

ORIGINAL ARTICLE

Indoor birch pollen concentrations differ with ventilation scheme, room location, and meteorological factors

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Abstract

Indoor pollen concentrations are an underestimated human health issue. In this study, we measured hourly indoor birch pollen concentrations on 8 days in April 2015 with portable pollen traps in five rooms of a university building at Freising, Germany. These data were compared to the respective outdoor values right in front of the rooms and to background pollen data. The rooms were characterized by different aspects and window ventilation schemes. Meteorological data were equally measured directly in front of the windows. Outdoor concentration could be partly explained with phenological data of 56 birches in the surrounding showing concurrent high numbers of trees attaining flowering stages. Indoor pollen concentrations were lower than outdoor concentrations: mean indoor/outdoor (I/O) ratio was highest in a room with fully opened window and additional mechanical ventilation (.75), followed by rooms with fully opened windows (.35, .12) and lowest in neighboring rooms with tilted window (.19) or windows only opened for short ventilation (.07). Hourly I/O ratios depended on meteorology and increased with outside temperature and wind speed oriented perpendicular to the window opening. Indoor concentrations additionally depended on the previously measured concentrations, indicating accumulation of pollen inside the rooms even after the full flowering period.

KEYWORDS

air temperature, *Betula*, indoor pollen concentration, indoor/outdoor ratio, ventilation, wind speed and direction

1 | INTRODUCTION

Allergic diseases are posing a major risk for human health implying substantial effects on human well-being and economic costs.¹ In Germany, for example, 15% of the population suffers from hay fever.² One of the most important allergenic tree species is birch (*Betula*), a typical pioneer plant that starts reproducing in very young age and as an anemophilous plant, it produces high amounts of pollen.

Airborne pollen monitoring is achieved on flat roofs of buildings to capture the background pollen concentrations not influenced by local plant abundance.^{3,4} However, people rather stay at ground level and

most importantly—not outside but inside houses. It is estimated that people in Europe and America spend more than 90% of their time indoors.^{5,6} Thus, indoor pollen concentrations are of major importance, not only for allergic people but also for children, because it is known that indoor allergen exposure is a major risk factor for sensitization during the first 3 years of life.⁷ As there is a relationship between personal allergen exposure and incidence of asthma, allergic rhinitis, allergic conjunctivitis, and eczema, there is also a strong need to focus on the authentic pollen conditions human beings are subjected to. Avoiding the exposure to aeroallergens, adapting the individual behavior, and starting medication proportionately and timely require

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detailed information of the indoor pollen concentrations that have the more meaningful influence on humans compared to outdoor or even background pollen concentrations.

Although there are a few studies on indoor pollen or mold spores,⁸⁻¹⁶ there is still a need for a comprehensive study that combines outdoor concentrations on rooftop level, ground level as well as indoor concentrations.¹⁷

Most of the studies reported decreased values of pollen concentration inside buildings, but some studies also showed that these concentrations were not correlated with outdoor levels (eg, Ref. 12). O'Rourke and Lebowitz¹¹ stated that atmospheric transport plays a negligible role for indoor pollen concentrations and identified feet and bodies of people and animals as main vectors. The great influence of pollen transport into houses via clothing was also supported by Jantunen and Saarinen.¹⁸ Furthermore, indoor pollen concentrations were found to increase when rooms were more frequently accessed and outdoor activities of people were higher.^{8,9} Equally for birch pollen antigens in dust, it has been suggested that they are carried indoors via footwear and clothes.¹⁹

However, there is a lack of knowledge about how meteorological parameters are able to influence the indoor concentration of pollen in relation to its outdoor concentration. We additionally realize that little is known about differences caused by different ventilation schemes. A deeper understanding of the influence of window ventilation will allow a better adaptation of the individual behavior.

Therefore, this study aimed to answer the following questions:

- Is there a significant correlation between outdoor and indoor pollen concentrations?
- Will indoor pollen concentrations and indoor/outdoor ratios change under different ventilation schemes and room locations?
- How do meteorological conditions, especially wind direction, influence the number of floating pollen in indoor air?

2 | MATERIAL AND METHODS

2.1 | Study site and rooms

The study was conducted inside and outside the forest faculty building of the Technical University of Munich at Freising, Germany (48°24'N, 11°45'E). The three-story building is situated at the western edge of the green campus area on which agricultural fields and forests border. The edifice itself is surrounded by extensively managed meadows, hedges, and groups of trees comprising different species, including some birch (*Betula pendula* Roth) specimen (Figure 1). Indoor (I) and outdoor (O) concentrations of birch pollen were assessed for five rooms in the building: three office rooms, one large combined laboratory/seminar room, and one small laboratory room (Table 1, Figure 1). Ventilation schemes and other properties of the rooms are listed in Table 1. All rooms have a central heating system with heating elements under the windows.

In all rooms, the windows were opened for starting and stopping the respective outdoor personal pollen samplers (see section Pollen

Practical Implications

- The assessment of indoor pollen is crucial for human well-being as people stay most of the day inside buildings. Although restricted to one season and five rooms, our study demonstrated that outdoor pollen concentrations varied with room location and that weather and ventilation schemes strongly influenced indoor/outdoor ratios. In addition to the wise choice of room location and adopted ventilation, for example, intermittent opening of windows if wind is not blowing perpendicular to the window, regular cleaning of rooms is generally recommended for pollen avoidance. Epidemiological studies should rely on perceived indoor pollen concentrations in addition to background pollen concentration at rooftop level.

monitoring) which were placed on the window sills. Windows were closed at the end of the day. All five rooms, especially the office rooms, were frequently entered by co-workers, students, and the regular users. All sampling days except the first one (April 19, 2015, DOY 109) were working days. Thus, the experimental conditions were in accordance with real-life situations. The rooms *East-Tilt* and *East-Vent* lie directly next to each other; one tall birch tree that was flowering during the measurements is situated right in front of their windows.

2.2 | Pollen monitoring

Indoor pollen and outdoor pollen were collected with 10 personal volumetric air samplers (Burkard Manufacturing Co. Ltd., Rickmansworth, UK) on 8 days (April 19th till 24th, April 27th, April 29th or DOY 109-114, 117, and 119) during the birch pollen season 2015. In each of the five rooms, one sampler was placed on a desk at 1.2 m height corresponding to the inhalation height of humans sitting on a chair and in 2.5 m distance from the window, and a second one at the window sill, which corresponds to a height of 1.0 m above room floor for *North-Open* and *South-Open*, and 0.65 m for the other rooms (Figure 2A,B). The samplers are based on the Hirst principle,²⁰ and measurements should represent indoor conditions adequately. Air is aspirated at 10 L min⁻¹ through a vertically oriented intake, and pollen is deposited on microscope slides that are coated with white and pharmaceutical Vaseline (Molyduval). Microscope slides were inserted every second hour for 60 minutes during 8 AM and 7 PM, resulting in six measurements per day (8-9 AM, 10-11 AM, 12 AM-1 PM, 2-3 PM, 4-5 PM, and 6-7 PM). In total, the sampling campaign resulted in 480 pollen samples of which five had to be discarded due to failure in the sampling. To prepare permanent samples, we applied a mixture of distilled water, gelatine, gelvatol, and safranin (staining) to cover slips and fixed them to the microscope slides. The edges were sealed with common transparent nail varnish. Samples were assayed under a light microscope at 400× magnification (Axio Lab. A1 connected to a Motic Moticam 3, 3.0 MP; Zeiss Microscopy GmbH, Jena, Germany).

