High post-season *Alnus* pollen loads successfully identified as long-range transport of an alpine species[[1]](#footnote-2)

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# Abstract

*Alnus* pollen, a relevant bioaerosol, is one of the Northern Hemisphere’s major allergens. In Central Europe, the genus is represented by three species (*Alnus glutinosa*, *Alnus incana*, and *Alnus viridis*). The most common one, *A. glutinosa* (L.) Gaertn., is widespread in lowland riparian forests, swamps, and forest edges. To investigate long-range transport of airborne pollen, we used backward air mass trajectories and tested this method for the year 2015, based on daily *Alnus* pollen concentrations at 26 sites in Bavaria, Germany. In addition to *A. glutinosa*’s main pollen season in February–March, a six-day, post-season episode was identified in June. For this episode and all sites, 72-h backward trajectories, started at 3-h intervals with hourly temporal resolution, were calculated using the HYSPLIT (hybrid single-particle Lagrangian integrated trajectory) model. This backward trajectory method identified *A. viridis* ([Chaix](https://de.wikipedia.org/w/index.php?title=Dominique_Chaix&action=edit&redlink=1" \o "Dominique Chaix (Seite nicht vorhanden))) [DC](https://de.wikipedia.org/wiki/Augustin_Pyramus_de_Candolle), from the alpine region in Switzerland and Austria, as a potential pollen source for the post-season episode in June. Both its unique spatial distribution and a considerably later flowering period affirmed this long-range transport that is frequently observed as a 23-year pollen time series.

Keywords: pollen, *Alnus*, green alder, backward air mass trajectories, HYSPLIT, off-season

# 1 Introduction

Scientists and clinicians pay a great deal of attention to pollen, a major bioaerosol in the atmosphere, because of the large amounts of allergenic pollen emitted into the air, which decreases quality of life and work performance. To support pollinosis sufferers effectively in their therapy, the pollen emissions of locally and regionally flowering plants need to be estimated in advance (Brożek et al., 2017; Stern et al., 1997). To define or forecast pollen seasons, several studies have used phenological information, but there was often a temporal mismatch between pollen and flowering dates, depending on the site, pollen type, and amount of pollens in the air (Estrella et al., 2006; Grewling et al., 2012; Jato et al., 2006). Because pollen species may travel long distances under certain meteorological conditions, pollen season information based only on local vegetation is obviously not sufficient and quantitative assessment of the contribution of atmospheric pollen arriving with long-range transport to the sites is needed to be considered.

In many European states, long-range pollen transportation is investigated to forecast the timing of pre- or post- season episode, as well as potential nonlocal origins, via meteorological conditions and air mass transport models. When a certain pollen type is transported from its source to another location, various conditions may apply at the receptor site. First, there may be few or no local pollen-emitting plants at all, clearly pointing to long-range pollen transport (Šauliene and Veriankaite, 2006). Sometimes, there is a local pollen source and an ongoing season at the receptor site, but part of the pollen is still transported from mid- or long-range distances. This type of transportation can be detected by examining the diurnal cycles (a common method in studying, e.g., ragweed transportation) (Stach et al., 2007) or assessing enhanced pollen levels in comparison to other nearby recording sites (Fernández-Rodríguez et al., 2014; Hernández-Ceballos et al., 2011; Skjøth et al., 2007). Long-range transportation studies regarding the elevated concentration of pollen have been performed for Ambrosia pollen in Spain (Belmonte et al., 2000), central northern Italy (Cecchi et al., 2007), and Poland (Kasprzyk et al., 2011). The last case of transported pollen is when local pollen sources exist at the receptor site, it may be that the local pollen season has not yet started or is already over (pre-season or post-season episodes) which may look like a pollen season prolong in the regions. Long-range transport as such used backward trajectory analysis to model the paths of air parcels and to indicated airborne pollen source region e.g., *olea* in Spain (Hernandez-Ceballos et al., 2014), ragweed pollen in Hungary (Makra et al., 2007). Moreover, in Europe, there are several studies on the genus *Betula* that interlinked pre- or post-season pollen events by back-trajectories to regions with likely different flowering seasons of the same birch species (Bogawski et al., 2019; Siljamo et al., 2008; Skjøth et al., 2007; Sofiev et al., 2006; Veriankaitė et al., 2010).

