean of the standardised rather than the absolute abundance indices, each species is given equal weight. The resulting time series of the annual multi-species geometric mean (grassland butterfly index) is then used to calculate the trend and the annual index for the EU Grassland Butterfly Indicator.

Like the bird indicators (Gregory *et al.* 2005), this approach provides a consistent measure of biodiversity in which an increase in one species can be offset by a proportional decrease in another species, resulting in a stable trend (indicator). On the other hand, if the number of declining species exceeds the number of increasing species, the multi-species trend will reflect an overall decline, and vice versa. Further details on the methods used to calculate population trends and the indicator at the EU27 level can be found in Annex I.

Agricultural grasslands managed not intensively, as here in Tuscany (Italy), can harbour strong populations of many grassland butterflies.

Chapter 4 / Grassland Butterfly Trends

The European Grassland Butterfly Indicator is built from the trends of 17 European butterfly species. In this chapter, we provide an overview of the trends in grassland butterflies across the EU27. The EU27 aggregated trends are calculated for each species by calculating the weighted geometric mean across Butterfly Monitoring Schemes (BMS) in the EU Member States. This method enables weighing the contribution of each BMS relative to the area of the species' range it encompasses.

Species trends in EU27

Across the 17 indicator species, none show a significant increase, six are stable, seven show a significant decline and for four species no significant linear trend could be detected in the EU27 countries (Figure 3).

When interpreting the species trends, it is important to recognise that:

- With fewer BMS in earlier years, the data cover a lower proportion of the species' populations and thus is likely to provide a less representative sample at the beginning of the time series (see also figure 1). As the number of countries and monitoring programmes increases over time, both the representativeness and the accuracy of the indices increase.
- Species monitored on relatively few sites and/or with very large year-to-year fluctuations in abundance are likely to have indices with wider confidence intervals around and uncertain trends.
- Although all EU27 member states have a Butterfly Monitoring Scheme, some have few sites and/or started relatively recently (i.e. as part of the ABLE and SPRING projects (2019 - 2024)), resulting in time series of different length and geographic coverage.
- As new countries and schemes join and contribute with new data, trends can change and differ from previous versions of the indicator. For some species, the addition of new regions can even impact the direction of the trend.
- For 13 of the 17 species, the median value of the linear trend is declining (Figure 4), though not all these trends are significant.

Although still common and widespread, the Large Skipper (*Ochlodes sylvanus*) shows a significant decline in the EU.