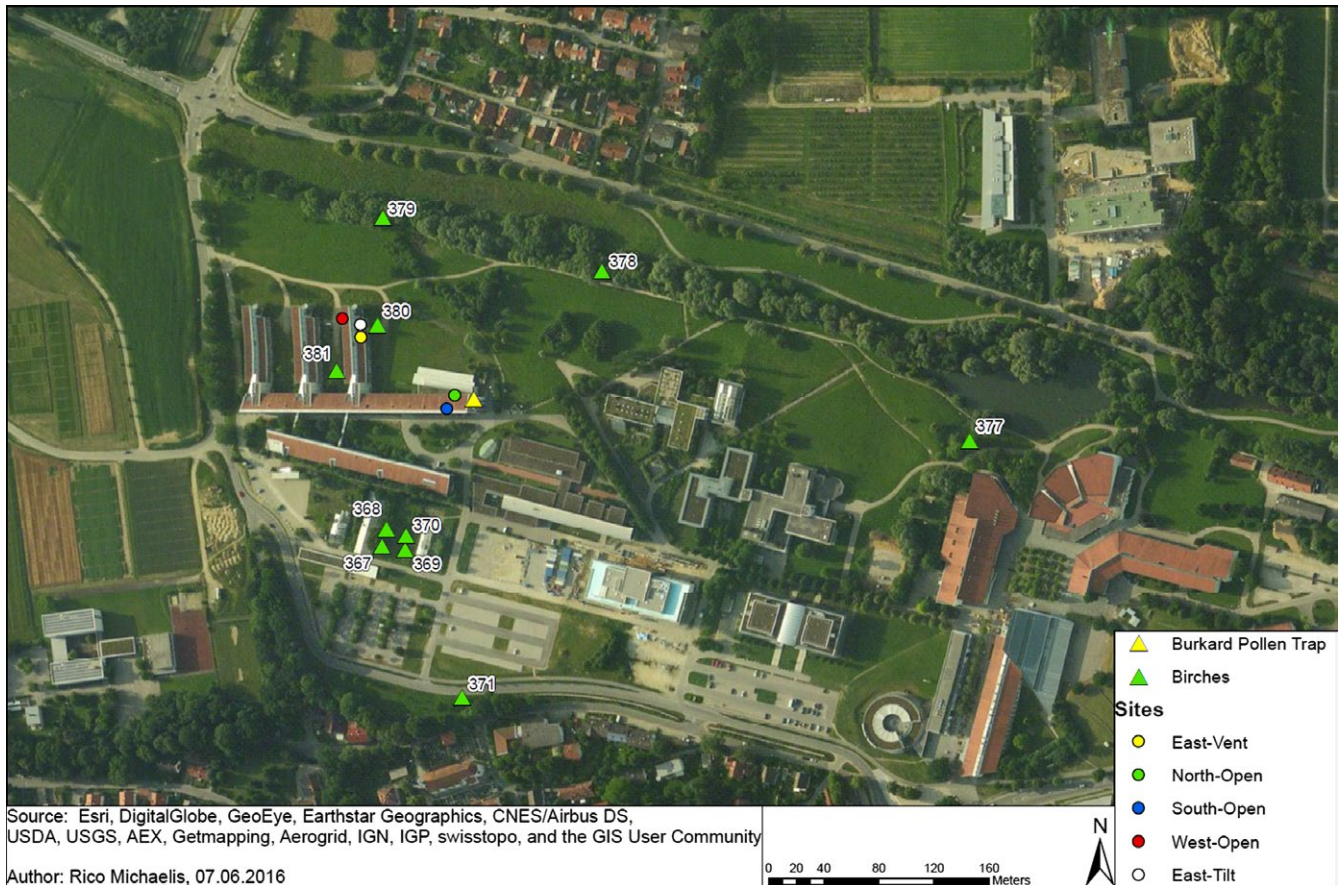


FIGURE 1 Aerial photograph of the sampling site in and around the forest faculty building showing the site of the Burkard rooftop pollen trap, the five investigated rooms and 10 of the phenologically observed *Betula pendula* trees closest to the building (see phenological observations)

TABLE 1 Properties of the five rooms in the forest faculty building for which indoor and outdoor birch pollen concentrations were assessed

| Name (aspect, ventilation) | Use/number of users | Floor | Ventilation scheme window/door | Room size [m ² , room height [m] | Window size [m ²] | Window/room volume [100 m ⁻¹] | Distance to closest birch tree [m] |
|----------------------------|---------------------|-------|--|---|-------------------------------|---|------------------------------------|
| North-Open | Laboratory/1-2 | 2nd | Open from 8 AM-7 PM/closed | 49.60, 3.04 | 1.360 | 0.90 | 65 |
| East-Tilt | Office/1 | 1st | Tilt all day long/open | 15.70, 3.11 | 1.307 | 2.68 ^a | 5 |
| East-Vent | Office/3 | 1st | 2 Opened every 2 h for 5 min/open | 22.30, 3.11 | 0.515 each | 1.49 | 5 |
| South-Open | Laboratory/none | 2nd | Open from 8 AM-7 PM ^b /closed | 10.90, 3.04 | 0.544 | 1.64 | 100 |
| West-Open | Office/none | 1st | Open from 8 AM-7 PM/open | 21.20, 2.62 | 0.542 | 0.98 | 45 |

^aAs the window was tilted inwards on top, this ratio does not mirror the effective opened fraction of about 0.45 [100 m⁻¹].

^bIn this room, an exhaust hood was constantly operating at a small extraction rate.

Counts on the 2-mm counting field around the middle of the stripe were converted to concentrations in birch (*Betula* sp.) pollen grains m⁻³ by dividing the number of birch pollen grains by the volume of air. Other pollen types were not counted.

Background pollen concentrations were obtained from a stationary Hirst-type pollen trap installed at the meteorological platform on the roof of the building in 15 m height above ground (south side, see Figure 2C). As the meteorological platform is not surrounded by

higher buildings or trees, the conditions were appropriate to measure airborne pollen concentrations according to the standards of the European Aeroallergen Network (EAN);⁴ Pollen sucked into the trap by a flow rate of 10 L min⁻¹ adhered to a plastic tape coated with Vaseline mounted on a continuously turning drum. Daily pollen measurements were taken from March till November 2015. Pollen counting was achieved along four longitudinal transects according to the minimal requirements of the EAN.⁴

