High post-season *Alnus* pollen loads successfully identified as long-range transport of an alpine species

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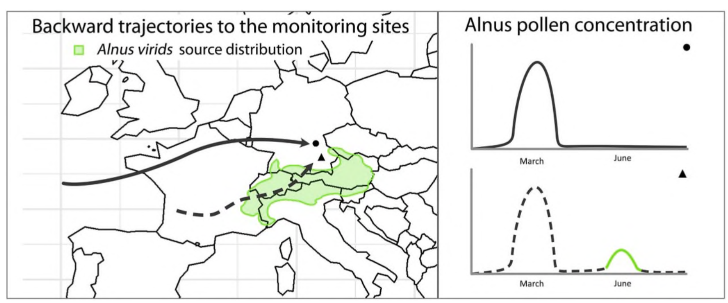
GRAPHICAL ABSTRACT



ABSTRACT

Alnus pollen is one of the Northern Hemisphere's major aeroallergens. 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. However, to date is still unknown if all of them - in terms of pollen exposure - are clinically relevant for sensitized individuals. To investigate the associated pollen exposure, particularly also because of 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. *A. glutinosa*'s main pollen season extends from February to March, but a six-day, post-season episode was additionally identified in June. For this episode and all sites, 72-h backward trajectories were calculated at 3-h intervals using high spatial and temporal resolution ERA5 reanalysis data and the HYSPLIT (hybrid single-particle Lagrangian integrated trajectory) model. This backward trajectory method identified air masses from the alpine region in Switzerland and Austria, where relevant areas of *A. viridis* (Chaix) DC as potential pollen sources exist. These may explain the post-season episode in June, as additionally confirmed by its unique spatial distribution, by a considerably later flowering period, and by repeated long-range transport events as observed in a 23-year pollen time series.

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1. Introduction

Airborne pollen monitoring has been a major focus of both scientists and clinicians since the ubiquitous allergenic pollen in the atmosphere results in decreased quality of life and work performance. To support pollen allergic patients towards a more effective allergy treatment, 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 pollen in the air (Estrella et al., 2006; Grewling et al., 2012; Jato et al., 2006). Since pollen species may travel long distances under certain meteorological conditions, pollen season information based only on local vegetation is obviously not sufficient and a quantitative assessment of the contribution of atmospheric pollen originating from more distant sources with long-range transport need to be considered.

In many European countries, long-range pollen transport is investigated to forecast the timing of pre- or post-season episodes, as well as potential non-local 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 transport can be detected by examining the diurnal cycles [a common method in studying, e.g., ragweed transport, as in Stach et al. (2007)] or assessing increased airborne 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 transport 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). Even if local pollen sources exist at the receptor site, far-transported pollen can be identified as periods, when the local pollen season has not yet started or is already over (pre-season or post-season episodes). These episodes may systematically prolong the regional pollen season and also provoke respiratory symptoms. A recent study by Damialis et al. (2019) has reported for the subnivale Zugspitze area (2650 m a.s.l.) that although immune responses and symptoms were lower due to lower exposure, even short occasional exposure due to long-range transport can still cause symptoms.

In order to identify such long-range transport, backward trajectory analysis has been used to model the paths of air parcels and to indicated airborne pollen source regions e.g., *Olea* in Spain (Hernandez-Ceballos et al., 2014), *Ambrosia* 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 episodes 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, 2015a; Sofiev et al., 2006; Veriankaitė et al., 2010). Similarly, *Alnus* pollen has the potential to be transported over long distances, e.g., together with *Betula* and *Corylus* from the Alps to northern Fennoscandia (Franzén et al., 1994), or from Belarus and Ukraine to Rzeszow (Kasprzyk and Borycka, 2019). In Poland remote sources may influence the recorded concentrations of *Betula* and to a small degree of *Alnus* (Bilińska et al., 2019; Ojrzyńska et al., 2020; Skjøth et al., 2015b). It has been reported that *Alnus*, *Betula* and *Salix* pollen from Western Europe even reached the North Pole (Rousseau et al., 2004). A study on pollen circulation patterns in Greece also confirmed long-range transport of *Alnus* and *Corylus* (Damialis et al., 2005).

The present work is focused on the long-range transport of *Alnus* pollen in Europe. *Alnus* pollen is considered one of the main allergy causes in Europe, being strongly cross-reactive to *Betula* pollen as well (D'Amato et al., 2007). There are reports of dramatic changes in *Alnus* symptom 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 *Alnus* airborne pollen concentrations. We integrated datasets of phenological, aerobiological and species distribution and examined the path along which air masses have travelled to the 26 Bavarian monitoring sites in 2015. Using back-trajectory analysis, we investigated *Alnus* spp. Pollen concentrations, with particular focus on six days in June when 10 sites captured a post-season episode, to determine the likely allochthonous sources of recorded *Alnus* pollen. These were compared against the local flowering phenology of *Alnus glutinosa*. Our hypotheses were that the most abundant local *Alnus glutinosa* populations may not be the only responsible species for the manifestation of allergic symptoms in sensitized individuals, and that more distant sources from other *Alnus* species may contribute to the symptoms of allergic patients in farther localities.