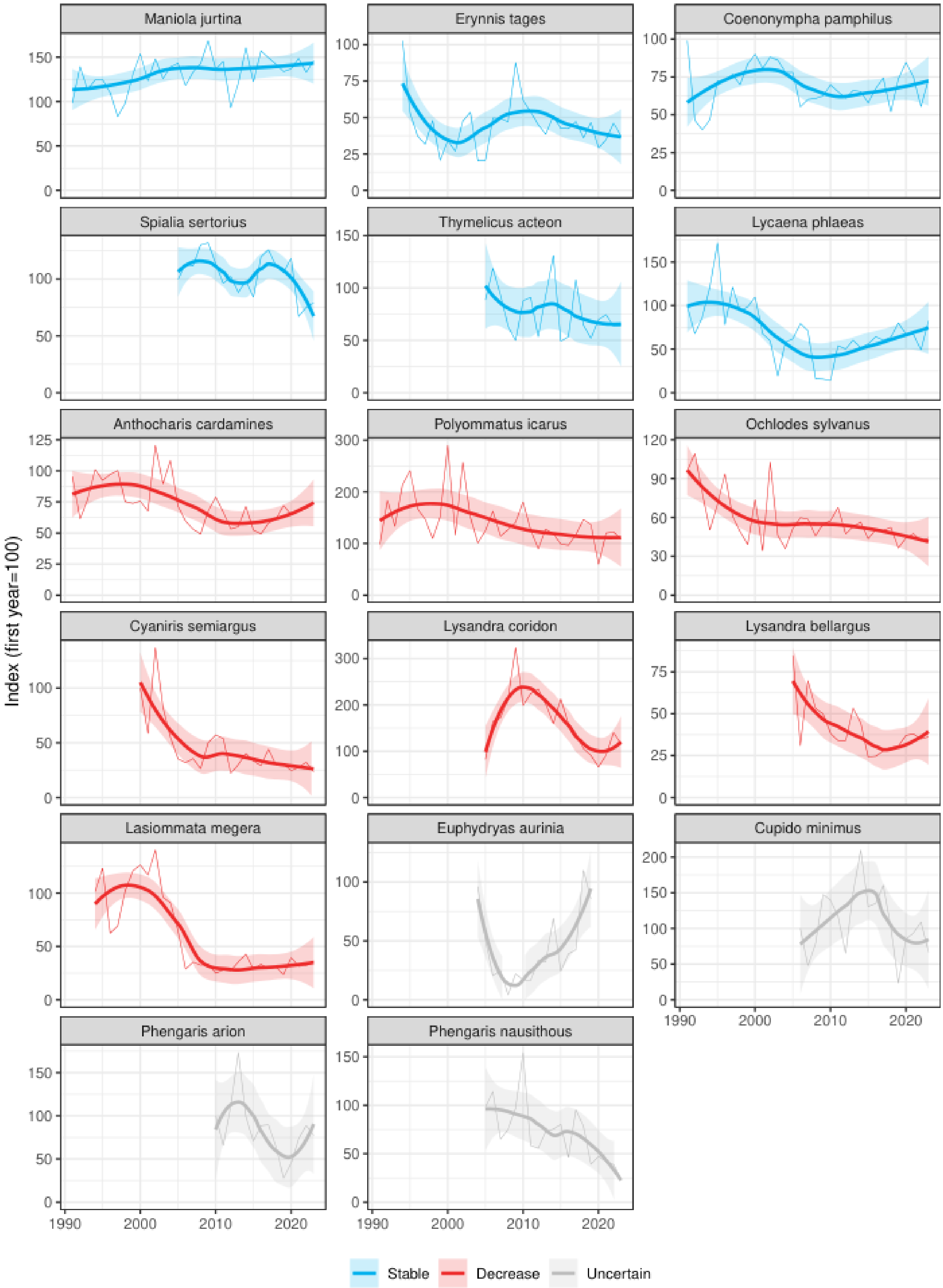


Figure 3: Indexes (thin line) and LOESS smoothed trends (thick line) in the EU27 for all 17 butterflies listed on the Grassland Butterfly Indicator from 1991 (or later, if the first year for which indexes could be calculated was after 1991) to 2023. The index of the first year is set to 100. The color indicates the linear trend.