The present work is focused on the long-range transportation of *Alnus* pollen in Europe. This pollen type is considered one of the main allergy causes in Europe (D’Amato et al., 2007). There are reports of dramatic changes in *Alnus* sensitization rates within a few years as a result of changes in exposure (Gassner et al., 2013). *Alnus* is also a relevant genus in European riparian vegetation and mixed forests. For these reasons, it is critical to determine airborne *Alnus* pollen loads and to understand this genus’ aerobiological behavior. We examine the path along which air masses have traveled to the 26 Bavarian monitoring sites in 2015 while considering the phenological observations that indicate the start of the local *Alnus* *glutinosa* pollen season. Using back trajectory analysis, we investigated pollen concentrations, with particular focus on 10 sites for six days in June, to determine the likely allochthonous sources of recorded *Alnus* pollen.

# 2 Method

## 2.1 Pollen data

At 26 monitoring stations scattered across Bavaria, Germany (Fig. 1), *Alnus* pollen data, along with 14 other pollen taxa, were collected between March 15, 2015 and September 14, 2015, using manual Hirst-type pollen traps. Daily average *Alnus* pollen concentrations were expressed as pollen grains per cubic meter of air (grains/m3). These measurements were made under the framework of constructing the electronic Pollen Information Network (ePIN) in Bavaria. Details on ePIN and its monitoring stations (see Table 1) are discussed in the work of (Oteros et al., 2019).

In addition to the 2015 ePIN data, we also used historical pollen data. The German Pollen Information Service [Stiftung Deutscher Polleninformationsdienst (PID)] has been collecting data from pollen traps in Germany since 1983. Thus, daily pollen concentration values at Oberjoch (DEOBER) from 1995 to 2017 (23 years) were also investigated in this study.

**Table 1**

ePIN pollen monitoring sites.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Code | Monitoring site | Latitude (°) | Longitude (°) | Altitude (m a.s.l.) |
| DEALTO | Altötting | 48.23 | 12.68 | 398 |
| DEAUGS | Augsburg | 48.33 | 10.90 | 497 |
| DEBAMB | Bamberg | 49.90 | 10.89 | 238 |
| DEBAYR | Bayreuth | 49.94 | 11.53 | 419 |
| DEBERC | Berchtesgaden | 47.64 | 13.01 | 573 |
| DEBIED | Biederstein (Munich) | 48.16 | 11.59 | 510 |
| DEDONA | Donaustauf | 49.04 | 12.21 | 425 |
| DEFEUC | Feucht (Nuremberg) | 49.38 | 11.20 | 365 |
| DEGAIS | Gaissach | 47.75 | 11.58 | 717 |
| DEGARM | Garmisch-Partenkirchen | 47.49 | 11.10 | 821 |
| DEHOF | Hof | 50.32 | 11.90 | 531 |
| DEKITZ | Kitzingen | 49.74 | 10.14 | 246 |
| DEKOES | Kösching | 48.82 | 11.51 | 391 |
| DELANDS | Landshut | 48.54 | 12.14 | 397 |
| DEMARK | Marktheidenfeld | 49.85 | 9.63 | 216 |
| DEMIND | Mindelheim | 48.04 | 10.50 | 610 |
| DEMUNC | Munich | 48.13 | 11.56 | 538 |
| DEMUST | Münnerstadt | 50.25 | 10.18 | 347 |
| DEOBER | Oberjoch | 47.52 | 10.40 | 870 |
| DEOETT | Oettingen | 48.96 | 10.60 | 431 |
| DEPASS | Passau | 48.56 | 13.44 | 318 |
| DETROS | Trostberg | 48.03 | 12.56 | 483 |
| DEUFS | Environmental Research Station Schneefernerhaus (UFS) | 47.42 | 10.99 | 2650 |
| DEVIEC | Viechtach | 49.08 | 12.87 | 459 |
| DEWEID | Weiden | 49.68 | 12.17 | 403 |
| DEZUSM | Zusmarshausen | 48.40 | 10.61 | 483 |

ePIN, electronic Pollen Information Network; m a.s.l, meters above sea level.

## 2.2 Phenological data

The phenological network of the German Meteorological Service (Deutscher Wetterdienst, DWD) is supported by volunteer observers. There are 222 stations in Bavaria, and in 2015, 162 stations reported the start of flowering dates of *A. glutinosa* (black alder) (Fig. 1). These DWD phenological data provided a first estimate of the start of the local *Alnus* pollen season. We applied the distance-weighted interpolation method (Hogewind and Bissoli, 2011) to plot a complete map depicting the *Alnus* start of flowering dates across Bavaria (Fig. 2), from which the corresponding dates at the 26 pollen monitoring sites were obtained.



