



# Changes in birch and tree pollen seasonal patterns due to climate change

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**Abstract** Climate change is clearly evident in Germany. Yet what changes does a 1°C increase in the annual average maximum temperature bring about in the natural environment, for example? Pollen serves as an excellent bioindicator for determining these changes. However, since pollen counts are subject to natural fluctuations, long time series are required to detect effects such as those caused by climate change. Studies in other European countries demonstrated an earlier onset of the pollen season for nearly all pollen types and found that pollen levels have increased. In Germany, data for birch pollen, for example, are currently limited. In Bavaria, an automated pollen monitoring network was established in 2019, running in parallel with existing manual monitors. For Bavaria, it is evident that pollen is appearing progressively earlier in terms of start, end, and peak dates. Compared to start dates over the past 30 years, the birch pollen season now begins approximately 1 month earlier. The amount of birch pollen has also increased in recent decades. For hazel and alder, the manual system—which has the longest data series—does not collect data in winter, resulting in gaps in pollen dispersal data and making it more difficult to detect changes. However, indicator parameters such as hazel pollen in December (normally in February) show the same pattern as for birch. In the future, however, birch pollen levels in Bavaria will decline as tree populations shrink due to climate change. Similar trends are expected for the rest of

Germany. For most people with pollen allergies, daily pollen levels—which are subject to significant natural variability—are more important than long-term trends. The new automatic pollen monitors with data available online display current pollen levels (e.g., Pollenscience.eu). Although the automatic network is not yet distributed evenly across Germany, the German Weather Service is currently expanding the network and expects to complete this by 2027.

**Keywords** Pollen · Allergy · Exposure · Germany · Automatic · Pollen monitoring

## Abbreviations

DOY	Day of the year
ePIN	Bavarian Electronic Pollen Information Network
PID	Pollen Information Service
SILAM	System for Integrated Modeling of Atmospheric Composition

## Introduction

Climate change is altering temperatures on Earth, which in turn affects precipitation, humidity, wind speed, and similar factors [1]. The rise in temperature is due to increased carbon dioxide emissions from the burning of fossil fuels, which raises the concentration of carbon dioxide in the air. The very small amount of carbon dioxide (380 ppm, parts per million) in the air has only a minor effect on atmospheric temperature. However, this increase leads to greater water evaporation. Due to its high proportion in the air, water is the most potent climate gas [2]. Carbon dioxide thus acts as a catalyst for climate change.

In addition to rising temperatures, the fact that carbon dioxide acts as an airborne plant fertilizer is also significant for the development of allergies. In Ger-

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many, allergies to house dust mites are the most common, followed by pollen-induced allergies [3]. Pollen production in plants depends on temperature, but carbon dioxide also plays an important role. When plants are fertilized, they produce more biomass, and thus more pollen. It has been demonstrated that carbon dioxide fertilizes plants, for example, in the case of strawberries in greenhouses [4], as well as for ragweed and its pollen [5].

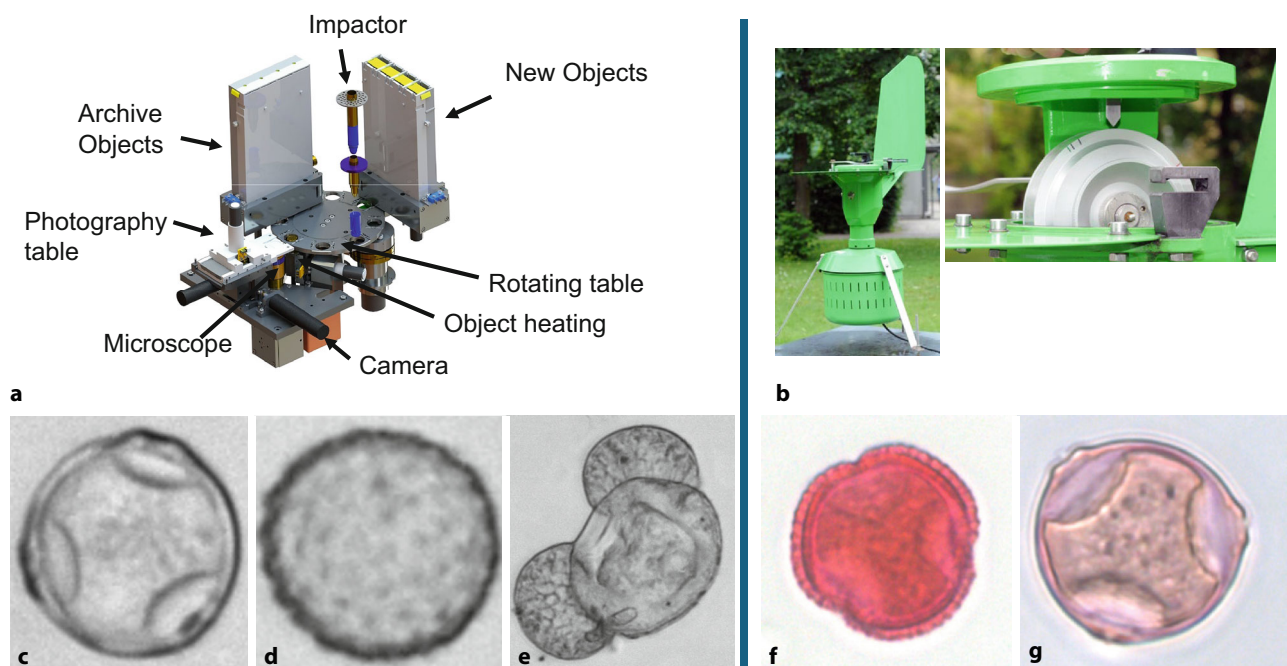
Because climate change is a slow process, long-term data series are needed to demonstrate its effects. While the physical parameters of climate change—such as meteorological data (including temperature)—are well known and clearly point to climate change in Germany, what does a 1°C increase in annual temperature mean for birch pollen dispersal, for example?

