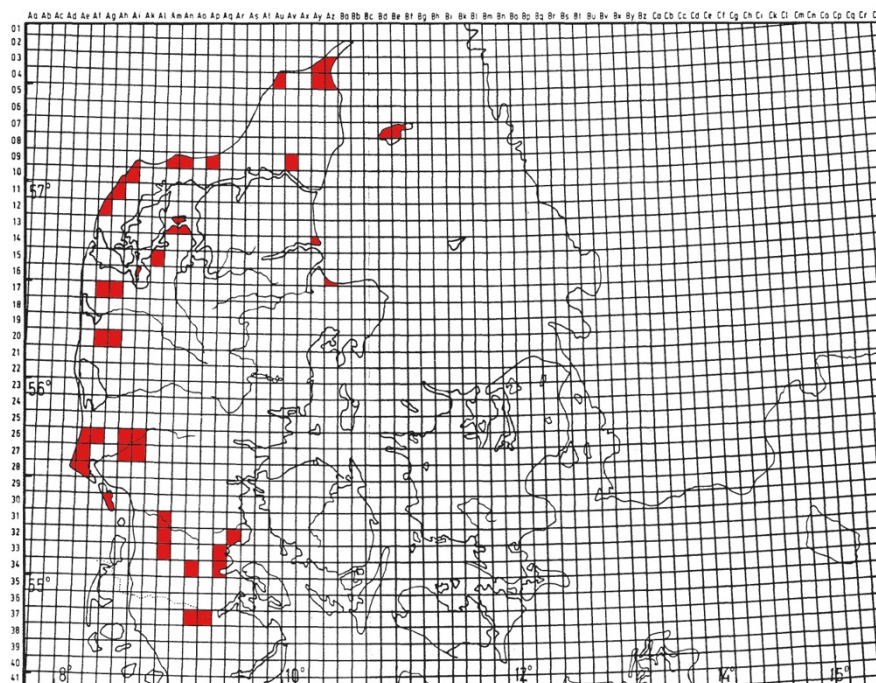


## Supplementary Methods S1: Mapping the distribution of the alcon blue butterfly and marsh gentian in Denmark

To illustrate the change in distribution of *Phengaris alcon* and its host plant, *Gentiana pneumonanthe*, over the last centuries, we combined various public sources of information (primarily available through the GBIF (Global Diversity Information Facility) web portal: [www.gbif.org](http://www.gbif.org)) supplemented with our own records and records extracted from both the preserved specimens of *P. alcon* that we examined and specimens of *G. pneumonanthe* held at the Danish national herbarium. Since some previous and current atlas projects were carried out at a resolution of  $10 \times 10$  km UTM grid squares, and to avoid publication of details of some sensitive populations of both species, we also converted data to presence or absence data in each  $10 \times 10$  km UTM grid square. As we divided our genetic data into that collected before and after the year 2000, this was also the basis of our distribution maps, although much finer grained data is available, and there have been several earlier attempts to map both species on a country-wide basis as outlined below.