**Fig. 1.** Map of Bavaria showing 26 ePIN pollen measuring sites (10 ePIN sites with second Alnus pollen peak in June in red and 16 pollen measuring sites without second pollen peak in June in blue) and 162 phenological stations of the DWD (empty circles).

## 2.3 Pollen season

The start of the airborne pollen season was derived from an *Alnus* pollen concentration time series using the “percentage” method. The percentage method is commonly used to define the length of the pollen season based on eliminating a certain percentage (5%, in this study) at the beginning and end of the pollen season (Andersen, 1991; Hogewind and Bissoli, 2011; Nilsson and Persson, 1981). Analyses were performed using R statistical software (R Core Team, 2019) together with AeRobiology package (Rojo et al., 2019).

## 2.4 Back trajectory model

We used the HYSPLIT (hybrid single-particle Lagrangian integrated trajectory) model to study air transport and characterize the pollen source regions (Draxler and Hess, 1998; Stohl, 1996). The underlying meteorological model, ERA5, was obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF). The ERA5 dataset provides hourly forecast weather data and covers the Earth at a 30-km resolution. The 72-h back trajectories were run at 3-h intervals from 00:00 to 21:00 hours from April to September 2015 for each of the 26 sites. The backward trajectory calculations were started at an altitude of 500 m above ground level. In addition, because the calculated trajectories contain air mass coordinates, we were able to determine whether or not the trajectory passed over areas of interest. The backward trajectories were processed using the openair package (Carslaw and Ropkins, 2012) within R.

# 3 Results and discussion

## 3.1 Pollen season

The median start of the *A. glutinosa* flowering season, as extracted for the 26 sites from the phenological interpolated map data (Fig. 2), was day of year (DOY) 71 (March 12, 2015; indicated by a black vertical solid line in Fig. 3). The corresponding 25th and 75th quantiles were DOY 69 and 73.75 (gray-shaded areas in Fig. 3).

In contrast, the median airborne pollen season, by the percentage method, started on DOY 76 (March 17) and lasted until DOY 110 (April 20). It is indicated by two vertical dashed lines in Fig. 3. Unfortunately, ePIN pollen stations did not start until DOY 74 (March 15); thus, it remains uncertain whether the earliest start of the airborne pollen season has already been captured because the median start of flowering is five days earlier than the median start of the pollen season.

The 2015 *Alnus* pollen season in Bavaria is largely consistent with that of other German cities. Werchan et al. (2018) published a pollen calendar based on a six-year monitoring period (2011–2016) using the percentage method (80%) on daily average levels of pollen data, and reported that the main *Alnus* pollen season occurred from February to April. However, large seasonal differences of up to 28 days were observed.

Moreover, Biedermann et al. (2019) reviewed the pollen season of birch, hazel, and alder pollen in Europe and provided the corresponding pollen exposure maps. They showed that *A. glutinosa* is prevalent in almost all of Europe; its pollen season begins in mid-January and may extend up to late March. However, the pollen seasons varied by locations or altitude.



**Fig. 2.** Start of flowering dates (DOY) of Alnus glutinosa in Bavaria. Data are interpolated from DWD phenological observations for the year 2015.

## 3.2 Post-season episode

Daily *Alnus* pollen concentrations (grains/m3) from March 15, 2015 to September 14, 2015, are shown in Fig. 3. To identify different episodes more clearly, low concentrations (<3 grains/m3) are excluded. Maximum *Alnus* concentrations of more than 200 grains/m3 were recorded on DOY 76 to 78 (March 17 to March 19). *Alnus* pollen counts then dropped below 15 grains/m3 on March 31. From April 18 to June 1 (~6 weeks), except for three random days at three random sites, there was not a single day with concentrations greater than or equal to 3 grains/m3, suggesting that the pollen season was over.



**Fig. 3.** Daily mean Alnus pollen concentration (grains/m3) for the 26 sites in 2015 (only days with ≥3 grains/m3 are shown). The solid vertical line and gray area show a corresponding summary of the start of A. glutinosa flowering from DWD data (the line indicates the median and the gray-shaded area represents the 25th–75th quantiles). The two vertical dashed black lines are the mean start and end of the airborne pollen season calculated by the percentage method. Colors indicate the respective sites of the ePIN network (see Table 1).