2. Methods

2.1. Pollen data

At 26 stations across Bavaria, Germany (Fig. 1), *Alnus* pollen monitoring, along with 14 other pollen taxa, was conducted from 15 March to September 14, 2015 using Hirst-type pollen traps. Daily average *Alnus* pollen concentrations were expressed as pollen grains per cubic meter of air (grains/m^3). These measurements were made in the framework of the establishment of 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 ePIN 2015 data, we also used historical pollen data. The German Pollen Information Service [Stiftung Deutscher Polleninformationsdienst (PID)] has been monitoring pollen in Germany using the same method. Thus, daily pollen concentration values at Oberjoch (DEOBER) from 1995 to 2017 (23 years) were also investigated in this study.

2.2. Phenological data

The phenological network of the German Meteorological Service (Deutscher Wetterdienst, DWD) is supported by volunteer observers at 222 stations across Bavaria. In 2015, 162 stations reported the start of the flowering dates of *A. glutinosa* (black alder) (Fig. 1). Assuming that monitored airborne pollen concentrations of *Alnus* spp. derive mainly from local sources, these DWD phenological data provided a first estimate of the start of the local *Alnus* pollen season. We applied the validated standard method of the DWD, distance-weighted interpolation method from multiple linear regressions in which regression coefficients are elevation, longitude and latitude (Müller-Westermeier, 1995; Maier et al., 2003; Hogewind and Bissoli, 2011) to plot a complete map depicting the *Alnus* start of flowering dates across Bavaria (Fig. 2), from which the corresponding flowering dates at the 26 pollen monitoring sites were obtained.

Moreover, because the common *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* species before investigating trajectories and transportation. We therefore include information of "the