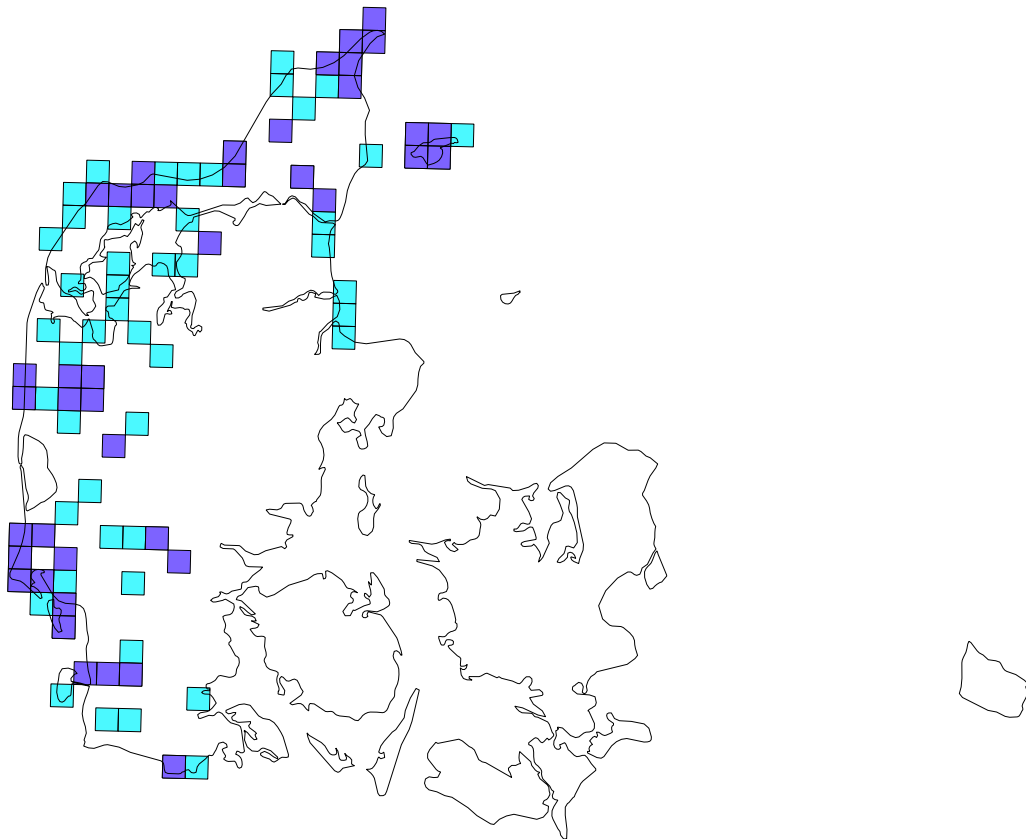
### Atlases of Danish butterflies

There have been several attempts to map the distribution of Danish butterflies, including *P. alcon*, on a national scale over the last century. The first of these, initiated by the late Jan Calov, was never published commercially, but was based on records from selected butterfly experts in Denmark based on their experience of locations where butterflies were present between 1960 and 1973. Participants were also asked to mark the position of localities on a copy of the “Lyneborg map” [1], which used a latitude/longitude system (dividing Denmark into areas of 7.5 minutes latitude and 5 minutes longitude). The resulting atlas was intended to be published in a special issue of *Lepidoptera*, the journal of the *Dansk Lepidopterisk Forening* (Danish Lepidopterological Society), but was never completed, possibly because it was realized that taking an approach of asking about well-known locations rather than a systematic survey was not sufficiently comprehensive. Nevertheless, the atlas, which was published privately by Calov in 1974, provides a snapshot of well-known localities for *P. alcon* in the 1960s-70s. Further information about the Calov atlas and other sources mentioned here can be found in [2].



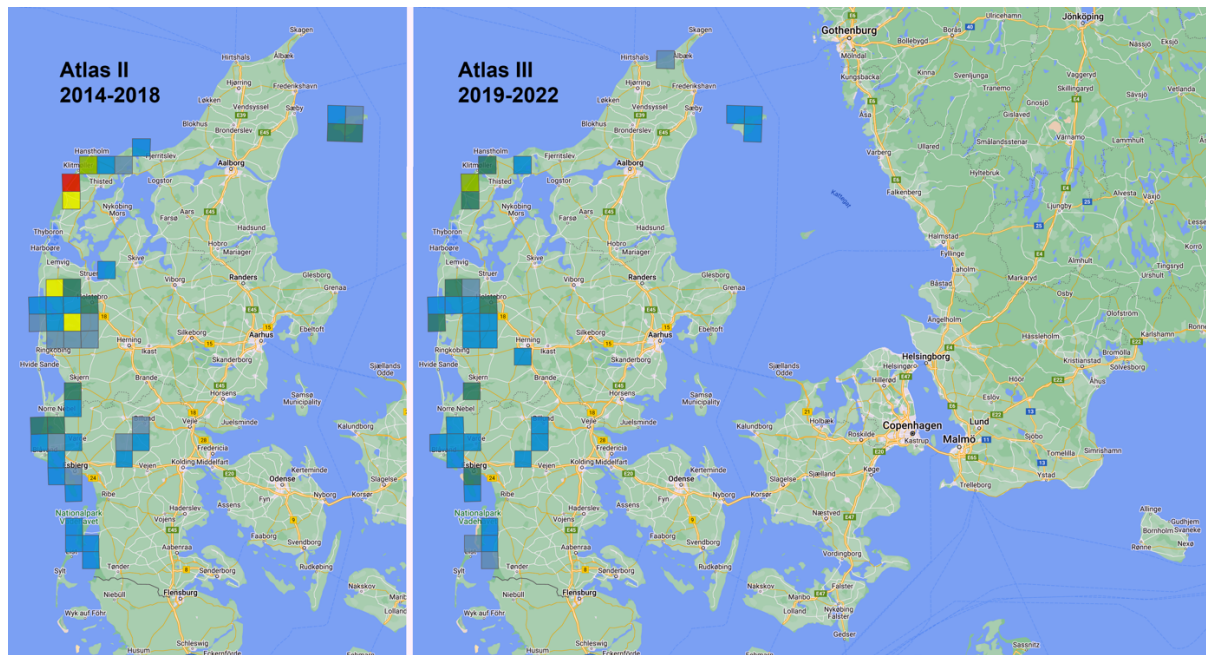
**Figure 1:** Records of *P. alcon* from Calov's atlas, after the hand-drawn original map.