Two months after the pollen season, specifically for six days in June (June 1–6, 2015, DOY 152–157), a second peak of pollen concentration was recorded at 10 sites including the remote mountain site Schneefernerhaus (Fig. 1). The 10 sites at which this episode was observed are marked with red circles in Fig. 1. Of the 10 sites, only Oberjoch (DEOBER) reported *Alnus* pollen concentrations on all six days. *Alnus* pollen levels were recorded at the Environmental Research Station Schneefernerhaus (DEUFS) and Gaissach (DEGAIS) for four and three days, respectively. Three other sites had two days, and four sites had only one day with *Alnus* pollen concentrations ≥3 grains/m3. However, we opted to investigate all six days because those trajectories included more information about the whole episode.

Since *A. glutinosa* was no longer flowering anywhere in Bavaria in June (see Fig. 2), we hypothesized that the pollen measured during this period was transported to the Bavarian sites from elsewhere. One additional fact that strengthened our hypothesis is the concentration recorded at the mountain site DEUFS during this episode. This site is located 2650 m above sea level (47°25′N, 10°59′E), nearly 300 m below the summit of Mount Zugspitze, the highest mountain in Germany. Because it receives well-mixed, free tropospheric air masses (Ghasemifard et al., 2019), and there is no woody vegetation, such as *Alnus* species, around the site (Friedmann and Korch, 2010), all measured pollen has to be transported to the site.

Moreover, because the “normal” *A. glutinosa* pollen season is usually over by early May, even in northern parts of Europe (Biedermann et al., 2019), we had to consider all different *Alnus* taxa before investigating trajectories and transportation. The European Commission’s science and knowledge service has published “the European atlas of forest tree species” with distribution maps of different species, including chorology and the frequency of occurrences (available online at: https://forest.jrc.ec.europa.eu/en/european-atlas/, accessed on October 10, 2019). *A. glutinosa* (L.) Gaertn. (common or black alder) is found all over Europe, and *Alnus cordata (*Loisel.) Duby (Italian alder) is native to the hills and mountain areas of southern Italy. *Alnus incana* (L.) Moench (gray alder) is also native to most of central Europe and overlaps with that of the common alder (*A. glutinosa*), but it extends further north. *Alnus viridis* (Chaix) DC (green alder) is native to the cooler parts of the Northern Hemisphere. In Europe, it is mainly found in the alpine areas of the Alps, Balkans, and Carpathians at elevations between 1600 and 2300 m (Caudullo and Mauri, 2016; Caudullo et al., 2017; Houston Durrant et al., 2016; Mauri and Caudullo, 2016). As *A. glutinosa*, *A. cordata*, and *A. incana* have their pollen periods in February–March, we hypothesized that pollen concentrations recorded in June can be attributed to *A. viridis* transported to Bavaria from the alpine region.

## 3.3 Backward trajectory analysis

We assumed *A. viridis* emitted the pollen observed in June 2015. The backward trajectory analysis results for the 10 sites containing the second peak (in June) are shown in Fig. 4. The 72-h backward trajectories indicate the path of *Alnus* pollen containing air masses over geographical areas and, consequently, potential source regions. One common factor among all 10 stations is that their air masses passed over the alpine area with southwesterly and westerly winds (Fig. 4). This area corresponds to *A. viridis*’ distribution across the Alps (Fig. 5, (Caudullo et al., 2017)). Thus, according to the air mass trajectories of these 10 sites, the alpine region is the only viable source region. More specifically, 48% of the trajectories containing *A. viridis* pollen with concentrations of ≥3 grains/m3 passed over this source region, as shown in Fig. 5.

Results for the pollen site of Oberjoch (DEOBER), which recorded *Alnus* pollen concentrations on all six days, clearly support this hypothesized transport. Its air masses mainly passed over Switzerland (~28.3%), but also Austria and Italy (~13.5% and 7.3%, respectively) (see Fig. A.1 in Appendix A). In the Swiss Alps, 70% of the shrub areas consist of *A. viridis*, as described in the recent spearing of *A. viridis* over the alpine area (Brändli, 2010). Caviezel et al. (2017) revealed *A. viridis* expands much faster and wider than assumed across the Alps. Therefore, scientists are using models to investigate climate change’s impact on land-use changes (e.g., increase in the area covered by *A. viridis*) (Alaoui et al., 2014; Caviezel et al., 2017; Fercher et al., 2018; Wiedmer and Senn-Irlet, 2006).



**Fig. 4.** HYSPLIT backward trajectories (3-h interval) of air masses reaching the pollen monitoring sites during the post-season Alnus pollen episode. The color of the trajectories shows the respective day.