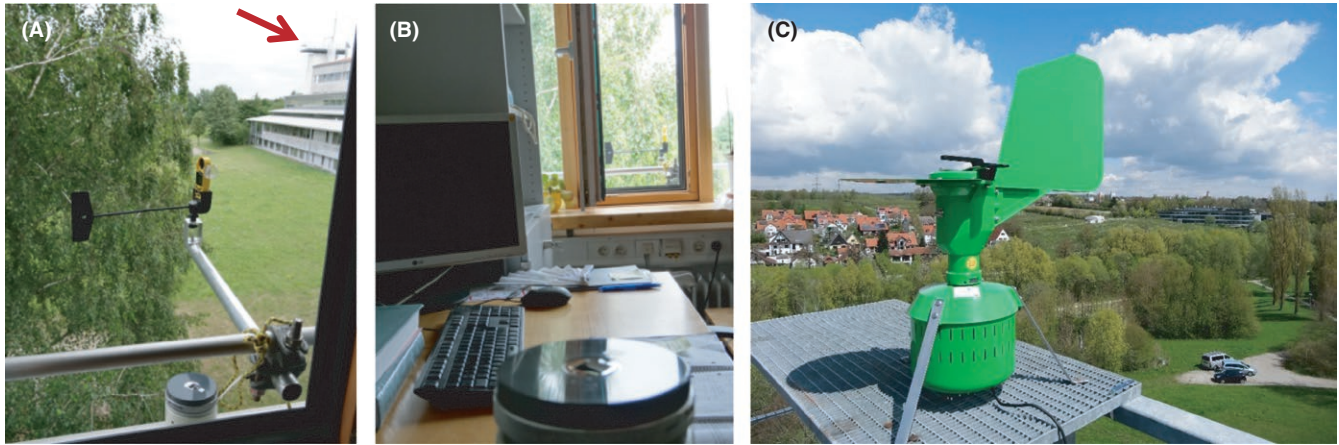


FIGURE 2 Personal volumetric air samplers fixed to the window sill (A) and positioned on an office desk (B) as well as the stationary Hirst-pollen trap on the meteorological platform (C). The latter one is also seen on the rooftop of the building in the background of (A)

2.3 | Phenological observations

From April 13th till April 29th 2015, the flowering phenology of 56 individual birch trees (*B. pendula* ROTH) was observed around the forest faculty building, at the campus, in the city of Freising and its nearer surroundings. Those 10 trees around the building were classified as near (see Figure 1), the remaining 46 trees in 0.5–15 km horizontal distance as distant. In the study area, the annual mean temperature is 7.9°C and annual sum of precipitation 785 mm (1971–2000).²¹ Trees were examined every third day and their mean flowering stage was registered according to the BBCH code.²² Beginning of flowering (B61) and full flowering (B65) were assigned when approximately 10% and 50% of all catkins emitted pollen, respectively. The end of flowering (B69) was recorded when catkins did not emit pollen anymore. If the individuals lacked reachable branches with male catkins close to the ground, long tree pruners were used to bump or cut sprigs or little branches and give reliable information at least for the lower part of the crown.

2.4 | Meteorological data

Meteorological data in terms of open field wind speed and direction (called main wind hereafter) were used from the climate station of the German Meteorological Service at Freising (Weißenstephan-Dürnast), situated 2 km west of the building. Each of the rooms was additionally equipped indoor with an air temperature and humidity logger (HOBO Pro v2; Onset Computer Corporation, Bourne, MA, USA) measuring those variables every 10 minutes. Outdoor, in front of each window, a Kestrel® 4500BT Pocket Weather & Environmental Meter Weather® Tracker (Nielsen-Kellermann, Boothwyn, PA, USA) was fixed on a 1-m rod (see Figure 2A) which recorded air temperature, relative humidity, air pressure, wind speed, and wind direction every 10 minutes. For further analyses, all meteorological data were averaged to hourly values. Although in meteorology, wind direction is reported by the direction from which it originates (eg, southerly wind), for clarity in the analyses, we refer to the direction it is going to (eg, wind toward north).

2.5 | Statistical analyses

Linear regressions were performed to determine the combined influence of outdoor pollen concentrations and meteorology, depending on ventilation scheme. Two sets of regressions were estimated: one with indoor pollen concentration as response variable and the other with the I/O ratio as response. Explanatory variables included temperature, main wind, window wind, dummy variables for room, day (of measurement), and hour. With indoor pollen concentrations as response, additional explanatory variables were outdoor pollen concentrations and indoor pollen concentrations from the previous measurement on the same day to account for the fact that pollen remain in indoor dust and might resuspend again. All continuous variables (temperature, wind, pollen concentrations) were also considered as interactions with room. Wind speed and direction were transformed into u and v components, that is vectors of east-west and north-south wind, where positive values of u mean wind toward east and positive values of v mean wind toward north. Hereafter, the u component and v component will be called wind W-E and wind S-N, respectively.

Model complexity was increased sequentially, starting from only dummies for room to a full specification including all variables to check the importance of each variable and dependencies between variables (see Figs S1 and S2 for coefficients, and Tables S1 and S2 for model summaries). For instance, including dummies for day influenced estimated effects of temperature, outdoor concentration, and previous indoor concentration. Because of this multicollinearity, the day variable was not considered. Then, starting from the full model (without day), insignificant variables were removed to arrive at a parsimonious model description. The final models were the following:

$$\begin{aligned} \text{pollen.indoor}_i = & \beta_0 + \gamma_0 \text{Room}_i + \beta_1 \text{pollen.outdoor}_i \\ & + \gamma_1 \text{pollen.outdoor}_i * \text{Room}_i + \beta_2 \text{pollen.indoor.previous}_i \\ & + \beta_3 \text{temp}_i + \beta_4 \text{window.wind.SN}_i \\ & + \gamma_2 \text{window.wind.SN}_i * \text{Room}_i + \epsilon_i \end{aligned} \quad (1)$$

where $i=1\dots 195$ is the observation id, Room_i is a four-dimensional dummy variable to account for room, $\text{pollen.indoor.previous}_i$ is the

indoor pollen concentration of the previous measurement of the same day of observation i , γ_0 to γ_2 are four-dimensional coefficient vectors incorporating the interactions with room, and ϵ_i errors; and

$$\begin{aligned} \text{pollen.io.ratio}_i = & \beta_0 + \gamma_0 \text{Room}_i + \beta_1 \text{temperature}_i + \beta_2 \text{main.wind.WE}_i \\ & + \gamma_1 \text{main.wind.WE}_i * \text{Room}_i + \beta_3 \text{window.wind.SN}_i \\ & + \gamma_2 \text{window.wind.SN}_i * \text{Room}_i + \epsilon_i \end{aligned} \quad (2)$$

where $i = 1 \dots 235$ is the observation id, and the rest as above. Residual plots showed that errors were heteroscedastic with respect to outdoor pollen concentrations; thus, we included a variance function that is an exponential of the outdoor pollen concentration with different parameters for each room. This corresponds to following formulation: $\text{Var}(\epsilon_i) = \sigma^2 \exp(\delta_r(i) * \text{pollen.outdoor}_i)$, where $\delta_r(i) = \delta_r$ for room $r = 1 \dots 5$, if observation i is of room r . Models were estimated using the `gls` function in R-package `nlme`. All statistical analyses were performed in R version 3.3.1 (R Foundation for Statistical Computing, Vienna, Austria).

3 | RESULTS

3.1 | Birch pollen and flowering season

The aerobiologically defined birch pollen season started on April 13th and ended on April 25th when 5% or 95% of the annual sum had been collected (Figure 3). The birch pollen concentration sharply increased to its annual peak on April 16th with 1722 pollen grains m^{-3} . A second much smaller maximum was recorded on April 22nd with 321 pollen grains m^{-3} . Just one day before the peak airborne pollen concentration, first near and distant birch trees entered the phenological stage B61, that is, beginning of flowering. One-third of the distant birch trees had started flowering when the peak concentration was measured. The second airborne pollen maximum matched with 85% of distant and 40% of the near birch trees entering the full flowering stage (B65, 50% of flowers open). The drop in pollen concentrations from April 23rd onwards coincided with 10% of distant birch trees having ended the flowering period (B69). Thus, the first 6 days of I/O pollen sampling (April 19th till April 24th) covered the period of full flowering of birch trees, whereas on the last two sampling days, 10% (April 27th) and 60% (April 29th) of the both

near and distant birch trees had already ended their flowering period, respectively.