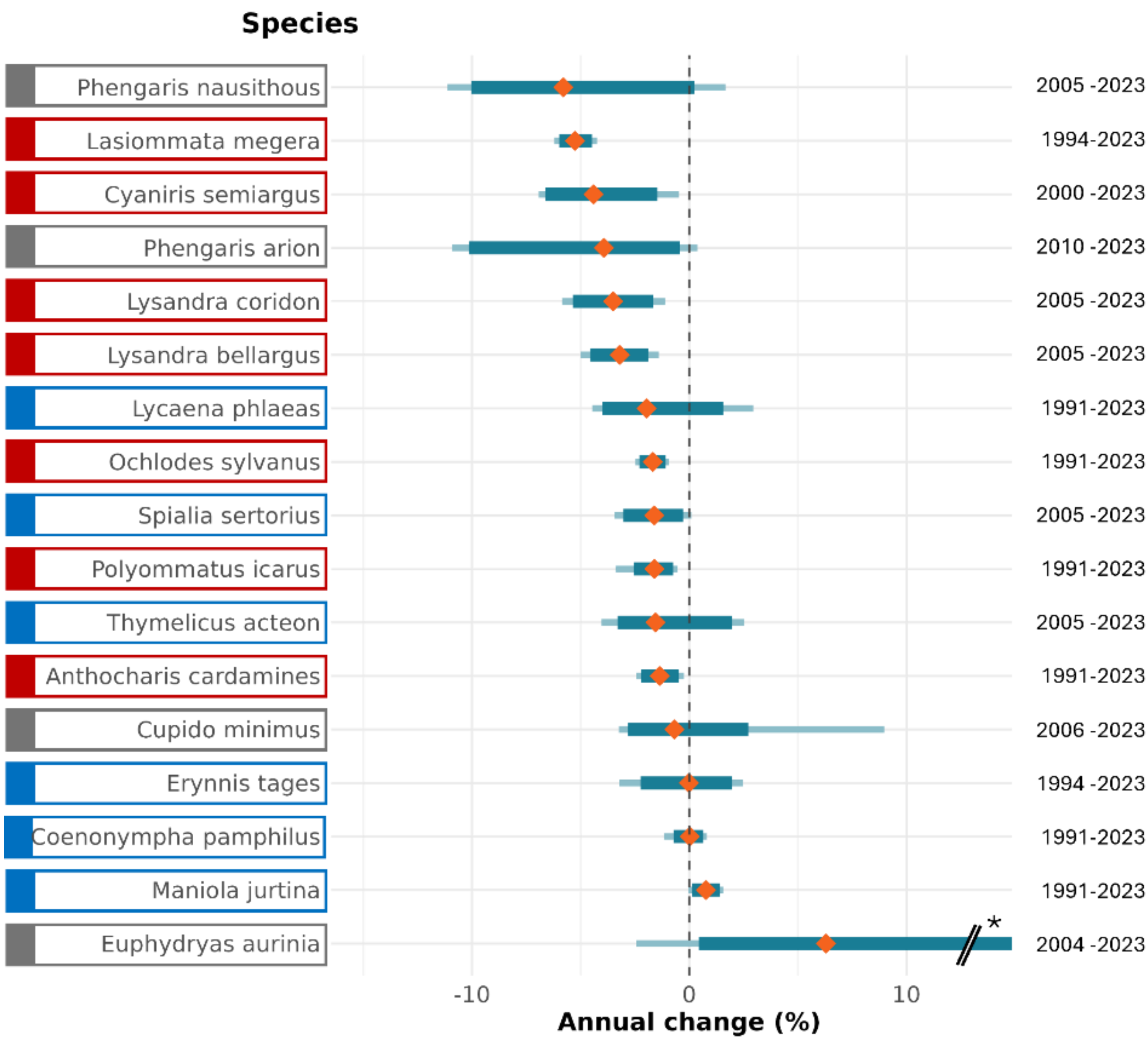


*Figure 4. Median annual percentage changes (linear trend) in EU27 population abundance indices (orange diamond) with bootstrap confidence intervals, CI 90% (dark teal blue) and CI 80% (light teal blue). Species trends are classified as Decrease (red), Stable (blue) and Uncertain (grey). * While the median trend of Euphydryas aurinia shows a notable increase, the trend is highly uncertain with confidence intervals extending beyond the x-axis of the figure, with CI 90%: -2.44 to 64.30 and CI 80%: 0.44 to 43.95.*

Chapter 5 / Grassland Butterfly Indicator

The EU27 Grassland Butterfly Index (GBI, Figure 5) is 50% lower in 2023 than in 1991, the first year for which we can compute the indicator (based on two operational Butterfly Monitoring Schemes in the EU27). See Annex II for GBI Europe.

In North-western Europe, the observed decline is primarily attributed to habitat loss resulting from the intensification of agricultural grasslands and nitrogen deposition and pesticides in nature reserves (WallisDeVries & Van Swaay, 2017). In Northern (Scandinavia, Finland and the Baltic states), Eastern and Southern Europe, the abandonment of grasslands is also a strong driver as shrubs and secondary forest encroachment result in less habitat for grassland butterflies. The 50% decline observed over the last 33 years probably reveals only part of the historical decline in grassland butterflies, as many populations were extirpated from the landscape before 1990. In the Netherlands, for example, the distribution of butterflies (including those found in grasslands) has dropped by more than 80% since 1890 (Van Strien *et al.* 2019). Similar patterns were also observed in Flanders (Maes *et al.* 2022). European butterflies are also affected by climate change. While some parts of Europe have seen an increase in the numbers of some of the widespread generalist butterflies with warmer climate, the recent series of extremely hot and dry summers has reversed this trend and resulted in additional declines.