When using meteorological parameters, annual averages are typically employed. However, this makes little sense when it comes to pollen dispersal. For birch trees to release pollen, temperatures must remain sufficiently warm for a certain period at the beginning of the year; more specifically, a minimum temperature must be exceeded on a certain number of days so that the plant can accumulate heat. This is referred to as a “heat sum.” This knowledge is incorporated, for example, into pollen forecasts: Birch pollen dispersal begins when the heat sum in an area exceeds a certain value. In a commonly used forecast model (System for Integrated Modeling of Atmospheric Composition [SILAM]), the starting date is March 1, and

only daily values above 3.5°C are summed. When the sum of the daily average temperatures exceeds  $87 \pm 2.2^\circ\text{C}$ , pollen is released by the birch tree. The same applies to the maximum daily pollen concentration (peak) and to the end date of the pollen season, each with different temperature values. Other meteorological values also play a role, but temperature is the dominant factor.

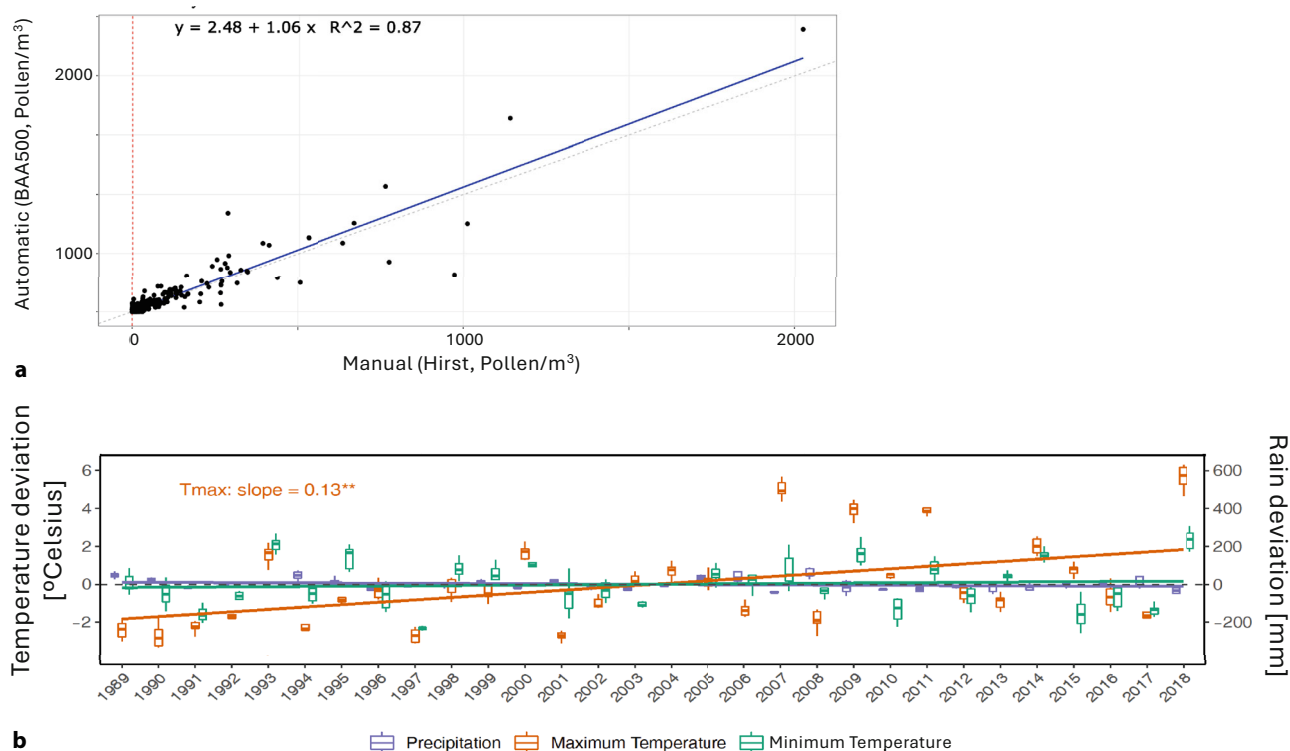
In Bavaria, we showed that while the annual average temperature has risen over the past few decades [6], the increase in March and April was particularly significant (see Fig. 2b). In April, a temperature jump of about 4°C can be observed over the years, whereas the increase over the entire year is about 1°C with consequences for future birch tree distribution [7]. This means that annual averages do not reflect the effects that are important for nature, as they are too coarse and, after all, only averages. To assess this effect, the relevant parameters must be determined. Pollen counts are one such (bio)-indicator of climate change.