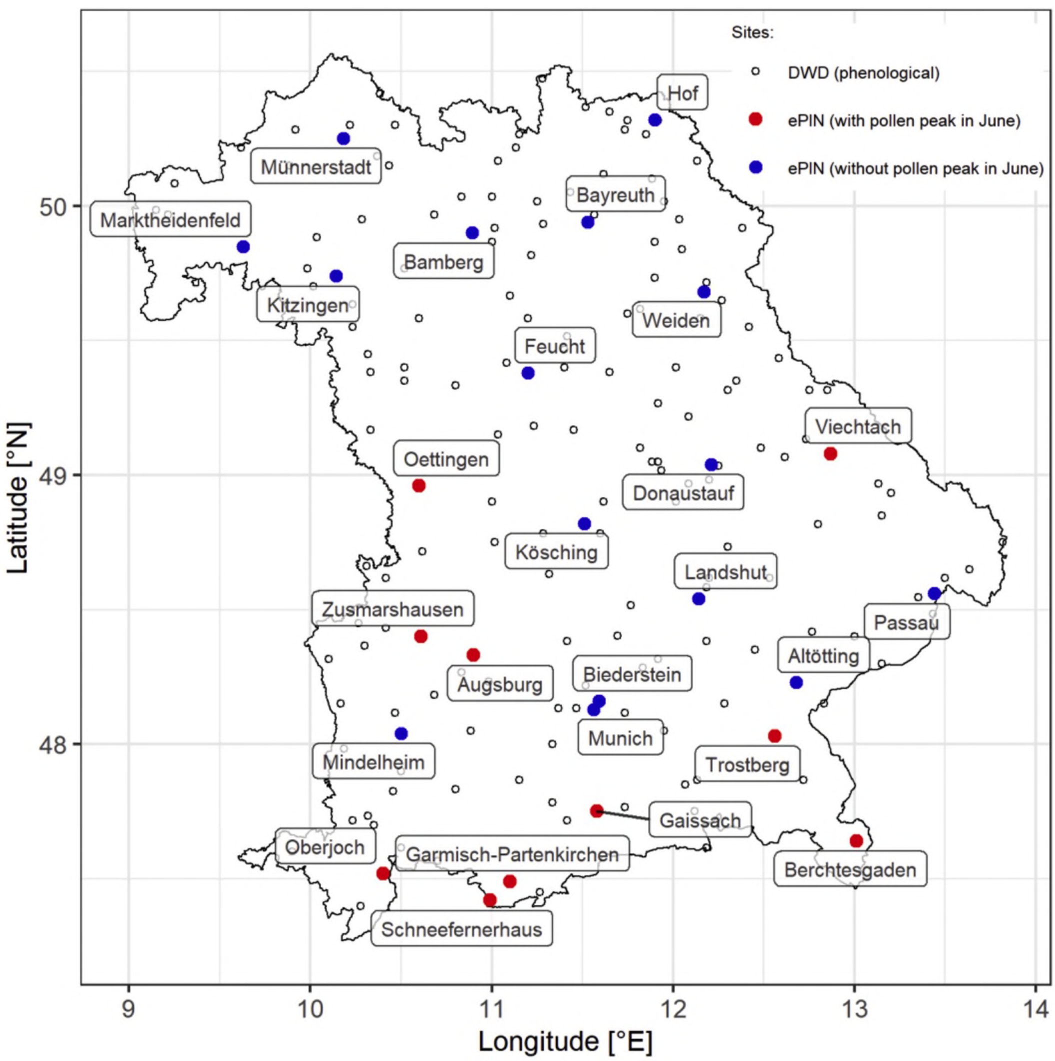

Fig. 1. Map of Bavaria showing 26 ePIN pollen monitoring sites (10 ePIN sites with a second Alnus pollen peak in June 2015 in red and 16 sites without the second pollen peak in June 2015 in blue) and 162 phenological stations of the DWD (empty circles). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

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	09.63	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.

European atlas of forest tree species" published by the European Commission's science and knowledge service, namely distribution maps of different *Alnus* species and their frequency of occurrences (San-Miguel-Ayanz et al., 2016).

2.3. Pollen season

For historical pollen data at the station Oberjoch, the start of the airborne *Alnus* pollen season was derived 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 total in this study) at the beginning and end of the pollen season (Andersen, 1991; Nilsson and Persson, 1981). Analyses were performed using R statistical software (R Core Team, 2019) together with AeRobiology package (Rojo et al., 2019). In order to apply this method on two peaks separately, we defined the end of the first major pollen peak when 10 consecutive days had pollen concentrations smaller than 3 grains/m^3.

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 estimates of climate variables and covers the Earth at a 30-km horizontal resolution on 137 vertical levels from the surface up to 80 km. The 72-h back trajectories were run at 3-h intervals from 00:00 to 21:00 o'clock 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. Prior sensitivity tests using different heights, more specifically 0, 500, 700, 1000, 1500, and 2000 m a.g.l., had shown that 500 m was the optimal height for our study question. Since 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.

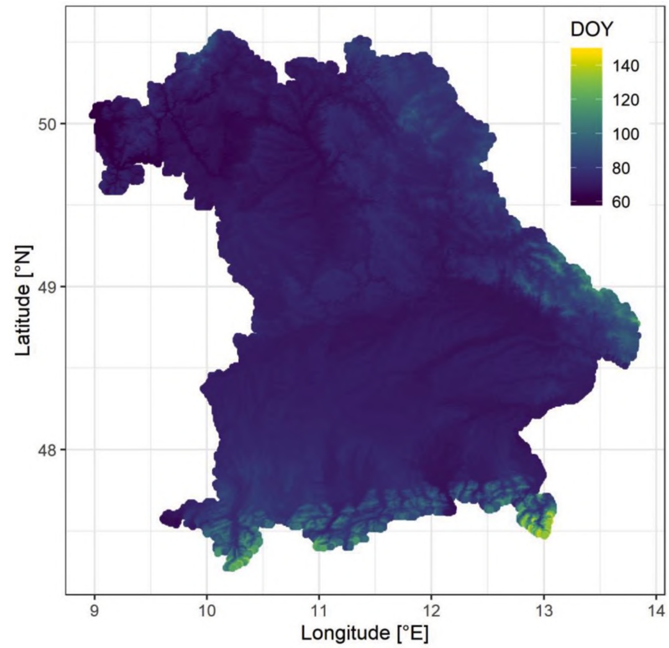

Fig. 2. Start of flowering dates (DOY) of Alnus glutinosa in Bavaria. Data are interpolated from DWD phenological observations for the year 2015 (see stations as open circles in Fig. 1).

3. Results

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 73.8 (gray-shaded areas in Fig. 3).

3.2. Post-season episodes

Daily *Alnus* pollen concentrations (grains/m^3) from 15 March to September 14, 2015 are shown in Fig. 3. To identify different episodes more clearly, low concentrations (<3 grains/m^3) were excluded, which out of days with pollen amounted to about 61% of data. Daily maximum *Alnus* concentrations of more than 200 grains/m^3 were recorded on DOY 76 to 78 (March 17 to March 19). On 31 March and thereafter, concentrations dropped below 15 grains/m^3. From 18 April to 01 June (~6 weeks), except for three random days at three sites, there was not a single day with concentrations greater than or equal to 3 grains/m^3, suggesting that the pollen season was over.