The first systematic attempt to draw up an atlas of Danish butterfly distribution was initiated by Michael Stoltze, who collected data on contemporary butterfly distributions from 1989 to 1993, with the help of many collaborators, attempting to visit every  $10 \times 10$  km UTM grid square and to make an accurate assessment of the butterfly species present in each grid square. This was supplemented by data from museum specimens and collectors, and ultimately formed the basis of his PhD thesis, and a book with distribution maps published in 1996 [3]. The data from this atlas project have since been digitized (at  $10 \times 10$  km UTM grid square level), and are available from the GBIF server [4] as the “Atlas Survey of the Butterflies of Denmark.”



**Figure 2:** Records of the presence of *P. alcon* from M. Stoltze’s *Atlas Survey of the Butterflies of Denmark* [3] as hosted on GBIF [4].  $10 \times 10$  km UTM squares with dark shading are those in which *P. alcon* was found in 1989-1993, while those with lighter shading were inferred to have *P. alcon* present at some point before 1989, based on collection data from Natural History Collections etc.

There is currently a citizen-science based atlas project, <https://www.sommerfugleatlas.dk/>, where observations of butterflies can be submitted, and which again uses the  $10 \times 10$  km UTM grid to display occurrences at a national level (although records can be also seen at higher resolution when zoomed in. Records for this site are quality controlled, and the vast majority of records are supported by photographs that have been checked by a team of editors. In addition, although this is a project to which anyone can submit data, there is a core of recorders who attempt to systematically cover every  $10 \times 10$  km UTM square every few years. This atlas project is now on its second generation (*Sommerfugleatlas III*, as Stoltze’s atlas project is considered version 1), which has been running since 2019. All data from this atlas project is also passed on to the ARTER portal (<https://arter.dk/>), which is the national biological recording scheme portal for Denmark [5], and which automatically feeds records into the GBIF portal.