In Germany, pollen in outdoor air is measured both manually (using traditional methods) under a microscope and automatically through artificial intelligence (AI)-based analysis of pollen images (see Fig. 1). A Europe-wide comparative analysis showed that modern automatic pollen monitors provide data similar to those obtained with manual methods (see Fig. 2a; [8]). The number of automatic pollen monitors has steadily increased. While in 2015 there was only one automatic pollen monitor in Europe (in Munich), there are now nearly 100 (see Fig. 3a). Ger-



**Fig. 1** Pollen counting instruments: **a** automatic (BAA500 by Hund GmbH), **b** manual (Hirst-type by Burkhard). Both are impactors, meaning that the pollen grains are propelled onto an adhesive strip by the velocity of the suction airflow, and subsequently analyzed under a microscope. **c** Birch pollen,

**d** ragweed pollen, **e** pine pollen (has two air sacs in its structure), **f** olive pollen (note the fine network on the exine), **g** hazel pollen. The pollen images are shown to demonstrate the higher resolution of the manual trap, although high resolution is not necessary for automatic AI image recognition



**Fig. 2** **a** Comparison of manual and automatic pollen data. The value for the manual traps is the average of four traps operating simultaneously, to compensate for errors in the manual traps. The two measuring instruments show good agreement; however, it is unknown which device displays the correct values, since there is no calibration for pollen-measuring devices using known pollen concentrations per  $\text{m}^3$ . Work on this calibration is underway in the EU project

BioAirMet. The data are available in interactive form at [https://autopollen.shinyapps.io/APP\\_AUTOPOLLEN\\_COMPARE/](https://autopollen.shinyapps.io/APP_AUTOPOLLEN_COMPARE/) (accessed in March 2026). **b** Climate change in April during the pollen season. In Bavaria, rainfall and minimum temperatures have changed little over the past 30 years, but the maximum temperature in April shows the greatest difference compared to other months (not shown). Adapted from Rojo et al. 2021 [6]

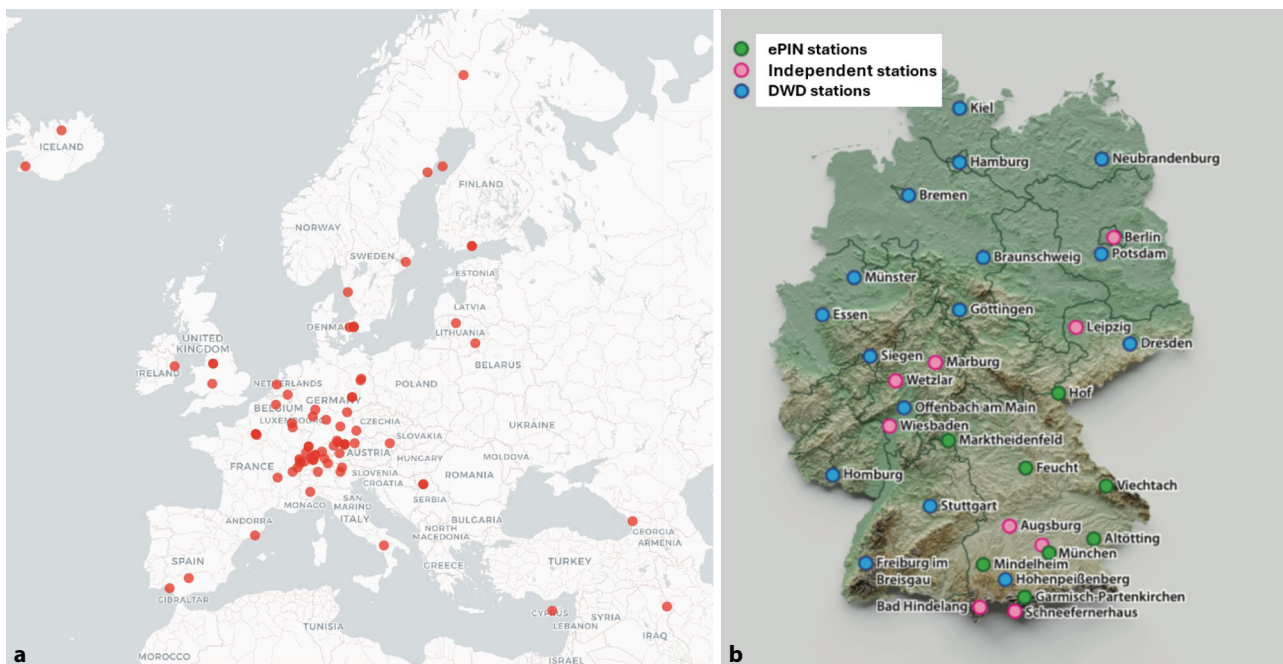
many is particularly well-positioned in this regard, as in addition to the automatic monitors in Bavaria and the individually operated automatic monitors, the German Weather Service is currently establishing a nationwide network (see Fig. 3b).