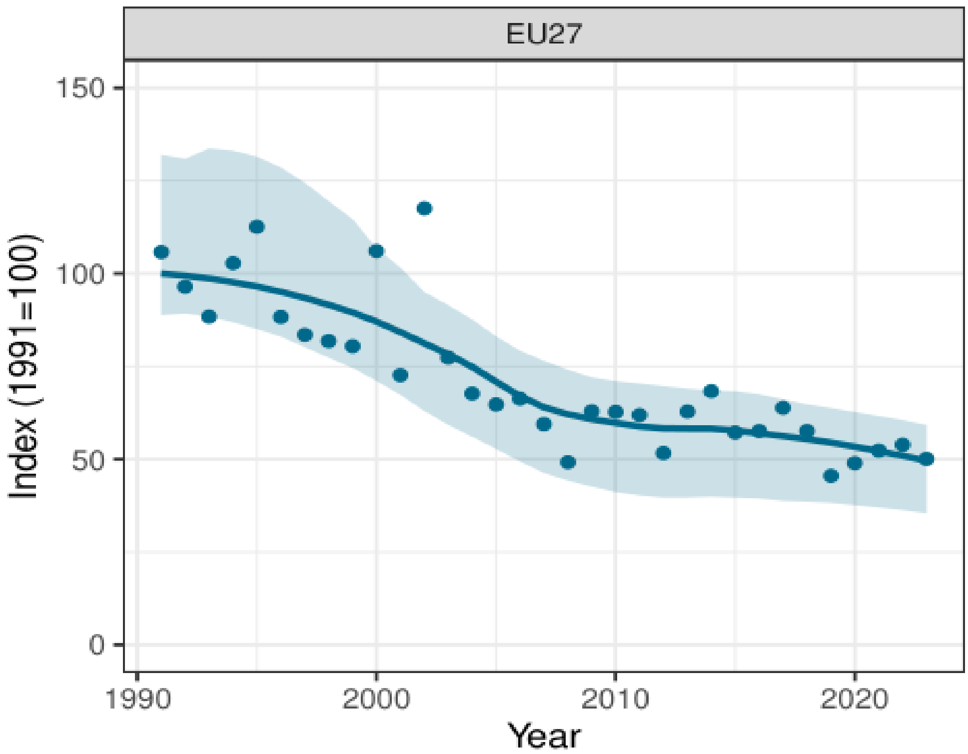


Figure 5. The Grassland Butterfly Indicator for the EU27 countries from 1991 to 2023

Chapter 6 / Conclusions

- This report gives an update of the Grassland Butterflies Index, with the trend (1991-2023) of 17 butterflies characteristic of grasslands in the EU27.
- The indicator is based on national Butterfly Monitoring Schemes active in all EU27 Member States (Figure 1).
- Since 1990, more than 8,900 separate transects have contributed to the EU27 GBI indicator (Figure 2). In Europe, we count more than 15,100 transects, with nearly 6,200 outside the EU27, mainly in the United Kingdom, Switzerland and Norway (Annex II: GBI Europe).
- From the 17 indicator species, none show a significant increase, six are stable, seven show a significant decline and for four species no significant linear trend could be established in the EU27 countries (Figure 3).
- The Grassland Butterfly Indicator has declined by 50% since 1991 across the European Union (EU27; Figure 4). More urgent restoration (and protection) action is required to stimulate recovery and reverse this trend, not only for butterflies but also for other wild insect pollinators and their ecosystem services.
- In North-western Europe, the intensification of farming practices is the most important threat to grassland butterflies. Protecting remaining semi-natural grasslands in these areas and reversing fragmentation is essential to halt further losses. Nitrogen deposition and pesticides from intensive agriculture can drift and reach the centres of even large nature reserves. Therefore, reduced nitrogen and pesticide use, together with effective mitigation measures, must be implemented to prevent such unintended impacts on grassland ecosystems and reduce the threat to grassland butterfly populations.
- In other parts of Europe, abandonment of farming practices is also a key factor in the decline of grassland butterflies. Sustainability and the perpetuation of long-established farming traditions will require clear recognition and support for young farmers and their families committed to sustainable farming practices and work with nature. Redirection of Common Agricultural Policy (CAP) funding to support sustainable farming of High Nature Value (HNV) areas is crucial and can provide a lifeline for grassland butterflies in the EU.

Intensification (left) and abandonment (right) both lead to a decline in the number of grassland butterflies.

- The increasing frequency and intensity of heatwaves, wildfires and droughts observed in the last decades have also contributed to the decline of grassland butterflies. Although further research is needed to determine the exact magnitude of the impact of climate change, urgent actions to reduce greenhouse gas (GHG) emissions and limit global warming would certainly benefit most grassland butterflies.
- The completion and appropriate management of the Natura 2000 network across Europe is a crucial step in helping grassland butterflies. Restoration and creation of landscapes with mosaics of habitats, both within and outside Natura 2000 areas, are essential to protect grassland butterflies in the EU.

The Orangetip **(Anthocharis cardamines*) is a typical spring butterfly which can be seen over large parts of Europe.***

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Annex I / Statistical method

BMS data collection

All data was first collected at a regional or national level, and after validation, added to the eBMS database (version 6.1) from which we extracted three tables with information on 1) Butterfly count, 2) Monitoring visit date, and 3) Monitoring site location and length (area).