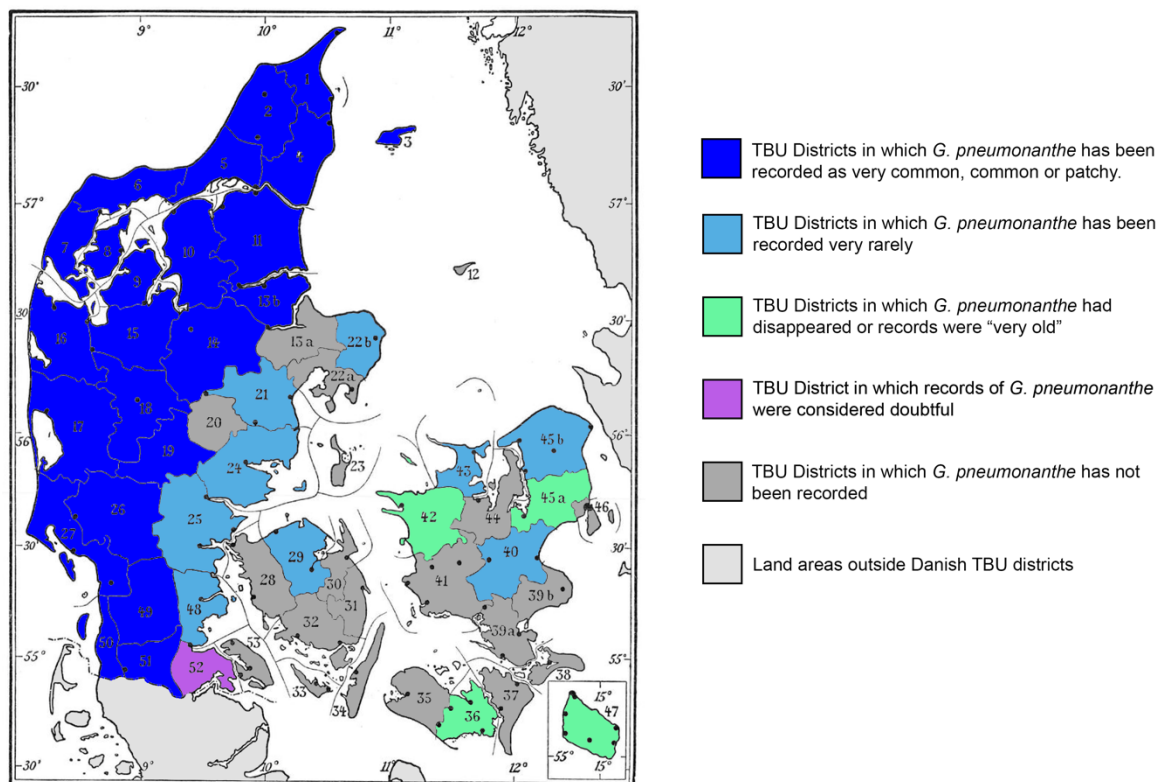
**Figure 3:** Screenshot showing records of the occurrence of *P. alcon* from the *Sommerfugleatlas II* and *III* projects (<https://www.sommerfugleatlas.dk/>), summing records from 2014-2018 and 2019-2023 in each  $10 \times 10$  km UTM square in Denmark. Hotter colours represent higher numbers of records.

#### Records used to prepare our map of *P. alcon* (Figure 1A of the main text)

Data were downloaded from GBIF [6], which consisted of 2341 occurrence records of *P. alcon* recorded in Denmark. Data was filtered to only include observations from sources with spatial uncertainty lower than 5 km (except for data from the *Sommerfugleatlas II* and *III* projects, which was labelled as with an accuracy of 7 km, but which is published with coordinates in the precise  $10 \times 10$  km UTM grid square where the record has been made). In addition, we included all of the georeferenced data found on the labels of the 1069 preserved specimens used in this study. This involved geocoding older material where location names were given, which was carried out by P.H.F. and D.R.N., primarily using google earth and historical atlases of Denmark. Based on label descriptions, an accuracy for each record was estimated, and again only records accurate to less than 5 km included. In cases where there was more than one location that could fit the description given on the specimen label, specimens were excluded. Many of the specimens from the natural history museums in Copenhagen and Aarhus already existed in the GBIF database, but we also found several instances where specimens were not already present. Specimens were matched with those in the GBIF dataset based on collection dates, which were usually easily read from the specimen labels. We also used field notebooks and GPS records to ensure that all records fieldwork that we have conducted on *P. alcon* in Denmark over the last 25 years were included. The position of all specimens GBIF records and field records was then plotted in the Macintosh program *Magic Maps 2* (v 2.4.0; <https://magicmaps.app>), and their positions aggregated into the  $10 \times 10$  km UTM grid for zone 32 to give the set of grid squares in which *P. alcon* had been recorded prior to and after the year 2000. As an additional check, any record from the labels of the specimens used in this study or field records that fell outside the  $10 \times 10$  km UTM grid squares from the GBIF records was double-checked for likely accuracy of geocoding. This revealed two  $10 \times 10$  km UTM grid squares where *P. alcon* was reliably present prior to 2000, but not in the GBIF dataset, and also identified some potentially problematic geocoding of specimens (in both our preserved specimen database and the GBIF database), which were then excluded. We have an on-going project to systematically examine these cases and to feed information back into GBIF, as well as making the missing specimen-based data available. Some eggs of *P. alcon* were found on herbarium specimens of *G. pneumonanthe* (see below) collected before 2000, and this data was also included in our dataset, but did not result in any additional  $10 \times 10$  km UTM grid squares being included in the distribution map of *P. alcon*.