Two months after the pollen season, specifically for six days in June (1–6 June 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

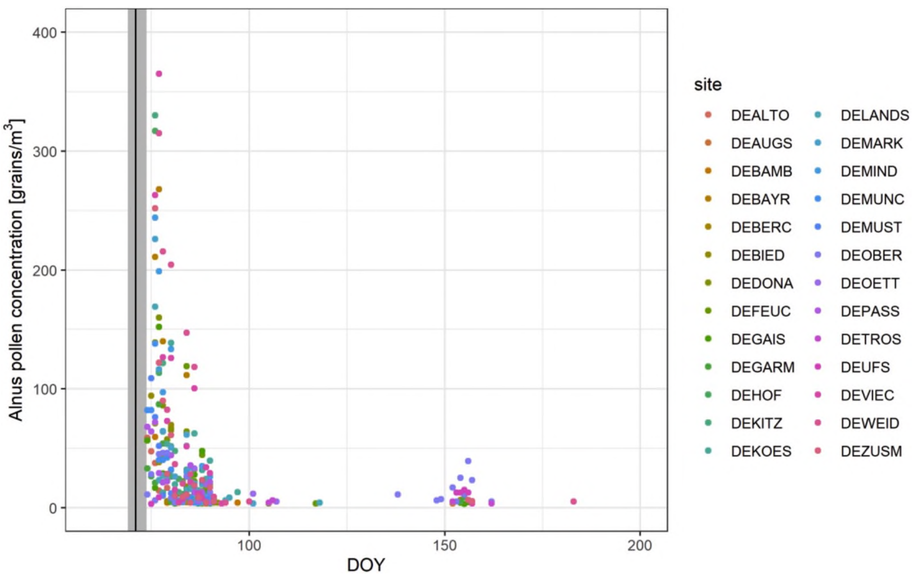

Fig. 3. Daily mean Alnus pollen concentration (grains/m^3) for the 26 sites in 2015 (only days with 3 grains/m^3 are shown). The solid vertical line and gray area show a corresponding summary of the start of A. glutinosa flowering from DWD data (the line indicates the median and the gray-shaded area represents the 25th to 75th quantiles). Colors indicate the respective sites of the ePIN network (see Table 1). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

(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/m^3. However, we opted to investigate all six days because those trajectories included more information about the whole episode.

3.3. Backward trajectory analysis

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 feature among all 10 stations is that their air masses passed over the alpine area with southwesterly and westerly winds (Fig. 4).

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/m^3) 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). During the 23 days with *A. viridis* concentrations (≥3 grains/m^3), 48% of the trajectories from these 10 sites passed over the source region; in contrast, 82% of the trajectories from the remaining 16 sites without *Alnus* pollen on episode days did not pass this source region.

3.4. Historical data of oberjoch

A review of *Alnus* pollen concentrations, measured over 23 seasons from 1995 to 2017 at Oberjoch (DEOBER), showed two peaks recorded for each year. 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 the first peak was 614 grains/m^3 in March 2006, and the maximum concentration of the second peak was 124 grains/m^3 in May 2005. Based on the daily average concentrations, the pollen season was calculated using the percentage method (5% threshold) for both peaks separately. Taking into account every 23 years, pollen concentrations for 30 days (DOY 100–130) were smaller than 3 grains/m^3. Therefore, we considered this the time separating the two peaks. The overall pollen seasons of *A. glutinosa* and *A. viridis* are from week 3–14 (January–April) and from week 19–27 (May–June), respectively.

Back trajectories were calculated for years 2005–2014 for the second peak and only for days with maxima and neighboring days with high concentrations (Fig. A1). Depending on the year, the number of depicted days in these second peak events varied from four to six days. For every year the westerly or southwesterly flows were dominating and passing over the alpine region.

4. Discussion

According to the DWD interpolation map, the start of the *Alnus* pollen season in Bavaria (March 12) is 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 (20% in total) on daily average levels of pollen data and reported that the main *Alnus* pollen season occurred from February to April. Nevertheless, 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, but the pollen seasons varied by location and altitude. In conclusion, *A. glutinosa* was no longer flowering anywhere in Bavaria in June 2015 (see Fig. 3). Therefore, 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. Since this site frequently receives well-mixed, free tropospheric air masses (Ghasemifard et al., 2019), and there is no woody vegetation, such as *Alnus* species in the close vicinity of the site (Friedmann and Korch, 2010), all measured pollen is highly expected to be far-transported to the site.