Step 1 – Species annual site index (per transect)

Regional flight curve

For each species and year, flight periods were estimated based on the combined effects of geographic location and climatic conditions (Schmucki *et al.* 2016). To optimise the estimation of the annual flight curves, we stratify our dataset into 15 geographic regions (Table S1) within which we aggregated monitoring transects per environmental zone, as defined in Metzger (2018). This stratification was broad enough to include a large number of sites per region, allowing us to borrow strength and share information across adjacent monitoring schemes, and estimate reliable annual flight curves in spatially contiguous and homogeneous bioclimatic regions. We used the regionalised generalised additive model (GAM) approach (Dennis *et al.* 2013, Schmucki *et al.* 2016), fitting a yearly GAM with a negative binomial distribution to the weekly (*j*) butterfly counts, using a “cubic spline” smoothing effect for weeks and a fixed effect for sites (*i*) (eq.1, Code 1). To optimise model fitting, we excluded all sites with fewer than three visits within a year and restricted the total number of sites per region to a maximum of 300. When the number of sites available within a region exceeded 300, we applied a spatially stratified resampling approach, prioritising the best-informed sites (those with the highest sampling effort). We used a 50km grid to stratify the sample across the entire region, ensuring that the sample was not biased toward sub-regions with the highest sampling effort. All flight curves were calculated with the R package rbms (Schmucki *et al.* 2024), which uses mgcv v1.8-4 (Wood, 2017) to fit the GAM.

$$E[y_{i,j}] = u_{i,j} = exp[SITE_i + s(WEEK_j; f)] \quad \text{(eq.1)}$$

where: $y_{i,j}$ represents the count at site i on week j,
$SITE_i$ $the\ site\ effect\ and$
$s(WEEK_j; f)$, the smoothing function on week j with f degree of freedom.

```
# R code
ts_flight_curve <- rbms::flight_curve(ts_season_count,
                                       NbrSample = 300,
                                       MinVisit = 3,
                                       MinOccur = 1,
                                       MinNbrSite = 1,
                                       MaxTrial = 4,
                                       GamFamily = 'nb',
                                       SpeedGam = FALSE,
                                       CompltSeason = TRUE,
                                       TimeUnit = 'w')
```

Code 1. *Specification and arguments used to estimate the annual flight curve for each species and bioclimatic region in each of the 15 regions (Table S1), using the flight_curve() function implemented in the rbms package (Schmucki et al. 2022).*

Table S1. *Regions and monitoring schemes used to compute the flight curve for each bioclimatic region across Europe. Where the environmental zones are: Atlantic Central (ATC), Atlantic North (ATN), Alpine South (ALS), Alpine North (ALN), Continental (CON), Mediterranean Mountain (MDM), Mediterranean North (MDN), Mediterranean South (MDS), Pannonian (PAN), Lusitanian (LUS), Boreal (BOR), Nemoral (NEM). This classification is based on Metzger (2018)* https://sdi.eea.europa.eu/catalogue/idp/api/records/6ef007ab-1fcd-4c4f-bc96-14e8afbcb688.

Region	BMS included	Environmental zones
1	Republic of Ireland, United Kingdom	ATC, ATN
2	France, Netherlands, Belgium (Flanders), Belgium (Wallonia), Luxembourg, Germany	ALS, ATC, ATN, CON, LUS, MDM, MDN, MDS, PAN
3	Portugal, Spain, Spain (Catalonia), Spain (Sierra Nevada), Spain (ZERYNTHIA), France	ALS, ATC, CON, LUS, MDM, MDN, MDS
4	France, Switzerland, Italy, Austria, Germany	ALS, ATC, ATN, CON, LUS, MDM, MDN, MDS, PAN
5	France, Spain (Catalonia), Italy, Greece, Malta	ALS, ATC, CON, LUS, MDM, MDN
6	Denmark, Germany, Sweden	ALN, ALS, ATC, ATN, BOR, CON, NEM, PAN
7	Denmark, Norway, Sweden, Finland, Estonia	ALN, BOR, CON, NEM
8	Estonia, Finland, Sweden	ALN, BOR, CON, NEM
9	Estonia, Latvia, Lithuania	BOR, CON, NEM
10	Germany, Poland, Czechia	ALS, ATC, ATN, CON, NEM, PAN
11	Germany, Switzerland, Slovenia, Italy, Croatia, Czechia, Hungary	ALS, ATC, ATN, CON, MDM, MDN, MDS, PAN
12	Greece, Croatia, Slovenia, Bulgaria, Romania, Cyprus	ALS, CON, MDM, MDN, MDS, PAN
13	Slovenia, Czechia, Hungary, Slovakia, Austria (Vienna)	ALS, CON, MDM, MDN, PAN
14	Estonia, Latvia, Lithuania, Finland, Sweden	ALN, BOR, CON, NEM
15	Germany, Switzerland, Slovenia, Italy, Croatia, Czechia	ALS, ATC, ATN, CON, MDM, MDS, PAN

Annual site index

The standardised annual flight curve has a total area under the curve equal to 1, and each point on the curve corresponds to the proportion of the total abundance expected over the entire season. This curve is used as an offset within a generalised linear model (GLM) fitted on the observed count and used to predict weekly counts at each site (eq.2, Code 2). The weekly counts predicted from this model can then be used as input for the missing weekly counts.