## Atlases of Danish plants

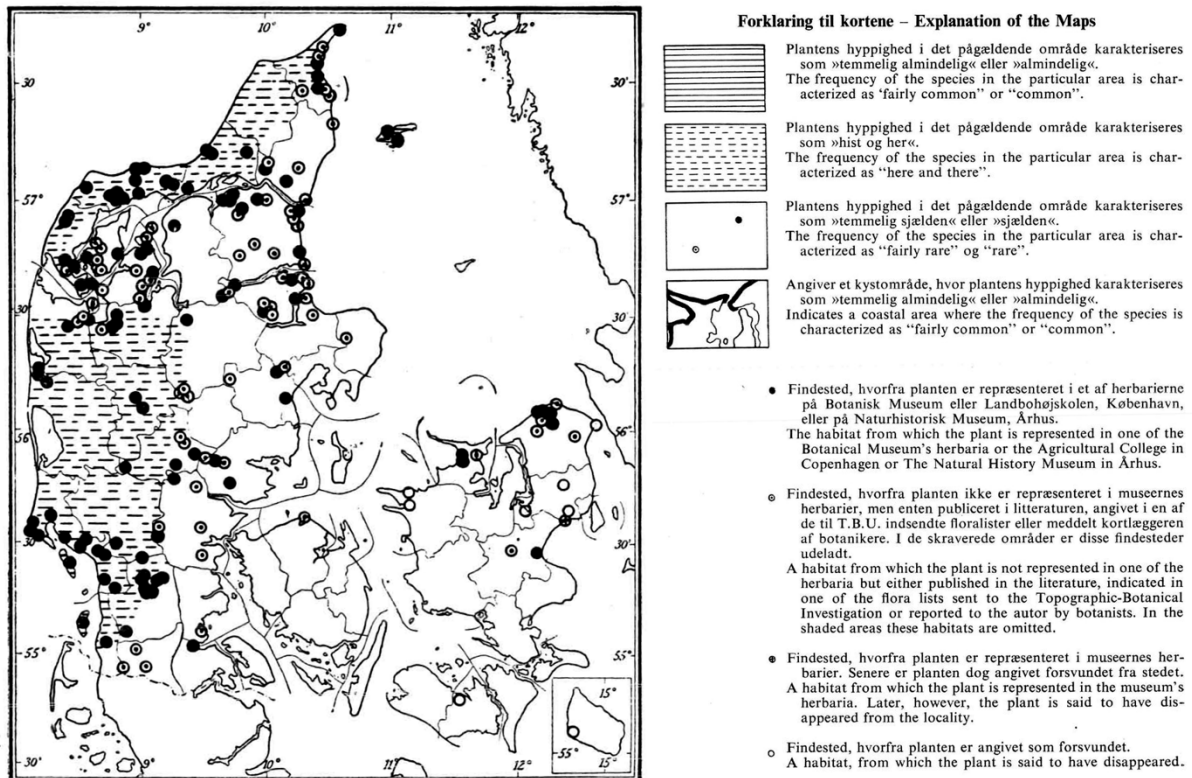
The *Dansk Botanist Forening* (Danish Botanical Society) has attempted to map the occurrence and to some extent, abundance of the vascular plants of Denmark, including *Gentiana pneumonanthe*, over the last 150 years. This resulted in the establishment of the *Topografisk-Botanisk Undersøgelse af Danmark* (TBU; Topographical botanical survey of Denmark) in the late 19<sup>th</sup> century, which divided Denmark initially into 47 TBU districts, which were later expanded to 57 districts through subdivisions and changes in country boundaries [7]. In 1926 Knud Jessen published an overview of the distribution of many vascular plants in Denmark, including *G. pneumonanthe*, based purely on whether they had been recorded in these districts which gives a first, albeit very coarse-grained distribution atlas for the marsh gentian in Denmark, suggesting that the species was widespread in Denmark, albeit mostly on Jutland. This already incorporated several districts from which the marsh gentian had previously been recorded, but where it was thought to have disappeared.