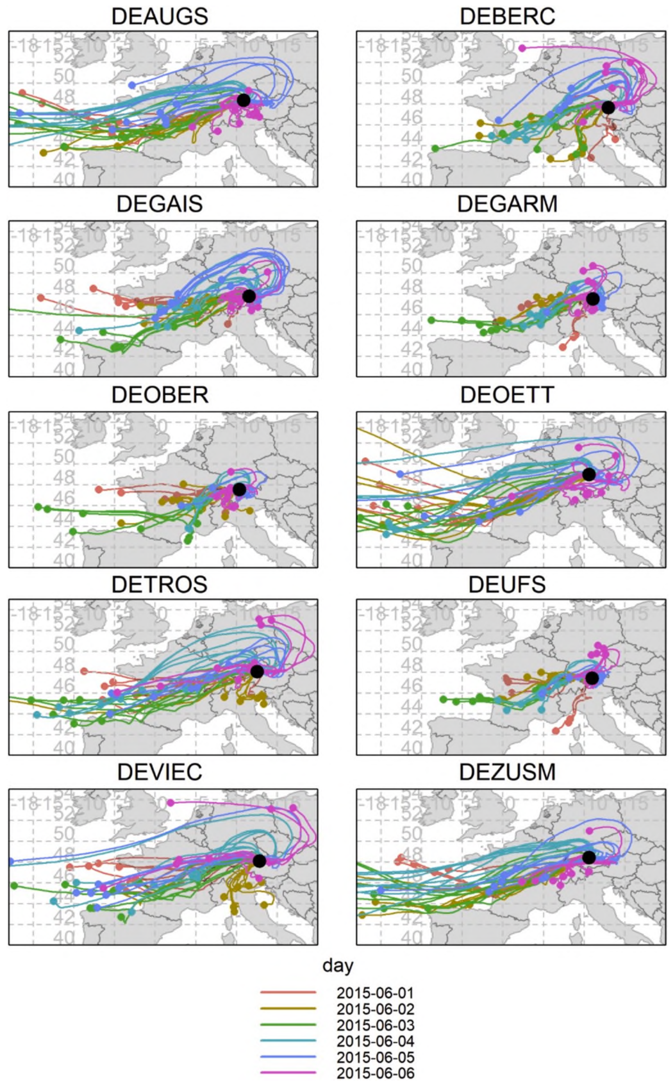

Fig. 4. HYSPLIT backward trajectories (3-h interval) of air masses reaching the pollen monitoring sites during the post-season Alnus pollen episode. The color of the trajectories shows the respective day. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

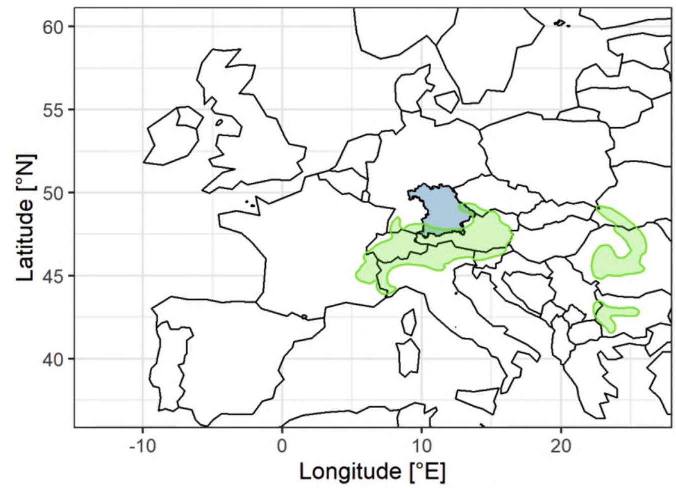

Fig. 5. Distribution map of Alnus viridis in green (Caudullo et al., 2017) and state of Bavaria in blue. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

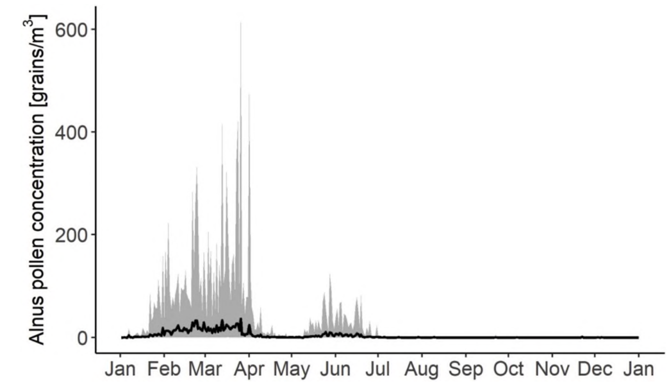

Fig. 6. Alnus pollen concentration at Oberjoch (DEOBER) for 23 monitoring years (1995–2017). Black line: daily average pollen concentration over the study period; gray color: maximum and minimum pollen concentration of each day over the study period.