When combined with the observed counts, we obtain local time series of weekly butterfly counts for each site and species over the entire monitoring season. These time series can then be used to calculate standardised annual abundance indices for each site, year and species. The abundance index is calculated as the sum of the weekly counts of adult butterflies observed and estimated throughout a standardised number of weekly counts over a monitoring season. This index represents the total number of adult butterflies of a given species expected to be counted during a monitoring season at a given site and year for a standardised sampling effort (*e.g.* 26 weeks between April and September).

$$E[y_{i,j,k}] = u_{i,k}(j) = exp[SITE_i + YEAR_k + \gamma_k(j)] \quad \text{(eq.2)}$$

where: $y_{i,j,k}$ represents the count at the site i and year k,
$SITE_i$ the site effect,
$YEAR_k$ the year effect and,
γ_k the standardised flight curve for year k at week j.

 # R code

```
# fit GLM
m2 <- glm(COUNT~ 0 + factor(SITE) + factor(YEAR) +
           offset(log(NM)),
           data = my.data,
           family = poisson(link = "log"))

# Where NM is the standardised flight curve estimated for week j
# on year k obtained from the object ts_flight_curve computed in
# Code Box 1.
```

Code 2. *Specification of the GLM fitted on observed count and utilised to account for species phenological pattern to input missing values and calculate standardised annual site abundance indices.*

Step 2 – species annual collated indices (per BMS)

Collated index

The local annual site indices computed in step 1 are then used to calculate time series of collated annual indices for each species and monitoring scheme. The collated index is estimated by fitting a GLM to the standardised annual abundance indices, using the transect length as an offset and the proportion of the flight period covered (sampled) by the weekly visits as weight (eq.3, Code 3). This weight accounts for a species-specific realised sampling effort observed at each site and year (Brereton *et al.* 2018). From this model, we can estimate the expected annual abundance (i.e., the number of butterflies) of a given species that is expected to be recorded on a 1-km transect. These estimates correspond to the annual collated indices calculated for each species, year and scheme. While the weight included in our model downweighs the contribution of poorly sampled sites, we also exclude all annual abundance indices where the mean absolute deviation was three times above the median within a scheme, thereby identifying them as being extreme and unrealistic, potentially due to unreliable flight curves or model estimates for local abundances. From this GLM fitted on standardised annual site indices, we derive annual estimates of the average number of butterflies of a given species expected to be recorded along a standardised 1-km transect. We computed these indices for each species and year within each monitoring scheme (BMS).

$$E[y_{i,k}] = u_{i,k} = exp[SITE_i + YEAR_k + \delta_i] \quad \text{(eq.3)}$$

where: $y_{i,k}$ represents the annual site index estimated at the site i and year k,
$SITE_i$ the site effect,
$YEAR_k$ the year effect and,
δ_i the length of transect at site i (measured in km).

```r
# R code
# SINDEX ~ 0 + factor(SITE) + factor(M_YEAR) + offset(log(TL))

# fit GLM
m3 <- glm(SINDEX~ 0 + factor(SITE) + factor(YEAR) +
          offset(log(TL)),
          weights = my.data$fc_prop,
          data = my.data,
          family = poisson(link = "log"))

# Where SINDEX is the standardised local abundance index, TL the
# transect length measured in kilometres, and fc_prop the
# proportion of the flight curve covered by the weekly visits. The
# weight is used in the likelihood function, affecting the
# influence each point has on the
```

Code 3. *Specification of generalised linear model used to calculate annual collated indices for a 1km transect. Collated indices are calculated per species and BMS.*

Confidence intervals of the collated index

We used a non-parametric bootstrapping approach to estimate the precision (uncertainty) of the indices, indicators and trends. Non-parametric bootstrapping is suitable for the GBI as it allows cascading uncertainties across multiple modelling stages (Dennis *et al.* 2013). Here, the site indices were randomly resampled (1,000 bootstrap samples with replacement), with the number of transects sampled remaining the same as in the original data. Each bootstrap sample was then used to calculate the annual collated species indices (time series) per species and BMS (Code 3), from which we derived the annual species index for the EU27 (multi-schemes) and the multi-species index (GBI). For each metric, we used the bootstrap sample percentile to estimate specific confidence intervals (80% and 90%).