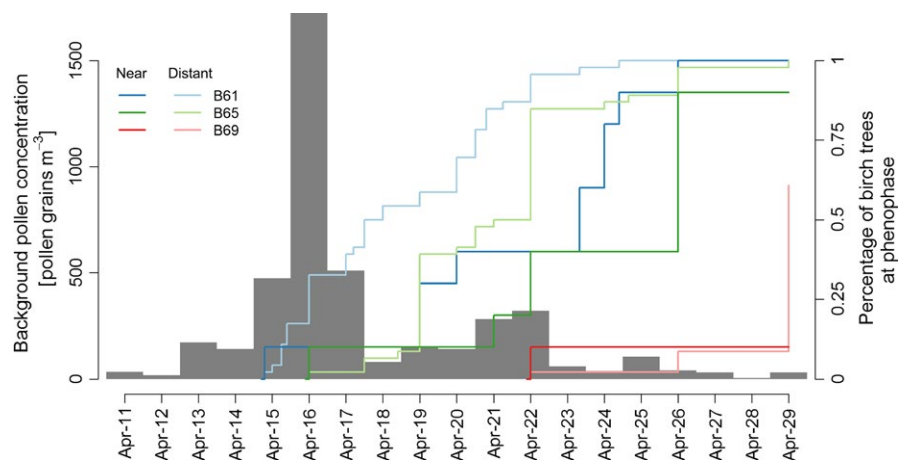
3.2 | Outdoor meteorological conditions

Under the influence of a high-pressure system, the weather from April 19th to 22nd was predominantly sunny with only a few clouds on April 22nd.^{21,23} Dry air masses from subpolar origin subsequently warmed up, and daily maximum temperatures increased up to $\sim 20^\circ\text{C}$. During nights, some frost was observed. Winds in this period were generally weak and toward west and south. On April 23rd, a small low-pressure system in the higher troposphere reached Bavaria from northwest and led to lower air temperatures. On the following day, it was sunny and warm again with weak winds toward east. There was light rain on the non-sampling days 25th and 26th. On April 27th, a low-pressure system moved over Bavaria and this was the only sampling day when 6 mm precipitation was registered. On April 29th, the weather was cooler but sunny again. The outdoor measurements (Figure 4) reflected the diurnal patterns with maximum temperatures around midday or in the early afternoon, depending on the aspect (east–midday, south and west–early afternoon). On the south and sometimes also on the west side, the highest temperatures were recorded, corresponding to the lowest air humidity values. Air pressure records mirror the frontal system passing on April 27th.

3.3 | Wind speed and directions

Wind speeds were generally low during the sampling days, not exceeding the category of moderate breeze (Beaufort scale 4, $5.5\text{--}7.9 \text{ m s}^{-1}$). Opposite to the general pattern toward east, 20% of winds were also toward west (Figure 5). The outdoor wind field in front of the windows, however, was driven by the building structure which channeled the flow parallel to the edifice (eg, wind toward west and east for the north and south aspects). Due to open meadows east of the building, 15% of the time there was orthogonal wind toward the two eastern rooms (*East-Tilt*, *East-Vent*). For *West-Open*, no orthogonal outdoor flow was recorded, most likely due to the shielding parts of the building (see Figure 1).

FIGURE 3 Birch pollen season in spring 2015 at the forest faculty building of the Technical University of Munich at Freising (gray bars) and corresponding flowering stages (B61 beginning of flowering, B65 full flowering, B69 end of flowering) of 10 *Betula pendula* trees near the building (see Figure 1) and of 46 distant ones in the city and the surroundings of Freising (colored lines, corresponding to the percentage of trees that have attained the respective flowering stage)



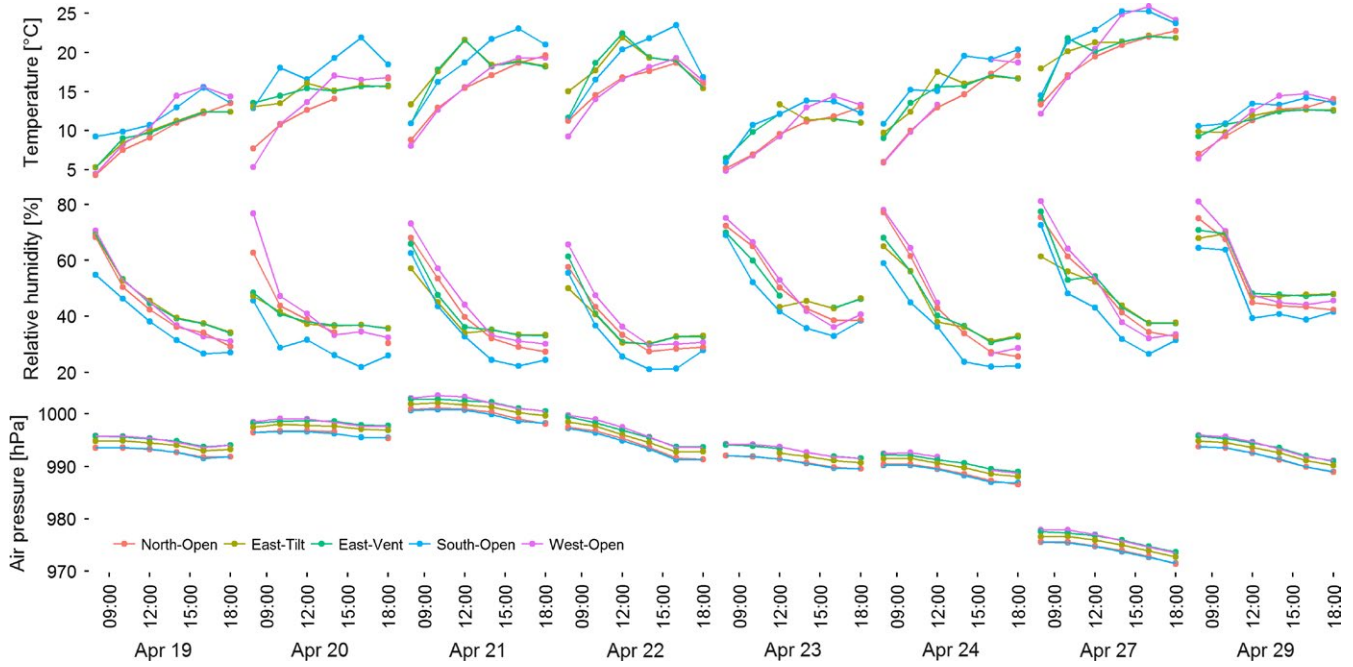


FIGURE 4 Outdoor meteorological conditions (air pressure [hPa], relative humidity [%], temperature [°C]) as hourly means in front of the studied rooms