Pollen dispersal is not regular, a phenomenon linked not only to rainfall during the pollen-blooming season but also to weather conditions during pollen maturation. So-called mast years are also well-known, meaning that a year with high pollen counts is followed by a year with low pollen counts, as has been demonstrated for birch [9], a phenomenon likely linked to the North Atlantic Oscillation [10]. Unfortunately, this phenomenon occurs regularly only in certain areas, such as Scandinavia; in Germany, specifically in Bavaria, years with high or low pollen counts are highly variable and do not follow a pattern (see Fig. 4d). The effect of climate change on birch pollen dispersal must therefore be analyzed against the background of natural variability. This requires long time series. Since pollen dispersal monitoring is not a public responsibility, pollen dispersal data are only available to a limited extent ([www.pollenstiftung.de](http://www.pollenstiftung.de), accessed in March 2026). However, some federal states have established pollen count monitoring as

a public responsibility starting in 2019 [11, 12]. These data are publicly available and were utilized.

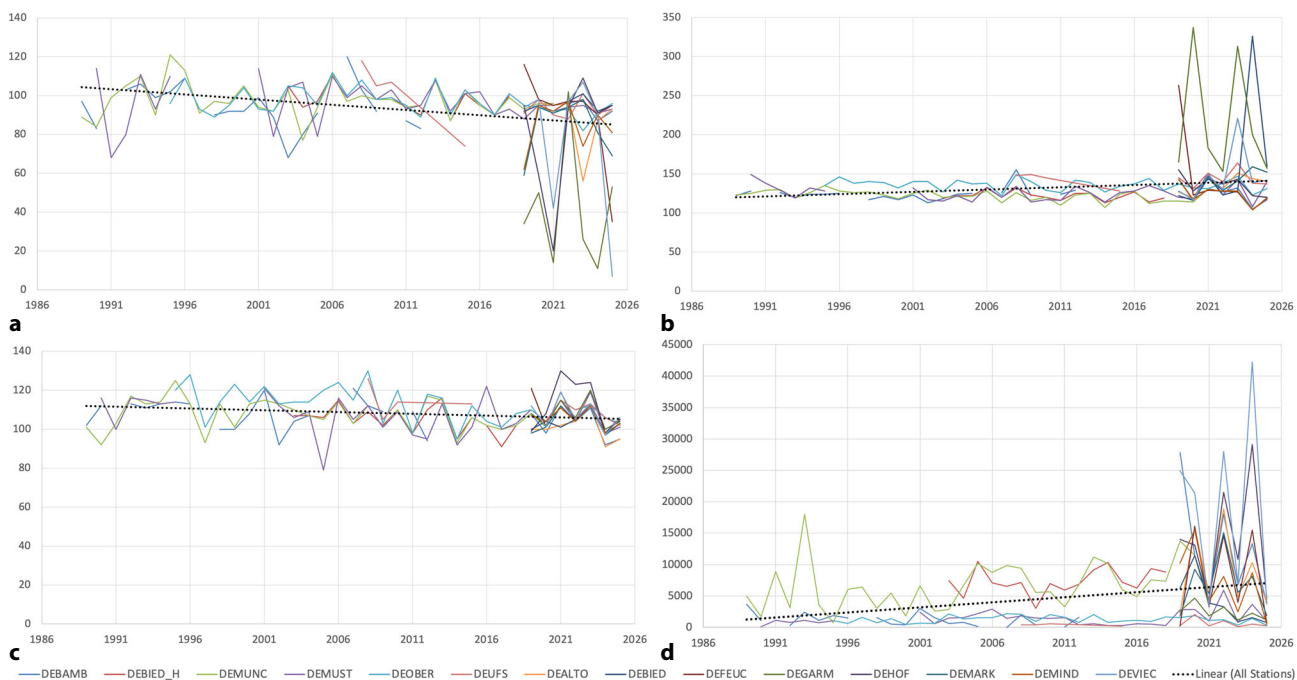
### Climate change and birch pollen season in Germany