Assessment and validation of species index estimates

Using the time series of annual collated abundance indices calculated for each species monitored in each BMS, we ask experts to assess the validity of the estimated collated indices. If the annual indices were judged unreliable by the experts, we excluded part or the entire time series from the following calculations. This mainly concerns shorter or early years of time series, which are often characterised by high uncertainty (CI) due to the smaller number of monitoring sites in the establishment phase of new monitoring schemes. We also systematically excluded each time series that had less than three years of data. In some cases, we excluded early years in which the collated indices are informed by only a few sites (BMS establishment phase) and where the uncertainty is very high.

Step 3 - Species collated indices for EU27 and Europe

Multi-BMS abundance index

For each BMS, the annual species index (expected number of butterflies per 1 km) was converted to the logarithmic scale (base 10) and standardised to a value of 2 for the first year. The logarithmic scale provides comparable estimates of the relative rate of change over time. For each species (Box 1), we matched the time series of the standardised collated indices across the BMS in the region of interest (i.e. the EU-27 Member States). The first year of the time series was set to the year in which data from at least two schemes were available.

The geometric weighted mean (eq.4, Code 4), calculated based on the exponentiated standardised index (i.e. 10^2 = 100 for the first year) across schemes, was then used to create time series of the collated index of multiple schemes for each species. The geometric mean was weighted by the area of the species' range sampled in each BMS. This area, measured in hectares, was estimated using the overlap between the convex hull of the monitoring site in each BMS and the species distribution map (www.iucnredlist.org). For BMSs that started collecting data after the first year, the first year of the time series was scaled (adjusted) according to the value of the weighted geometric mean calculated for the already active schemes. For example, if the weighted geometric mean of three schemes in year x is 95, the first year of a fourth scheme that started in year x is set to 95.65 and the rest of the time series is adjusted accordingly (i.e. the first year is set to 95.65; Table S2 *red*). The weighted geometric mean of the following year *x*+1 is then calculated for the four schemes. This approach allows us to align several time series with different lengths and different starting years and thus create a multi-BMS index without affecting the trend at the entry point and previous years. If values were missing after the first year, we input the last (previous years) non-missing value in that time series (Table S2. *blue*).

$$\bar{x} = \left(\prod_{i=1}^{n} x_i^{w_i}\right)^{1/\sum_{i=1}^{n} w_i} \quad \text{(eq.4)}$$

where: x_i is the standardised abundance index for BMS i,
w_i the weight of BMS i and
n the number of BMS

```
# R code
# Weighted Geometric Mean

MultiBMS_INDEX = prod((INDEX)^(weight))^(1/sum(weight)))
```

Table S2. *Example for aligning time series of multiple lengths and input values for missing years. For simplicity, this example uses an equal-weighted geometric mean to calculate the Multi-BMS index.*

Year	BMS-1	BMS-2	BMS-3	BMS-4	Multi-BMS index
1990	100	100	100	NA	100
1991	97	95	101	NA	97.63501
1992	95	94	98	95.65166 <--	95.65166
1993	89	90	97	93	92.19806
1994	85	89	NA --> input 97	91	90.39731
....	...	...	...	...	...
2023	75	67	80	76	74.34639

Step 4 – Multi-species Index & EU27 Grassland Butterfly Indicator (GBI)

The Grassland Butterfly Indicator (GBI) corresponds to a time series of annual indices that aggregate the multi-BMS index (EU27) for 17 species. In the same way that we combined the index across BMS in step 3, we calculated the geometric mean for each year, assigning the same weight to each species. For species with shorter time series, the first year of the series was set to the value of the indicator in that year. If values were missing within or at the end of the time series, the value of the last non-missing index was used. Using this approach, we can calculate a single time series of multiple species indices, with annual values corresponding to the grassland butterfly index. From these annual indices, we produced a smoothed time series corresponding to the grassland butterfly indicator. The smoothed indicator was created using LOESS smoothing with a span of 0.75 and a degree of 2 (Soldaat *et al.* 2017).

Applying this approach to bootstrap samples, we created 1,000 time series of collated (step 2), multi-BMS (step 3) and multi-species (step 4) indices from the bootstrap samples. These samples were then used to estimate 80% and 90% confidence intervals (CIs) for each of the measures, including the smoothed GBI. The upper and lower bounds of the confidence interval were estimated using the corresponding quantiles of the bootstrap samples. All values were rescaled so that the first year of the median of the smoothed indicator was 100 (Figure 5).