**Figure 4:** Map of Danish TBU districts from [8], showing those that were considered by Jessen in 1926 [7] to have *G. pneumonanthe* occurring somewhere within the district filled according to the colour code given on the right.

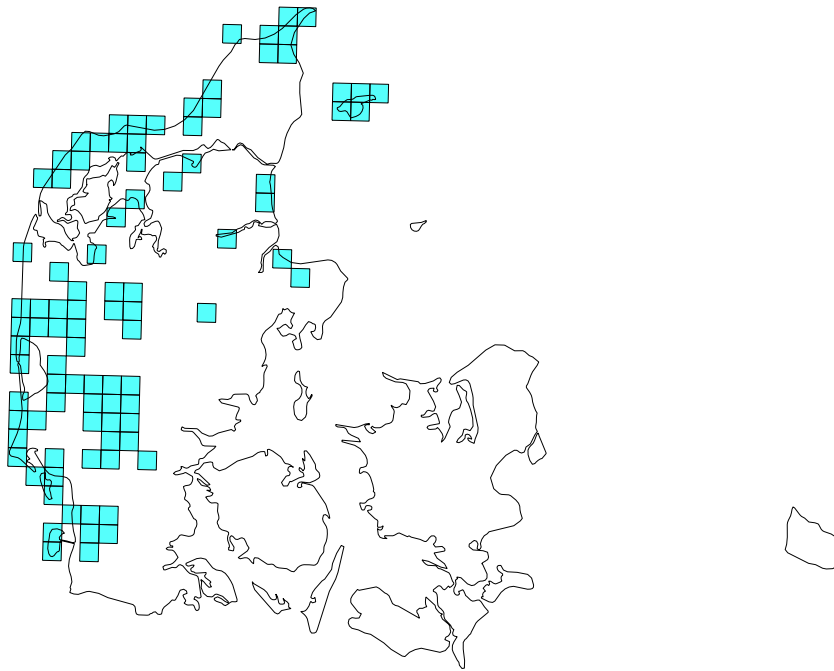


A specific volume of the TBU dealing with Gentianaceae was published in 1958 by Alfred Hansen [8], which incorporated more information, based on herbarium records and published records, particularly in areas outside the main range of *G. pneumonanthe* in central and northern Jutland.



**Figure 5:** Distribution map for *G. pneumonanthe* produced by Hansen in 1958, with a key to the symbols and shading used. Note that TBU district boundaries are also shown. A single site from the north coast of Funen was regarded as reliable, albeit without representation in the herbaria.

The most recent attempt to map the flora of Denmark, is the *Atlas Flora Danica*, which was initiated in the 1990s, and which was published in book form in 2015. This aimed to produce maps of the occurrence of vascular plants across Denmark, by examining at least two of the 5 × 5 km UTM grid squares within every 10 × 10 km UTM grid square across Denmark, with the aim of recording all species present [9]. All data from the atlas project was also made available via the GBIF portal. A few datasets, including that for *G. pneumonanthe* are also presented on the web site <http://atlasfloradanica.dk>.



**Figure 6:** Distribution map for *G. pneumonanthe* based on *Atlas Flora Danica* (2015) aggregated into 10 × 10 km UTM grid squares.