**Fig. 5.** Distribution map of Alnus viridis (Caudullo et al., 2017).

Although an overview of all trajectories depicts very similar patterns for the 26 sites in the first week of June, only 10 sites recorded *Alnus* concentration (≥3 grains/m3) for at least one day out of the six-day episode (23 days in total). This can be explained via the paths of the air masses determining the frequency of trajectories passing over the source region (green area in Fig. 5). On the 23 days with *A. viridis* concentrations (≥3 grains/m3) at the 10 sites 48% of the trajectories passed over the source region; in contrast 82% of the trajectories on days or sites without *Alnus* pollen did not pass this source region.

## 3.4 Historical data

A review of *Alnus* pollen concentrations, measured over 23 seasons from 1995 to 2017 at Oberjoch (DEOBER), showed two peaks. We postulate that the first peak is most likely attributable to *A. glutinosa* pollen, and the second peak can be ascribed to *A. viridis* pollen (Fig. 6). The maximum concentration of *A. glutinosa* was 614 grains/m3 in March 2006, and the maximum concentration of *A. viridis* was 124 grains/m3 in May 2005. Based on the daily average concentrations, the pollen season was calculated using the percentage method (95% threshold) for both peaks separately. Week 18 had the lowest *Alnus* pollen concentration; therefore, we considered this the time when the two peaks are separated. The overall pollen season of *A. glutinosa* and *A. viridis* is from weeks 3 to 14 (January–April) and from weeks 19 to 27 (May–June), respectively. In accordance with our results, Sindt et al. (2017) observed significant quantities of *Alnus* pollen at a French monitoring site (Annecy) during June. After an investigation of *Alnus* pollen concentrations at several alpine sites, including Swiss sites (Génève, Neuchâtel, Visp, and Buchs) over five years, they noticed that each of these sites recorded *Alnus* pollen during the month of June, and they also specifically ascribed these off-season pollens to *A. viridis*.



**Fig. 6.** Alnus pollen concentration at Oberjoch (DEOBER) for 23 years of measurements (1995–2017). Black line: daily average pollen concentration over the study period; gray color: maximum and minimum pollen concentration of each day over the study period.

# 4 Conclusion

Long-range transport of allergenic pollen seems to be very common, and scientists need to inform allergy sufferers about which time of the year they can expect local and transported pollen. In this study, the pollen measurement results, combined with air mass trajectory calculations, identified *A. viridis* as the most plausible source of pollen during the recurrent post-season episode. Pollen plumes were recorded at 10 monitoring sites in Bavaria, Germany, on the first six days of June in 2015. These plumes reached the monitoring sites with westerly and southwesterly winds, and results indicated the alpine region was the likely source.

Validation and quantification were possible due to a unique pollen data set used in our study, both in terms of number of stations (26 in the year 2015) and of years (23 for one station). Whereas previous long-range transportation studies (e.g., *Betula*) analyzed only two or three locations in a country, our study on 26 closely co-located sites allowed a spatial validation of the long-range *A. viridis* transport, since only 10 of 26 sites recorded the June event; however, those had considerably higher shares of back-trajectories over the alpine *Alnus viridis* distribution range.

Since trajectory models are sensitive to meteorological input, this fine spatial differentiation in our study was only possible due to higher resolution meteorological input data (ERA5) than commonly used in previous studies. Nevertheless, this study provides a classical example of how species of the same genus but totally different flowering times can be separated in continuous pollen records, even if the similar-looking pollen are not distinguishable under the microscope.

It should be noted here since *Alnus viridis* pollen amounts are low compared to the main *Alnus* pollen season of the other two species (covering less than the last 2.5 percentile), the standard method to define start and end of the *Alnus* pollen season will always neglect or discard this post-season episode in June. However, 23 years of pollen recording in Oberjoch reveals that this post-season event is observed every year prolonging the pollen season (in terms of days with allergologically relevant pollen concentrations). Further research is necessary to assess what other factors may affect pollen concentrations and whether *A. viridis* from alpine areas also reaches other parts of Germany or other neighboring countries. Our study demonstrated that trajectory analysis, along with pollen and phenological data, is an appropriate tool that enables the community of scientists and clinicians to detect the potential pollen sources and seasons, and such knowledge can also be used in pollen forecast modeling.

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# Appendix A. The height of trajectories

**Fig. A.1.** Six days (DOY: 152–157) of trajectory analysis. The height of trajectories is shown for 72 h backward. The color of the trajectories shows the respective location.

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1. Table of Abbreviations

   DOY Day of year

   ECMWF European Centre for Medium-Range Weather Forecasts

   HYSPLIT Hybrid single-particle Lagrangian integrated trajectory [↑](#footnote-ref-2)