According to the European atlas of forest tree species, *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. In contrast, *Alnus viridis* (Chaix) DC (green alder) is native to the cooler parts of the Northern Hemisphere; in Central 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 2015 can be attributed to *A. viridis* transported to Bavaria from the alpine region.

Investigations of long-range transport using backward trajectory showed that southwesterly and westerly flows travelled across the Alps and an area which - according to the European atlas - corresponds to *A. viridis*' distribution (Fig. 5, Caudullo et al., 2017). In the Swiss Alps, 70% of the shrub areas consist of *A. viridis*, as described in the recent survey of *A. viridis* over the alpine area (Brändli, 2010). Caviezel et al. (2017) revealed that *A. viridis* expands much faster and wider than assumed across the Alps. Thus, with future impacts of climate change and/or land-use changes these distributional areas may further be altered (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).

As shown in Fig. 5, the pollen monitoring site Oberjoch (DEOBER) is located at the edge of the species distribution and therefore being closest to this source region concentration records during the six days of the post–season episode were the largest. Air masses to Oberjoch passed over Switzerland (~28.3%), but also Austria and Italy (~13.5% and 7.3%, respectively) (see Fig. A2 in Appendix A). In order to explore the post season episode in detail, we studied the historical data of Oberjoch. From Fig. 6, 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. This air mass transportation of *A. viridis* to Oberjoch is confirmed by backward trajectories in ten post-season episodes during 2005–2014. In accordance with our results, Sindt et al. (2017) observed significant quantities of *Alnus* pollen at a French monitoring site (Annecy) in June. After a systematic investigation of *Alnus* pollen concentrations at several alpine sites, including the 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, which was specifically ascribed to off-season pollens of *A. viridis*.

5. Conclusion

Long-range transport of allergenic pollen seems to be common, at least more common than expected, and scientists need to inform allergy sufferers about which time of the year they can expect local and far-transported pollen. In this study, an integrated dataset of aerobiological, flowering phenology and species distribution data, 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 of this transport were possible due to a unique pollen dataset used in our study, both in terms of numbers of stations (26 different stations across Bavaria in the year 2015 allowing a fine spatial analysis) and of years (23 years for one station, allowing an assessment of the frequency of such far-transport events). Whereas previous long-range transport studies (e.g. for *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 optical 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, the standard method to define start and end of the *Alnus* pollen season may occasionally neglect or discard this post-season episode in June if covering less than the last e.g. 2.5% percentile. 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 which other factors may affect pollen concentrations and whether *A. viridis* from alpine areas also reaches other parts of Germany or other neighboring countries.

Moreover, the investigations should expand to other taxa as well, to check for similar patterns and, optimally, combine all these analyses with real-life allergic symptoms. In such low-exposure environments, as in the alpine, incidents of unexpected abundances or seasons of airborne pollen and fungal spores and correlation with real-life allergic symptoms of prospective dedicated human cohorts, would demonstrate the impacts of long-distance aeroallergen transport, the clinical relevance and would highlight an underestimated health risk.

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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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Homa Ghasemifard: Conceptualization, Writing - original draft, Data curation, Formal analysis, Visualization, Writing - review & editing. **Wael Ghada:** Methodology, Writing - review & editing. **Nicole Estrella:** Conceptualization, Methodology, Writing - review & editing. **Marvin Lüpke:** Visualization, Writing - review & editing. **Jose Oteros:** Data curation, Writing - review & editing. **Claudia Traidl-Hoffmann:** Data curation, Writing - review & editing. **Athanasios Damialis:** Data curation, Writing - review & editing. **Jeroen Buters:** Data curation, Writing - review & editing. **Annette Menzel:** Conceptualization, Methodology, Writing - review & editing.