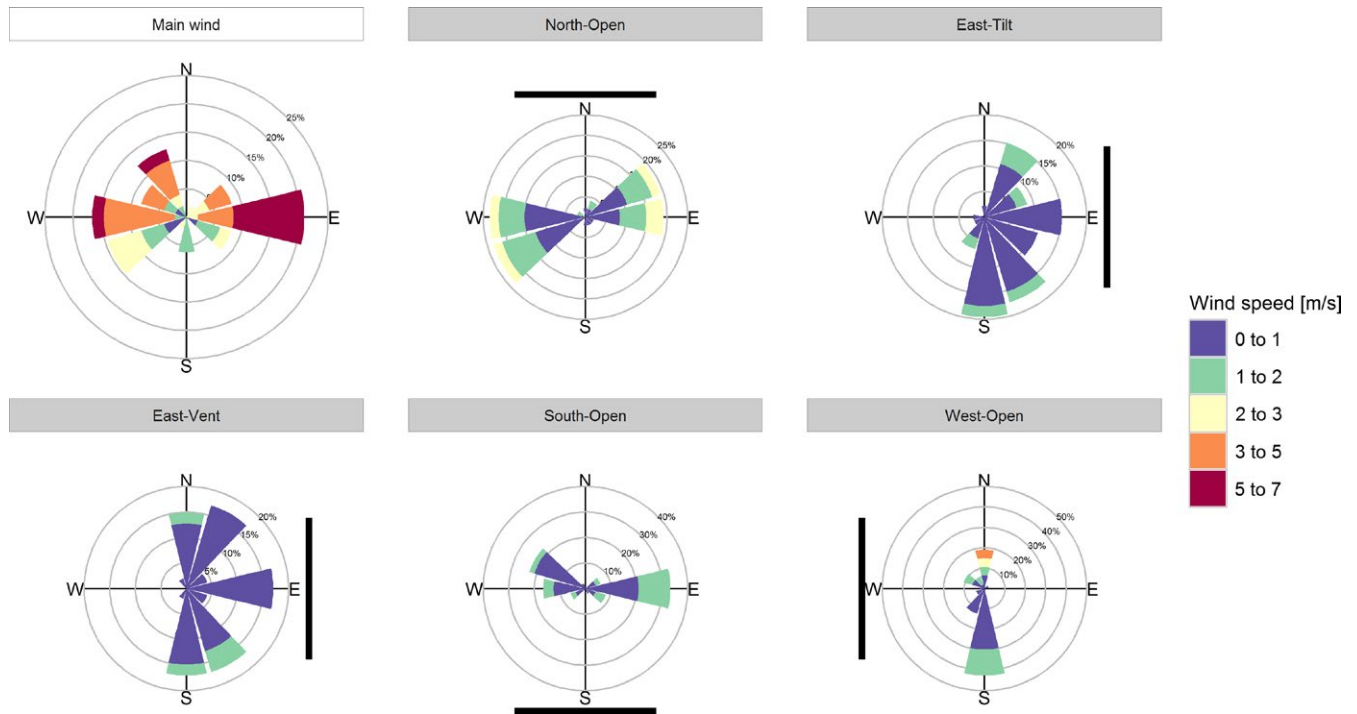


FIGURE 5 Wind roses displaying wind speed and meteorological wind direction for the sampling days, that is N signifies wind coming from north. Main wind corresponds to the climate station Weihenstephan-Dürnast, the five other panels to the outside of the different rooms for which the opening of the window is given as a black bar. The percentages are the fraction of wind coming from the respective direction during the sampling hours of the study period

3.4 | Outdoor and indoor birch pollen concentrations

With respect to outdoor pollen concentrations, the eight sampling days can be divided into two periods: medium-to-high pollen

concentration on the first four sampling days (April 19th till 22nd) of up to 600 pollen grains m^{-3} and low concentrations rarely exceeding 50 pollen grains m^{-3} on the last four sampling days (April 23rd, 24th, 27th, and 29th) (see Figure 6). This dichotomy is equally seen in the

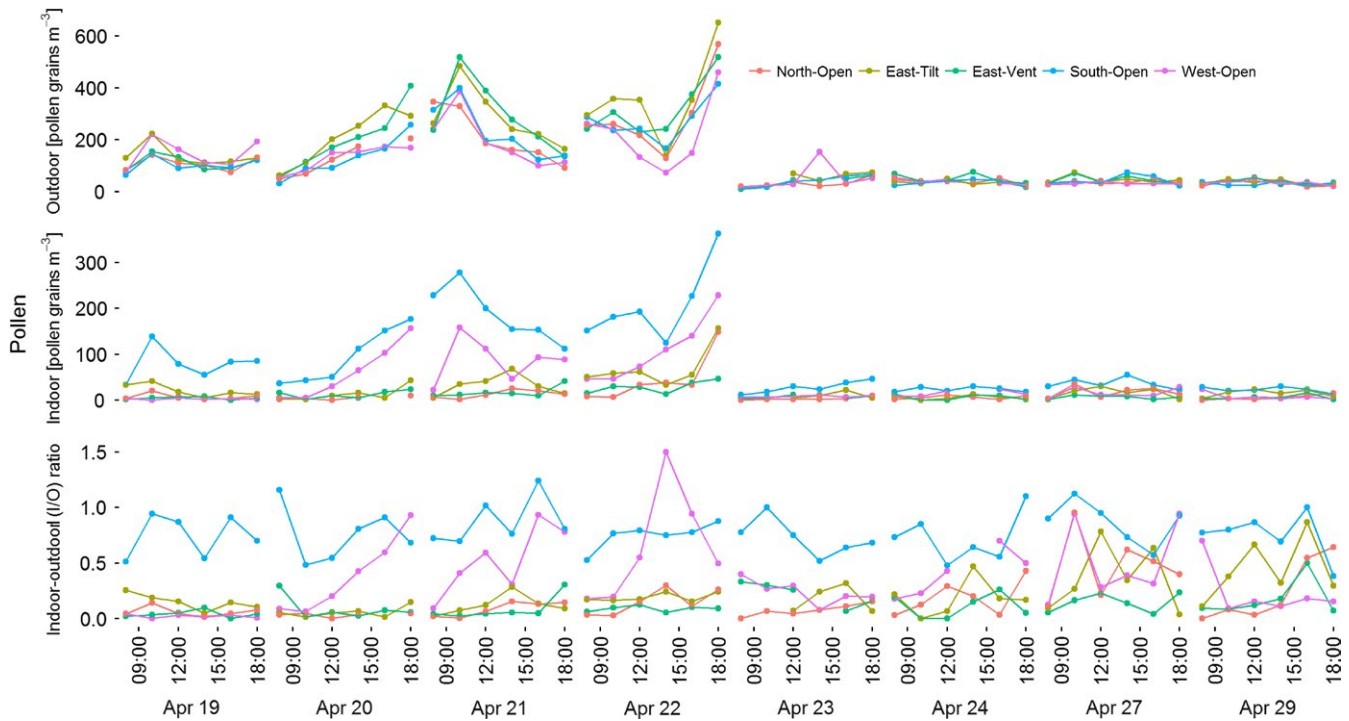


FIGURE 6 Hourly outdoor and indoor birch pollen concentrations as well as the respective indoor/outdoor (I/O) ratios for the eight sampling days. Note: Scale of y-axis for indoor and outdoor concentrations differs by a factor of 2

respective indoor pollen concentrations, however, with lower absolute values. Mean daily I/O ratios are within the range of 0.02 (April 19th, *West-Open*) to 0.88 (April 21st, *South-Open*). In the first period, I/O ratios for the rooms *East-Tilt*, *East-Vent*, and *North-Open* were low, whereas for *South-Open*, they were generally high and those of *West-Open* increased with time of the day and with the succession of the measuring campaign. In the second period, although pollen concentrations were substantially lower than in the first period, corresponding I/O ratios were equally high (*South-Open*, to a smaller extent also for *West-Open*) or even higher. For this latter period, no diurnal patterns were obvious anymore.