For each species, the linear trend of the annual multi-BMS indices was estimated by fitting a simple linear model (regression) to the log-transformed indices. The slope of the regression (coefficient of the year) was then used to estimate the annual rate of population growth (or decline). The coefficient obtained from the bootstrap samples was used to estimate the median and the 80% and 90% CI of the trend calculated for each species (Figure 4). These metrics (multiplicative slope) were used to classify and assess the uncertainty of the trend of each species, based on the same parameters (Table S3) used in TRIM (Pannekoek & van Strien, 2005).

Table S3. *Parameters used to classify the species trend, based on the confidence intervals of the multiplicative annual growth rate derived from the linear model fitted on the log(index).*

Annual growth rate (multiplicative rate)	**Classification**
Lower limit larger than 1.05	Strong increase
Lower limit larger within]0, 1.05]	Moderate increase
Upper limit lower within [0.95, 0[	Moderate decline
Upper limit lower than 0.95	Strong decline
Upper limit lower than 1.05 & Lower limit larger than 0.95	Stable
Upper limit larger than 1.05 & Lower limit lower than 0.95	Uncertain

Annex II / GBI Europe

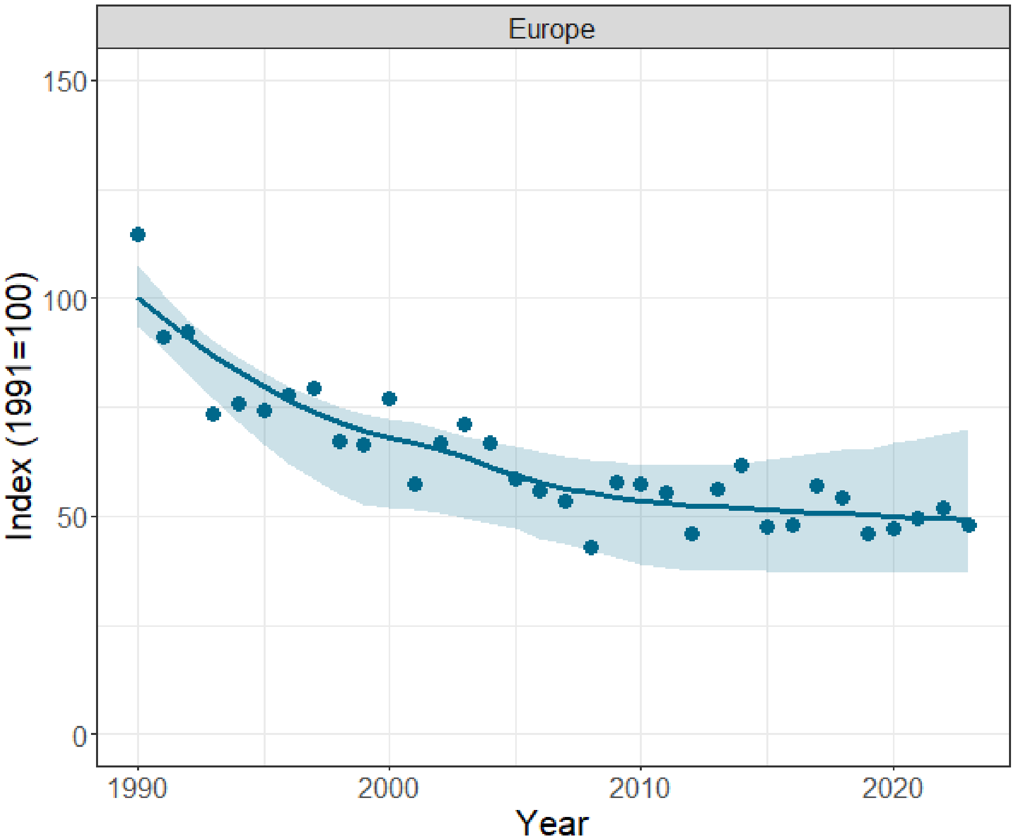

Figure S1. *The Grassland Butterfly Indicator for Europe from 1990 to 2023.*

Annex III / Glossary

- ABLE: Assessing ButterfLies in Europe: an EU project aiming at capacity building for butterfly monitoring, collecting butterfly monitoring data into the eBMS, producing tools for analysis of the data and produce trends and indicators.
- BGR: Biogeographical Region
- BMS: Butterfly Monitoring Scheme
- CAP: Common Agricultural Policy
- CBD: Convention on Biological Diversity
- eBMS: European Butterfly Monitoring Scheme, the database that holds all butterfly monitoring data.
- EMBRACE: Expanding Monitoring of Butterflies for Restoration and Conservation across Europe 2021-2026
- HNV: High Nature Value
- SPRING: Strengthening Pollinator Recovery through INdicators and monitorinG