This article analyzes birch pollen counts, as there are sufficient data for birch pollen but fewer data for other early-blooming plants. Since pollen does not circulate in the winter, many manual pollen traps are put into winter mode. This was also the case initially with the automatic pollen monitors (continuous measurements did not begin until 2024). There are good practical reasons for this, as manual pollen traps are usually mounted on rooftops (over 12m; [13]) and staff must replace the samples in the snow. The low or even absent pollen count does not justify the effort or the danger involved in changing the collection drums in winter. The winter break, usually from late October to February, is redefined each year by the Pollen Information Service (PID). According to historical data, hazel typically blooms in February/March. However, due to climate change, the blooming period appears to be shifting, and hazel pollen is occasionally detected in December, more frequently in January (dur-



**Fig. 3** Automatic pollen monitors in Europe (a) and Germany (b). While all monitors in a are already in operation, the blue dots in b will not be activated by the German Weather

Service until 2027 (the other colored dots are already in operation). In 2015, there was only one red dot on both maps, located in Munich [42]



**Fig. 4** Changes in birch pollen dispersal over time in southern Germany. a Start date, b end date, c date of seasonal peak, d pollen index (annual sum of birch pollen). All data are displayed; however, only stations with >7 years of data

were used for the linear regression calculation (see Table 1). DEBAMB (Bamberg) to DEVIEC (Viechtach) are the different monitoring stations

ing the winter break). The same applies to alder, with a time lag. This is why the winter data are incomplete. Interestingly, early-blooming plants react most strongly to climate change. Thus, the measurement parameter “days of pollen dispersal in December” is a good indicator for describing climate change [14]. Data on year-round pollen dispersal have only been available since the introduction of automatic monitors, and even then, only since 2023, which makes it difficult to conduct an analysis due to incomplete data. This is not the case with birch, however. Since it is also an early-blooming species, observations of birch can be taken as representative of other early-blooming species such as hazel and alder.

Figure 4 presents the available data. Despite the natural variability in birch pollen counts, it is clear that the number of birch pollen grains has increased over time. This finding has already been published: Pollen counts in Munich have increased over a 30-year period [15]. However, since the data come from only one station, the effect could also be attributable to conditions specific to that area, such as new plantings in the vicinity of the station. When data from other monitoring stations are included, however, the same pattern emerges: The birch pollen index has been rising over the years in southern Germany. The start date of birch pollen season (DOY, day of the year) is also occurring earlier; in other words, birch pollen season is beginning progressively earlier in the year. The start date is the more robust indicator of climate change, since the measured pollen count (number) in outdoor air depends not only on the flowering of the species but also on the location of the monitoring station [13], whereas the start date depends solely on the

presence of pollen on a specific day. The amount of pollen in outdoor air is irrelevant for the start date, and the values are easily comparable across monitoring stations. Combined with the finding that higher pollen levels cause more symptoms [16] and are correlated with increased sensitization (see below), this raises concern for people with birch pollen allergies.

Figure 4 shows the trends in key indicators of birch pollen dispersal in southern Germany over the past 30 years. With such long time series, a recurring challenge is that not all data are available. This is also the case with pollen: Some stations have long time series, while others have shorter ones. In addition, the system switched to automatic pollen monitoring in 2018, which has led to more pollen measurements. Furthermore, it cannot be ruled out that the change in measurement methodology (from manual to automatic) has led to differences in the measured pollen concentrations. The comparison of the average values from six manual traps with those from six manual plus eight automatic traps should therefore be interpreted with caution. Although the transition from manual to automatic measurements was documented through simultaneous measurements with both instrument types, some bias may still have been introduced. However, this is not the case if each data point is analyzed individually using the same method. In this study we used the trend lines of each individual station, thereby circumventing this problem. A trend line indicates, for example, whether the number of pollen grains has increased, regardless of the exact number of pollen grains.

Significant differences are evident in the trend lines. Regardless of which parameters are considered, most

**Table 1** Statistical parameters of birch pollen dispersal. A trend line was fitted for each station for every birch pollen data series spanning more than 7 years. The slope of the curve indicates the extent of change over time and whether this change is statistically significant ( $p < 0.05$ ). Not all stations show an increase in pollen count or an earlier start, end, or peak date. However, in almost all cases, birch pollen season starts significantly earlier, reaches its peak earlier, ends earlier, and there is more pollen per year.