Background (building rooftop) and outdoor (window) pollen concentrations were highly correlated for all rooms (all $P < .001$, Table 2). Outdoor and indoor pollen concentrations were highly correlated

for *South-Open* and less for the other rooms, with no significant correlation for *North-Open*. The correlations between indoor and background concentrations were very similar to the indoor-outdoor correlations.

3.5 | Modeling

The significant explanatory variables for modeling indoor pollen concentrations were outdoor pollen concentrations interacted with room, indoor pollen concentrations of the previous measurement, window wind S-N interacted with room, and temperature, roughly in that order of importance (Figure 7, model $R^2 = .71$).

The association between indoor and outdoor pollen concentrations depended on room: Indoor pollen concentrations were 0.60 times the outdoor pollen concentrations for *South-Open*, 0.20 for *West-Open*, 0.08 for *East-Tilt*, and 0.03 for *North-Open* and *East-Vent*. Indoor pollen concentrations of the previous measurement were linked to a quarter of the actual indoor concentrations.

The impact of south to north winds in front of the window (window wind S-N) was mostly apparent for room *West-Open* where stronger wind toward south increased indoor pollen concentrations. This sounds counter-intuitive because this is wind blowing not perpendicular to the window; however, this is linked to high outdoor pollen concentrations for this window and wind direction (Fig. S3).

Finally, higher temperatures were associated with higher indoor pollen concentrations, but the relative impact was low compared to the other variables.

TABLE 2 Spearman's rank correlations between background (building rooftop), outdoor (in front of window), and indoor pollen concentrations with P-values indicated by stars: * $P < .05$, ** $P < .01$, *** $P < .001$. P-values were adjusted for multiple testing using the Bonferroni correction

| | Background– outdoor | Outdoor– indoor | Indoor– background |
|-------------------|------------------------|--------------------|-----------------------|
| <i>North-Open</i> | .82*** | .31 | .26 |
| <i>East-Tilt</i> | .86*** | .58*** | .50** |
| <i>East-Vent</i> | .83*** | .62*** | .51** |
| <i>South-Open</i> | .82*** | .95*** | .81*** |
| <i>West-Open</i> | .77*** | .40* | .45** |

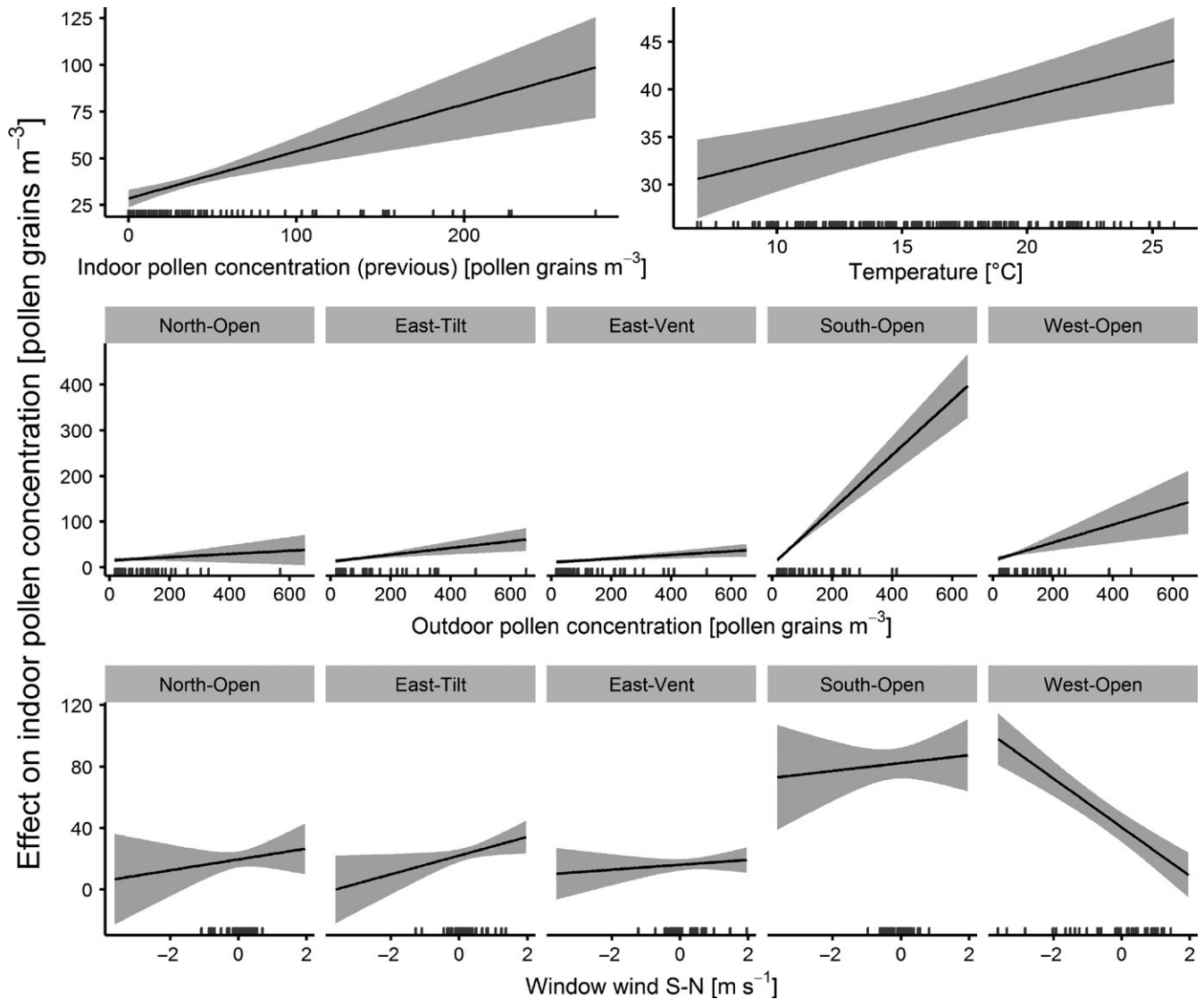


FIGURE 7 Effects of explanatory variables on indoor pollen concentration. Shown are fitted values for each variable included in the final model, holding all other variables constant. Gray areas show 95% confidence intervals. Small gray vertical lines at the bottom of each panel indicate the actual values of that variable in the data set. Effects of non-significant variables are not shown

Modeling the I/O ratio of pollen resulted in the significant variables temperature, window wind S-N interacted with room, and main wind W-E interacted with room, roughly in that order of importance (Figure 8, model $R^2=0.70$). Increasing temperatures were linked to higher I/O ratios with $0.013/^\circ\text{C}$. Window wind S-N had strong effects on the I/O ratio for rooms *North-Open* and *West-Open* where stronger winds toward south were associated with higher I/O ratios. A minor effect was also found for room *South-Open*, but in the opposite direction, that is, stronger wind toward north linked to higher I/O ratios. Main wind W-E had effects on rooms facing east or west such that stronger winds toward the respective window opening were associated with higher I/O ratios.