### Records used to prepare our map of *G. pneumonanthe* (Figure 1B of the main text)

Data were downloaded from GBIF [10], which consisted of 2780 occurrence records of *G. pneumonanthe* recorded in Denmark. Data was filtered to only include observations from sources with spatial uncertainty lower than 5 km. In addition, we included all of the georeferenced data found on the labels of the preserved specimens of *G. pneumonanthe* present in the national herbarium of Denmark. This involved geocoding older material where location names were given, which was carried out by K.J.S. and D.R.N., primarily using google earth and historical atlases of Denmark. Based on label descriptions, an accuracy for each record was estimated, and again only records accurate to less than 5 km included. In cases where there was more than one location that could fit the description given on the specimen label, specimens were excluded. Some of the specimens from the herbarium already existed in the GBIF database, but we also found many instances where specimens were not already present. Specimens were matched with those in the GBIF dataset based on collection dates, which were usually easily read from the herbarium sheet labels. There were several questionable records in the GBIF database, including two recent records from north Zealand, so we removed all unverified records from sources (such as iNaturalist) where verification was possible. We also used field notebooks and GPS records to ensure that all records from fieldwork that we have conducted on *G. pneumonanthe* in Denmark over the last 25 years were included. We also included all records of *P. alcon* in our dataset, since as this butterfly is monophagous on *G. pneumonanthe* in Denmark, its presence also indicates the presence of the gentian. The position of all specimens, GBIF records and field records of both *G. pneumonanthe* and the records for *P. alcon* used for mapping were then plotted in the Macintosh program *Magic Maps 2* (v 2.4.0; <https://magicmaps.app>), and their positions aggregated into the 10 × 10 km UTM grid for zone 32 to give the set of grid squares in which *G. pneumonanthe* had been recorded prior to and after the year 2000. As an additional check, any record from the labels of the specimens used in this study or field records that fell outside the 10 × 10 km UTM grid squares from the GBIF records was double-checked for likely accuracy of geocoding. This revealed three 10 × 10 km UTM grid squares where *G. pneumonanthe* was reliably present prior to 2000, but not in the GBIF dataset, and also identified some potentially problematic geocoding of specimens (in both our preserved specimen database and the GBIF database), which were then excluded. We have an on-going project to systematically examine these cases and to feed information back into GBIF, as well as making the missing specimen-based data available.

## References

1. Lyneborg, L. Et arbejdskort til brug for faunistiske undersøgelser i Danmark. *Entomologiske Meddelelser* **1971**, 39, 68-70.
2. Eskildsen, A.; Carvalheiro, L.G.; Kissling, W.D.; Biesmeijer, J.C.; Schweiger, O.; Høye, T.T. Ecological specialization matters: long-term trends in butterfly species richness and assemblage composition depend on multiple functional traits. *Diversity and Distributions* **2015**, 21, 792-802, doi:10.1111/ddi.12340.
3. Stoltze, M. *Danske dagsommerfugle*; Gyldendal: Copenhagen, Denmark, 1996; p. 383.
4. Calabuig, I. Atlas survey of the Butterflies of Denmark. Occurrence dataset <https://doi.org/10.15468/v5f2e2> Available online: <https://www.gbif.org/dataset/7f513bfc-f762-11e1-a439-00145eb45e9a#description> (accessed on 27 October).
5. Møller, J.; Wenøe Breddam, D.; Calabuig, I.; Skovgaard Mathorne, J.; Skipper, L. Species recordings from the Danish National portal Arter.dk. Miljøstyrelsen / The Danish Environmental Protection Agency. Occurrence dataset. **2020**, doi:10.15468/q3yy4u.
6. GBIF Org User. Occurrence Download - *P. alcon* in Denmark. **2022**, doi:10.15468/DL.XWFGZY.
7. Jessen, K. Oversigt over Karplanternes Udbredelse i Danmark. *Botanisk Tidsskrift* **1926**, 39, 10-211.
8. Hansen, A. Gentianaceernes, Menyanthaceernes, Asclepiadaceernes og Apocynaceernes udbredelse i Danmark. In *Danmarks Topografisk-Botaniske Undersøgelse*, Dansk Botanisk Forening, Ed.; Munksgaard: 1958; Volume 24, pp. 305-332.
9. Bruun Asmussen Lange, C.; Hermann, J. Atlas Flora Danica. Version 1.1. Botanical Society of Denmark. Occurrence dataset. Available online: <https://www.gbif.org/dataset/8df9af24-1fbd-4699-a545-9a2867ff25fe#description> (accessed on 27 October).
10. GBIF Org User. Occurrence Download - *G. pneumonanthe* in Denmark. **2022**, doi:10.15468/DL.A8SKQQ.