Station	Number of years		Start		End		Peak		Pollen index	
			Slope	$p$	Slope	$p$	Slope	$P$	Slope	$p$
DEBAMB	28	Manual	-0.10	0.41	-0.06	0.84	-0.24	0.09	327	0.04
DEBIED	16	Manual	-0.44	0.39	-0.35	0.42	-0.61	0.12	122	0.44
DEMUNC	33	Manual	-0.11	0.71	-0.32	0.01	-0.09	0.39	109	0.02
DEMUST	32	Manual	-0.13	0.04	-0.06	0.82	-0.23	0.06	32	0.56
DEOBER	31	Manual	-0.24	0.11	-0.18	0.21	-0.46	0.01	-1	0.97
DEUFS	11	Manual	-1.00	0.19	-0.13	0.59	-0.56	0.14	7	0.64
<i>Average</i>	<i>25</i>	<i>-</i>	<i>-0.34</i>	<i>-</i>	<i>-0.18</i>	<i>-</i>	<i>-0.36</i>	<i>-</i>	<i>99</i>	<i>-</i>
DEALTO	7	Automatic	1.61	0.88	3.39	0.37	-0.79	1.00	-233	1.00
DEBIED	7	Automatic	0.43	0.55	18.29	0.07	0.32	0.76	-1409	0.02
DEFEUC	7	Automatic	-9.18	0.02	-16.86	0.07	-2.14	0.37	22	1.00
DEGARM	7	Automatic	-0.32	1.00	-6.00	0.76	-0.39	0.76	-345	0.23
DEHOF	7	Automatic	5.46	0.65	-4.18	0.10	-0.18	1.00	358	1.00
DEMARK	7	Automatic	0.39	1.00	3.93	0.23	0.25	0.88	-69	1.00
DEMIND	7	Automatic	1.04	1.00	-3.68	0.18	-0.82	0.45	-1589	0.13
DEVIEC	7	Automatic	-7.57	0.55	5.64	0.23	-1.14	0.76	-656	1.00
<i>Average</i>	<i>7</i>	<i>-</i>	<i>-1.02</i>	<i>-</i>	<i>0.07</i>	<i>-</i>	<i>-0.61</i>	<i>-</i>	<i>99</i>	<i>-</i>

stations show the same pattern: The start of the birch pollen season is occurring progressively earlier, closer to winter; the peak pollen count and the end of the birch pollen season are also being reached increasingly earlier. While there are exceptions, the overall picture is the same across all time parameters (see Table 1). Birch trees are blooming earlier. How much earlier? About 1 month earlier than 30 years ago. For a climate change effect on nature, this is a rapid change.

The impact of climate change on the amount of pollen is more difficult to assess. Regardless of whether there was a lower or higher level of pollen in the air in a given year, the date of the maximum value remains unchanged. Due to mast years [17], i.e., years with high pollen production followed by years with less pollen, the picture regarding pollen counts is even more variable than for the parameters of start, end, and maximum values for DOY. Nevertheless, these data also show that the total amount of birch pollen released per year has increased (see Fig. 4 and Table 1).

Ziska et al. demonstrated that birch pollen production in the United States increases as temperatures rise (due to climate change). This has also been observed in Europe and Scandinavia [18]. Data from Switzerland and other countries and locations confirm these findings [19–21]. The number of publications on birch in Germany is low and is based on individual observations [15]. In Bavaria, we demonstrated that the climate is shifting toward a more continental character [6]. The consequences of climate change are that almost all pollen types (including birch pollen) are present earlier in the year, pollen dispersal has become more intense over the years, and the season ends earlier. The same is expected for the rest of Germany. For example, in northern Germany, studies have shown that climate change has reduced the distribution of beech trees [22], although pollen levels from beech pollen have not (yet?) decreased at the same time [23].

It is well known that allergies are on the rise. But does the increase in pollen levels also have an effect on allergic sensitization? A study in Italy demonstrated that ragweed pollen levels and allergic sensitization to this pollen have increased simultaneously over the years, while sensitization to house dust mites has remained stable in the same region [24]. In Legnano, northern Italy, a comparison with Lugano, Switzerland, also showed that ragweed pollen levels in Lugano increased only slightly over time, as Swiss legislation requires the eradication of ragweed plants [25]. Ragweed pollen levels and sensitization rates barely increased in Lugano (Switzerland) over a period of about 10 years [26]. By contrast, ragweed was not controlled on the Italian side of the border, and thus ragweed pollen levels in Legnano, Italy, increased, and years later, so did the rate of ragweed sensitization [27]. Similar observations were made in

the United States: Increased ragweed pollen dispersal led to higher sensitization rates [28].

These examples show that higher pollen levels not only cause more symptoms [16], but also lead to increased allergic sensitization: Changes in exposure have consequences. This has not yet been investigated for birch, although exposure to birch pollen is increasing toward the north and, at the same time, sensitization to birch pollen allergen is also rising [20]. It can therefore be assumed that the increase in birch pollen dispersal caused by climate change will lead to more allergic symptoms but also to more sensitizations. Whether this increase in sensitization to birch pollen will be significant, given the already considerable number of people sensitized to birch pollen in Germany, has not been assessed [3].

There are several other reasons why the population is becoming increasingly allergic, and it is not only due to an increase in pollen counts [29]. Nevertheless, the rise in allergens is a cause for concern for (future) people with birch pollen allergies.