Modeled mean values of indoor pollen concentrations and I/O ratios differed between rooms, after adjusting for the influence of temperature, wind, outdoor, and previous indoor concentrations (Table 3). Concerning mean indoor pollen concentrations, room *East-Vent* had

the lowest value ($16.0 \text{ pollen grains m}^{-3}$), followed by *North-Open* ($19.5 \text{ pollen grains m}^{-3}$) and *East-Tilt* ($22.1 \text{ pollen grains m}^{-3}$); however, these were not statistically different from each other. Mean indoor concentrations of *West-Open* ($41.0 \text{ pollen grains m}^{-3}$) were significantly different from the three above, and also from *South-Open* ($82.6 \text{ pollen grains m}^{-3}$). Results were similar for the I/O ratios; however, mean I/O ratios were also significantly different between *East-Vent* (0.07) and *East-Tilt* (0.19) (Table 3).

4 | DISCUSSION

Background pollen concentration and phenological observations largely matched; however, some small discrepancies are obvious which have to be carefully interpreted in light of a three-day temporal resolution of the phenological observations. The peak concentration

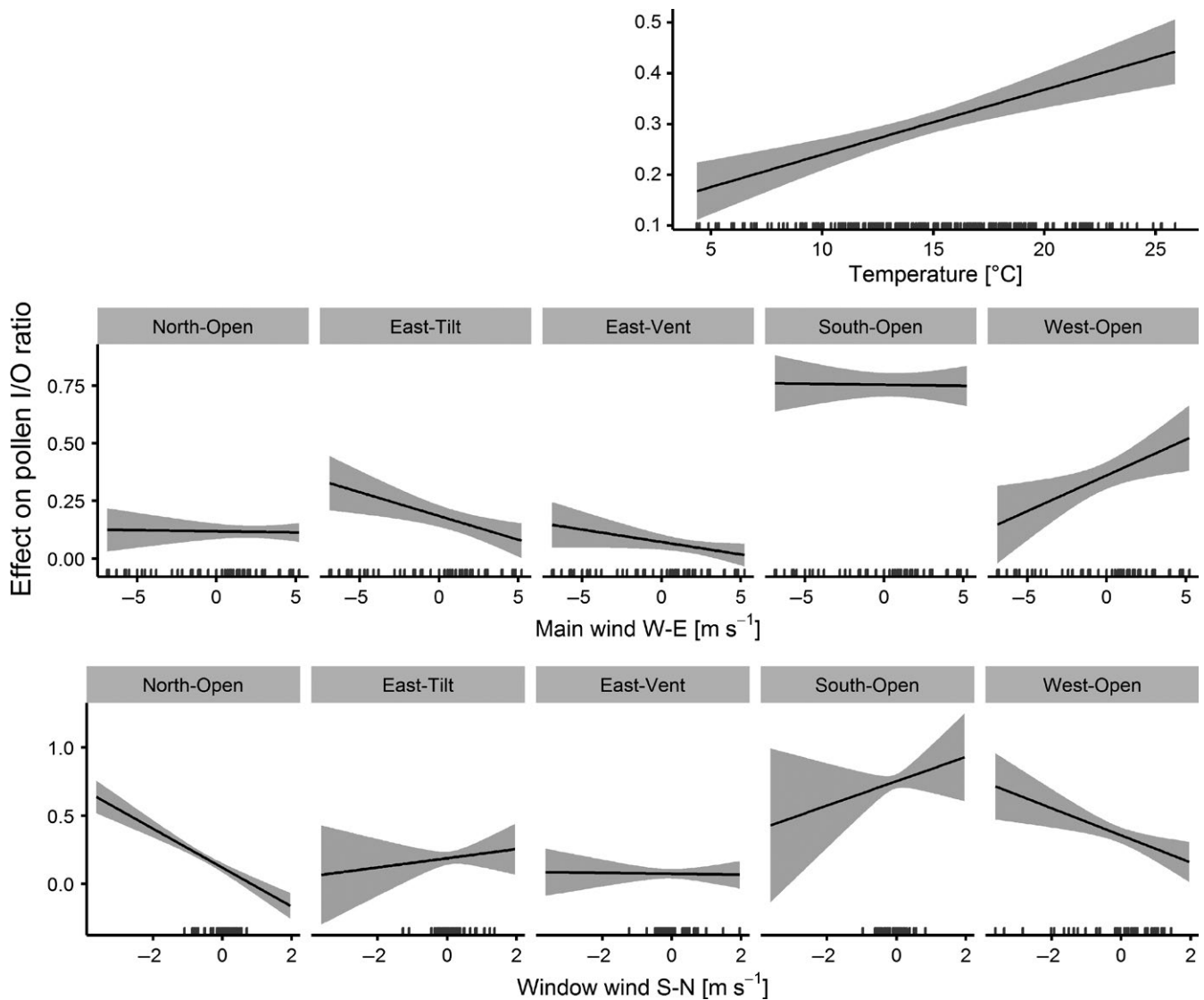


FIGURE 8 Same as Figure 7, but for effects on the I/O ratio of pollen

in background birch pollen on April 16th might be too early to be solely explained with observed birches just starting flowering (see Figure 3), even if we take the more distant birch trees into account which were flowering a bit earlier than the 10 nearest ones. There is no obvious explanation except natural variability why the specimens at the University campus flowered later than in the wider surroundings of Freising. We suggest that additional pollen was transported from warmer spots with earlier birch flowering, for example, the city of Munich (see also Refs 24-26) or even by long-range transport. A clear drop in background pollen concentrations before a majority of the birch trees had reached end of flowering may be due to rainy conditions from April 25th to 27th.

Daily pollen concentrations measured at the rooftop/meteorological platform corresponded quite well to the concentrations in front of the windows (correlations larger than .82); however, for the room *West-Open*, the value was smaller (.77), probably due to its largest distance to the roof trap and the building structure (see Figure 1). For complex city structures, the representativeness of pollen traps is

known to be limited.²⁷ The presence of high buildings and complex surfaces may, for example, increase turbulence, thereby causing pollen concentrations to differ considerably over short distances both vertically and horizontally.²⁸⁻³¹

For most allergic people, due to their living and working conditions, indoor pollen concentrations are more relevant than outdoor background concentrations and the suitable siting of office or living rooms and their ventilation matters.^{13,32} How relevant these differences between outdoor and indoor conditions may be is underlined by our study. First symptoms in people allergic to *Betula* pollen occur when airborne pollen concentrations exceed ~20 pollen grains per m³,^{33,34} a threshold which was exceeded on nearly all days of the birch pollen season (see Figure 3). This is the range which can be underrun by the “best performing” room in our study (16 pollen grains per m³ in *East-Vent*) that even has a birch tree at 5 m distance in front of its window.

The average I/O ratio of birch pollen grains found in this study (.33) largely matches results reported in the literature; especially the

TABLE 3 Mean indoor pollen concentrations and I/O ratios after controlling for temperature, for wind, and for indoor pollen concentrations, also outdoor pollen concentrations and indoor concentrations of the previous measurement

| | Mean indoor pollen [pollen grains m ⁻³] | Mean I/O ratio |
|-------------------|--|------------------------------|
| <i>North-Open</i> | 19.5 ^a (12.6, 26.5) | .12 ^{ab} (.07, .16) |
| <i>East-Tilt</i> | 22.1 ^a (16.5, 27.7) | .19 ^a (.13, .25) |
| <i>East-Vent</i> | 16.0 ^a (11.1, 20.9) | .07 ^b (.03, .12) |
| <i>South-Open</i> | 82.6 ^b (69.0, 96.2) | .75 ^c (.69, .82) |
| <i>West-Open</i> | 41.0 ^c (28.2, 53.8) | .35 ^d (.28, .43) |

Different superscript letters correspond to significantly different values (adjusted for multiple testing using the Bonferroni correction); that is, if rooms share the same letter, then their mean indoor pollen concentration or mean I/O ratio is not significantly different.

average rate for the four rooms which were not influenced by an installed ventilation system (.22) is in line with previous studies.^{8,9,13,32} However, our study revealed distinct and significant differences between the five rooms.