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Appendix A

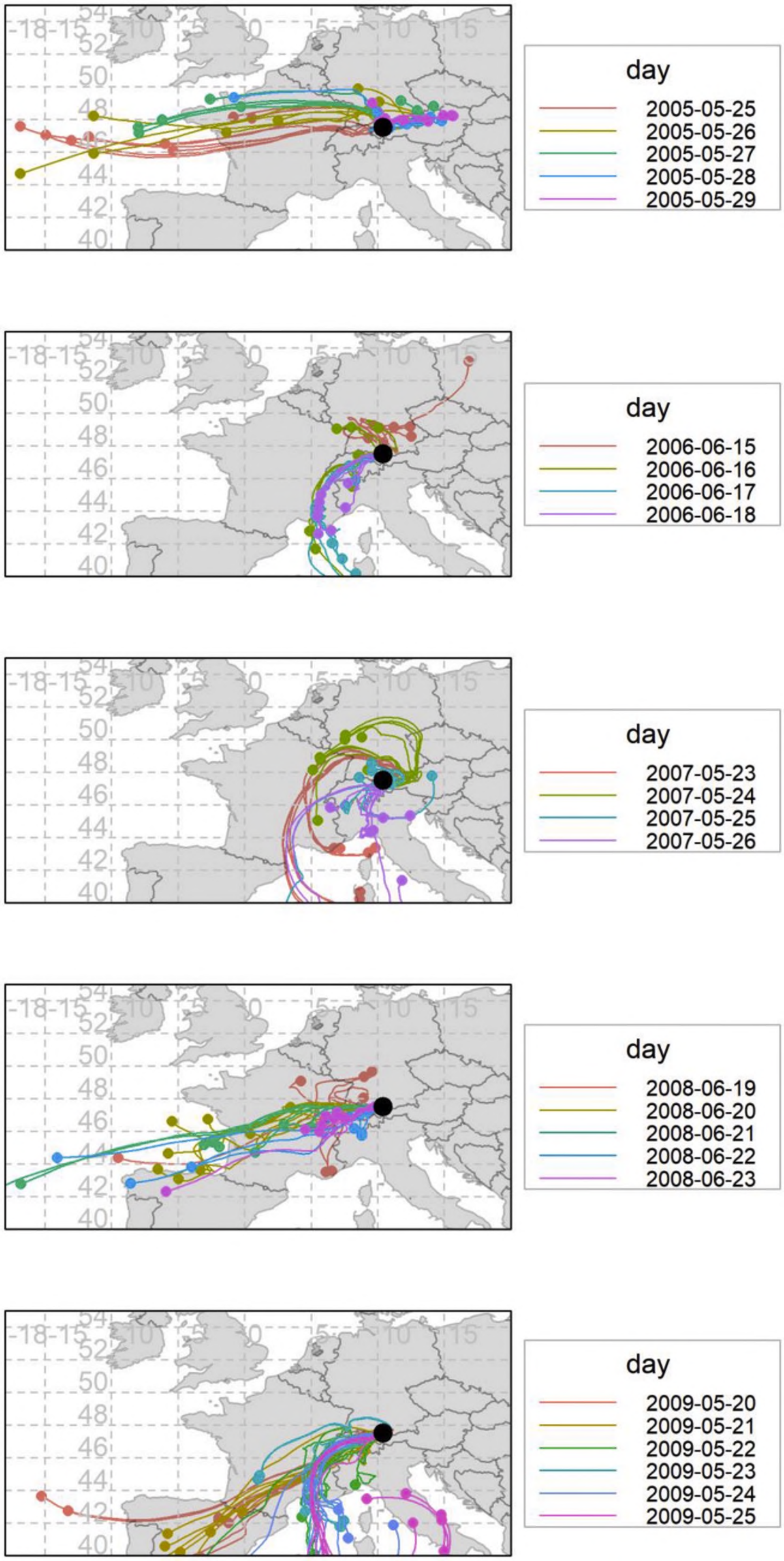

Fig. A.1. Ten years backward trajectories (2005–2014) of air masses reaching Oberjoch during the post-season episodes. Legends correspond to individual year and the color of the trajectories shows the respective day.