### Allergenicity of birch pollen

Pollen, such as birch pollen, is not itself an allergen; rather, it carries an allergen that is released upon contact with mucous membranes. This allergen then causes allergic symptoms. It is also noteworthy that there are birch pollens that contain hardly any allergens [30]. This means that not only the amount of birch pollen in the air, but also the allergen content per pollen grain, is relevant to allergy symptoms. For example, a study in London showed that the amount of pollen allergens in outdoor air correlated more strongly with allergy symptoms than the sheer number of pollen grains in the air [31]. Even with birch pollen, there is a roughly tenfold difference in allergen potency (corresponding to the allergen per pollen particle) in Germany [32] as well as across Europe [33]. The amount of allergen released also varies from year to year, from day to day, and depending on where the pollen comes from. The reason why pollen varies in potency is well understood and depends on the interaction of two factors.

1. Pollen matures inside the anthers, producing increasing amounts of the allergen Bet v 1 over time [34].
2. Catkin maturation follows a different pattern from that of pollen. Pollen release depends on humidity. Dry air causes the catkins to open more quickly, for example, when pollen maturation has just begun and allergen production has been low.

Thus, when the weather is good, catkins may release birch pollen early, resulting in pollen that is less potent than when the environment is humid (bad weather), during which the pollen continues to mature inside the catkins and is released later, making it more po-

tent. In addition, birch pollen also responds to climate change during its maturation [35].

It would be desirable to measure allergen levels in outdoor air in order to better inform patients; however, high costs currently prevent this. Although pollen counts are still mostly determined manually, they are increasingly being measured by automatic pollen monitors. This has significant advantages, because:

- a. Pollen count data are available in real time (with a delay of about 4.5 h).
- b. The data are available online for everyone and are free of charge.
- c. Because all automatic pollen monitors in Germany use the same algorithm for pollen classification, they maintain consistent data quality. Even when errors occur, they are usually known and consistent across all devices, meaning they are systematic. Errors such as misclassified pollen types can be verified using the pollen images on the website <https://validation.pollenscience.eu> (accessed in March 2026).

The manual system has advantages, which is why, for example, some manual pollen traps continue to operate in Bavaria alongside the automatic monitors. The images from manual microscopes are clearer, different sections of the specimen can be examined, and humans are more flexible in interpreting images than machines are. Humans can provide better information in cases of doubt (see Fig. 1) and can identify newly emerging pollen types as well as artifacts. On the other hand, there are disadvantages to the manual system [36]:

- A delay in data delivery of (usually) 1 week
- Instrument errors during sampling (variable flow rate [37]; sensitivity to wind and temperature [38], etc.)
- Variability between pollen counters [39]

When the manual system was introduced in 1952, the then-new volumetric method represented a major step forward [40]. The new automatic instruments are the next step in development and therefore offer certain advantages (see above). More and more automatic systems are being installed in Europe: While there was only one BAA500 automatic pollen monitor in Munich in 2015, that number will increase to about 30 in Europe by the end of 2027 (Dr. Stephan Gilge, personal communication; see Fig. 3). This development speaks volumes about the usefulness of automatic pollen monitors.

The transition from manual to automatic pollen monitoring is already well underway, whereas moving to airborne allergen measurements is still awaited. However, the process from manual to automatic pollen monitoring is costly and time-consuming. Many users have already observed a strong correlation between pollen counts and allergic symptoms. It

therefore makes sense to establish a reliable pollen forecast service using “simple” methods (i.e., counting airborne pollen) that are sufficiently accurate for allergy sufferers in practice, rather than waiting until an even better—but also more expensive—method (allergen measurement in ambient air) becomes available. Automatic monitoring of the substitute parameter pollen counts for allergen exposure makes sense.

Germany, together with Switzerland, is a European pioneer in the automation of pollen traps, as both countries have already established operational networks of automatic pollen monitors—the first of their kind worldwide.

Since the data are available online free of charge, they can also be used to study the effects of climate change. Although the data series spans only 8 years, which is a short period for statistical analysis, an attempt is made here, given the large number of monitors already in place (see Table 1).