The highest mean I/O ratio of .75 was found for *South-Open*, strongly supported by the highest correlation between indoor and outdoor pollen concentration (.95, see Table 2). This relatively small laboratory room is characterized by a high window/room volume ratio (see Table 1); thus, the constantly opened window allowed considerable exchange of air, boosted by the exhaust hood working at a very small extraction rate which obviously constituted an effective ventilation system.

The second highest mean I/O ratio was found for *West-Open* (.35), a medium-sized office room. This fact is most likely related to the main wind toward east (Figure 5), transporting comparably high pollen loads (Fig. S3). The laboratory room *North-Open* was larger than *West-Open*; however, their window to room volume ratio was similar (Table 1). The smaller I/O ratio (.12) of *North-Open* may be explained by the prevailing wind directions.

Although wind toward west was also quite frequent, *East-Tilt* and *East-Vent* had low I/O ratios (.19 and .07, respectively). This can most likely be explained by the particular ventilation schemes which allowed less air and hence less pollen from the nearby birch to enter the office rooms (see Figure 2A,B showing the room *East-Vent*). However, a second indoor pollen trap near the window might have been of help to validate this result and exclude other factors such as air currents. While being tilted, the open fraction of *East-Tilt* was one-third of *East-Vent* (see Table 1), thus timing and duration of the ventilation most likely mattered, because mean outdoor pollen concentrations for *East-Tilt* and *East-Vent* were not significantly different (paired *t* test, *df*=44, *P*=.25, see also Figure 6). The 2.5 times higher I/O ratio of *East-Tilt* compared to *East-Vent* indicates that intermittent ventilation with short but effective openings of the windows is more suitable for keeping pollen outside than a permanent tilting of the window. Previous studies indicated that strong draft due to more than one open window may increase the intrusion of pollen, whereas the opening of only one window can maintain a low pollen

concentration.³² However, because the office rooms were frequently used and doors to the aisle mostly opened, draft could not be excluded in our study. However, in *East-Vent*, two small windows were opened for 5 minutes every 2 hours, and still *East-Vent* had 2.5 times lower I/O ratios than the neighboring *East-Tilt* room. In spite of a fully opened window, the I/O ratio *North-Open* was similar to *East-Tilt* and *East-Vent*. This might be explained by the huge size of the room, the placement of the indoor trap, and by the few occasions of a main wind direction toward south.

Our results indicated strong and significant correlations between background pollen concentrations measured at the rooftop of the building and local outdoor pollen measurements at window sills modulated by microclimatic conditions (especially wind direction) and the distance to pollen sources. Although the correlations between window sill and indoor concentrations were lower than between rooftop and window sill, they partly contradict findings by Stock and Morandi¹² and O'Rourke and Lebowitz¹¹ who claimed large independence of these parameters.

The most influential meteorological parameters in the models for indoor pollen concentration and I/O ratios were window wind S-N and temperature as well as temperature, window wind S-N, and main wind W-E, respectively.

With higher temperatures, indoor pollen concentration increased, mirroring higher pollen shedding. I/O ratios increased with temperature too, suggesting efficient transport during midday and on sunny days. From the literature, it is well known that pollen concentration in the air is positively correlated with air temperature and sunshine, whereas rainfall and an increased relative humidity result in decreased airborne pollen concentrations.³⁵⁻³⁷

I/O ratios were consistently affected by window wind directions. For *North-Open* as well as *South-Open*, I/O ratios decreased and, respectively, increased with higher wind speeds in the S-N component, indicating a reinforcing effect of wind when it was perpendicular to the window opening. Due to the special building structure blocking any flow to South, especially trapping air in front of *West-Open* (see Figure 1), *West-Open* was similar to *North-Open*, and I/O ratios increased with stronger winds toward south as well. In contrast, for *East-Tilt* and *East-Vent*, I/O ratios increased with higher wind speed toward west, again perpendicular to the window openings. Consequently, for *West-Open*, the ratio decreased with higher winds toward east, whereas *North-Open* and *South-Open* were unaffected by main winds in W-E direction.

Our five study rooms are situated in a rather isolated building, not surrounded by street canyons that can have a strong effect on the pollen concentrations on the leeward sides of buildings,²⁸ and thus, they clearly showed the following: If wind in front of the window is perpendicular, I/O ratios remarkably increase and thus ventilation should be omitted.

Date, that is, the day of measurement, was not included in the final models due to its multicollinearity with other variables. Nevertheless, for three of the studied rooms (*North-Open*, *East-Open*, and *East-Tilt*), the data show that I/O ratios significantly increased with time (Figure 6, tested by regressing outdoor concentrations on date, all

date coefficients had $P < .05$) and were higher in the second-half of the sampling period (t tests comparing the first to the last four measurement days, all $P < .05$) During this time, both outdoor and indoor concentration of pollen grains decreased substantially. The linear model for indoor pollen concentrations revealed still an additional dependence on the previous concentration after accounting for outdoor pollen concentration; thus, most likely pollen grains also accumulated inside the rooms, which at the end may also influence I/O ratios. As the sampling sites were not cleaned daily, pollen grains probably have settled down and accumulated over time. Even if the ground is cleaned, pollen grains from inaccessible areas of a room can be moved to open areas and appear in the samples beyond the pollen season.³⁸ In addition, pollen grains are able to accumulate in house dust. Thus, they can reach a peak even a long time after pollination season and maintain their antigenic activities until the next pollination season.^{39,40} Yli-Panula⁴¹ and Enomoto et al.⁴² also emphasized the importance of antigens in settled dust. Consequently, removal of dust and regular, proper room cleaning reduce the allergen level and related allergenic symptoms.

Due to the limited number of measurements, only one indoor pollen trap not capturing the pollen distribution inside the room, the varying room sizes, and window sizes, as well as irregular frequentation of each room, the results must be interpreted with caution. Pollen grains can be intruded into dwellings not only by open windows but also by clothes adhered to people^{13,18} which can affect highly frequented rooms more than less frequented ones.⁹ Furthermore, the amount of pollen intruded depends on the activity of the people that enter a room. A higher outdoor activity of the frequenting people is linked to a higher amount of pollen inside the rooms.⁸ To further study the effects of meteorological parameters examinations of vacuum-cleaned and unfrequented rooms with identical sizes and window openings would be important, especially because relationships between indoor pollen counts or I/O ratios and distance to ventilation openings (windows and doors) have been found.³²

5 | CONCLUSIONS

As the majority of people spend most of their time indoors, a good air quality inside dwellings is very important for human health and welfare. Our study demonstrated that indoor pollen concentrations are influenced by meteorological parameters, outdoor concentrations, previous indoor concentrations, and ventilation schemes. Thus, allergic people can also actively reduce the amount of indoor pollen by applying an adopted ventilation of rooms. In general, short and efficient ventilation can keep indoor concentrations low. However, prevailing wind directions in front of the windows have to be taken into consideration as well.

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