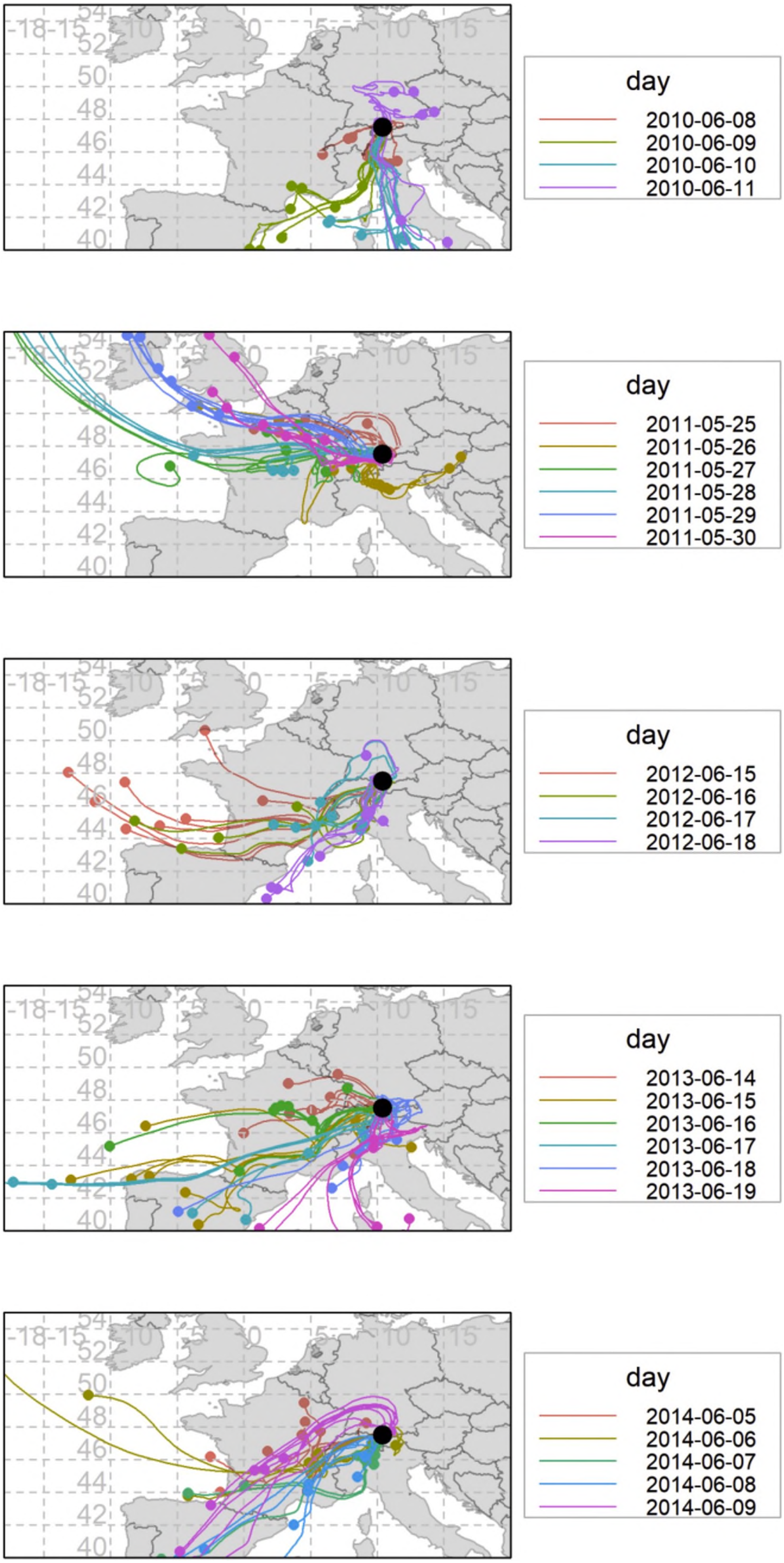

Fig. A.1. (*continued*).

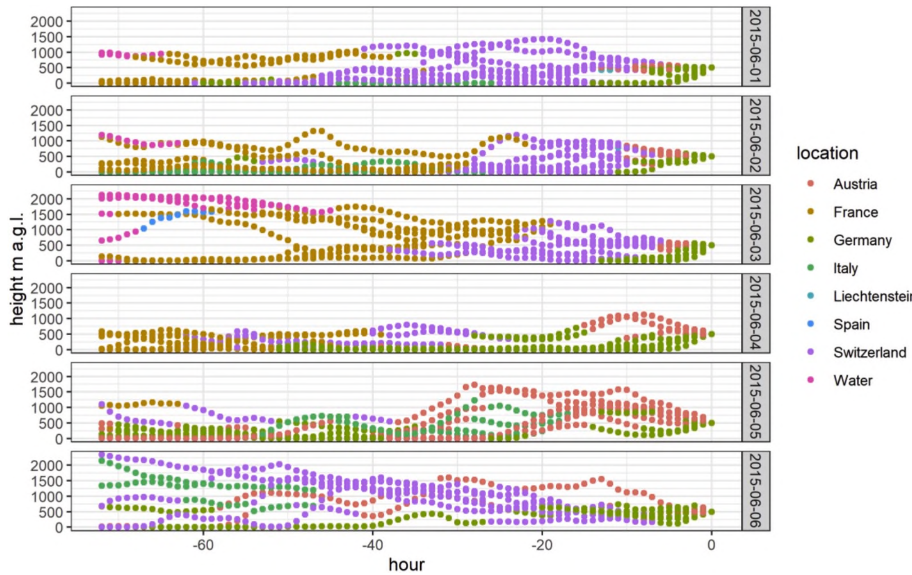

Fig. A.2. Six days (DOY: 152–157) of trajectory analysis. The height of trajectories is shown for 72 h backward. The color of the trajectories shows the respective location.

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