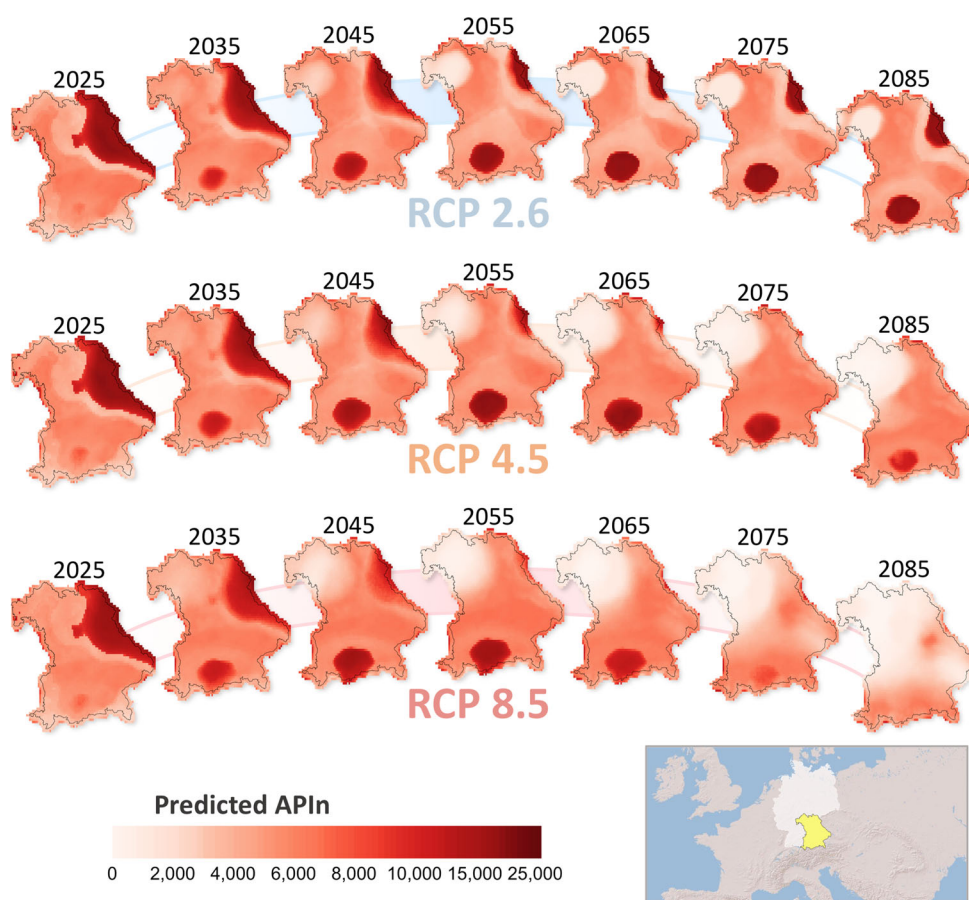
### The future of birch pollen season in Germany

As with stocks, past performance is no guarantee of future results. It is scientifically invalid to extrapolate a past trend into the future. Instead, one must identify the factors that influence birch pollen production—and thus future pollen levels—in order to model them [7].

A study from the United States shows an increase and shift in exposure to pollen species in the future [41]. A limitation of the study is that it models the effects of climate change on existing populations of plant species, which release varying amounts of pollen depending on climate change. The changes in the distribution of the plants themselves caused by climate change are not modeled.

However, it is necessary to determine not only the effect of climate change on birch pollen production, but also how the birch trees themselves respond to these climatic factors (drought, temperature, length of winter, etc.). Even if climate change causes the trees to produce more pollen, the overall birch pollen load will decrease if the number of birch trees declines. These complex calculations are rarely performed, but for birch trees in Bavaria they showed that the birch pollen index (total pollen count over a pollen season) will decrease in the future (see Fig. 5). The largest amount of birch pollen is produced in the Ural Mountains, and Germany lies on the edge of the birch tree’s range. This also means that peripheral regions such as Germany will be most severely affected by climate change. In the core region of the birch, conditions are optimal, and thus the plant is in the “green zone” and can withstand changes. In the peripheral regions, conditions for the plant are more strained, and as a result, even temporary changes can lead to extinction of the species. In Bavaria, models have shown that birch pollen levels will decline in the future, particularly due

**Fig. 5** Modeled future distribution of birch pollen in Bavaria through 2075. Depending on the climate model, the environment for birch trees is changing at a slower or faster rate. According to all climate models, the distribution of birch trees—and thus the level of birch pollen exposure—will decrease. While individual trees will release more pollen due to climate change, there will be fewer birch trees overall. RCP 2.6 assumes a modest increase of CO<sub>2</sub> and thus temperature, while RCP 8.5 assumes a “worst-case” scenario. Adapted with permission from Rojo et al. 2021 [6]. We assume that the findings will not differ across the rest of Germany. RCP representative concentration pathway



to a decline in the birch tree population (extinction; [6]). The same is expected across the rest of Germany.

## Conclusion

The data show that, in southern Germany, the birch pollen season begins earlier and ends earlier, and that there is more birch pollen than in the past. In the future, however, birch pollen levels will decrease. This would be good news for people with birch pollen allergies! However, the rate of climate change (RCP2.6 or another scenario) will determine when birch pollen levels will start to decline. Unfortunately, this does not apply to grass pollen. In this case, grass species that are better able to tolerate changing conditions are expected to become dominant, leading to an increase in grass pollen levels as a result of climate change [7].

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**Data Availability** To obtain a homogeneous pollen dataset, the original ePIN data since October 2019 were reanalyzed within the project “Optimization of ePIN: Pollen Forecasts and

Software Adaptation (ePIN-Opt)” using the AI-based image recognition software (S1.37S0.3C3.0) currently in use. ePIN-opt is part of the joint project “Climate Change and Health” (VKG) in Bavaria. The VKG is funded by the Bavarian State Ministries of Health, Care, and Prevention (StMGP) and of the Environment and Consumer Protection (StMUV).

## Declarations

**Conflict of interest** J. Buters, C. Schmidt-Weber, I. Wessels and M. Suarez-Suarez declare that they have no competing interests.

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