Elsevier Editorial System(tm) for Environmental Research
Manuscript Draft

Manuscript Number: ER-19-37

Title: Near-ground effect of height on pollen exposure

Article Type: Research paper

Section/Category: Exposure

Keywords: Height; pollen exposure; aerobiology; monitoring network; big data

Corresponding Author: Dr. Jesús Rojo, Ph.D.

Corresponding Author's Institution: Technical University of Munich, Zentrum Allergie und Umwelt (ZAUM)

First Author: Jesús Rojo, Ph.D.

Order of Authors: Jesús Rojo, Ph.D.; Jose Oteros; Rosa Pérez-Badia; Patricia Cervigón; Zuzana Ferencova; A. Monserrat Gutiérrez-Bustillo; Karl-Christian Bergmann; Gilles Oliver; Michel Thibaudon; Roberto Albertini; David Rodríguez-De la Cruz; Estefanía Sánchez-Reyes; José Sánchez-Sánchez; Anna-Mari Pessi; Jukka Reiniharju; Annika Saarto; M. Carmen Calderón; César Guerrero; Daniele Berra; Maira Bonini; Elena Chiodini; Delia Fernández-González; José García; M. Mar Trigo; Dorota Myszkowska; Santiago Fernández-Rodríguez; Rafael Tormo-Molina; Athanasios Damialis; Franziska Haering; Claudia Traidl-Hoffmann; Elena Severova; Elsa Caeiro; Helena Ribeiro; Donat Magyar; László Makra; Orsolya Udvardy; Purificación Alcázar; Carmen Galán; Katarzyna Borycka; Idalia Kasprzyk; Ed Newbigin; Beverley Adams-Groom; Godfrey P Apangu; Carl A Frisk; Carsten Skjøth; Predrag Radišic¨; Branko Šikoparija; Sevcan Celenk; Carsten Schmidt-Weber; Jeroen Buters

Abstract: The effect of height on pollen concentration is not well documented and little is known about the near-ground vertical profile of airborne pollen. This is important as most measuring stations are on roofs, but patient exposure is at ground level. Our study used a big data approach to estimate the near-ground vertical profile of pollen concentrations based on a global study of paired stations located at different heights. We analyzed paired sampling stations located at different heights between 1.5 and 50 m above ground level (AGL). This provided pollen data from 59 Hirst-type volumetric traps from 25 different areas, mainly in Europe, but also covering North America and Australia, resulting in about 2,000,000 daily pollen concentrations analyzed. The daily ratio of the amounts of pollen from different heights per location was used, and the values of the lower station were divided by the higher station. The lower station of paired traps recorded more pollen than the higher trap. However, while the effect of height on pollen concentration was clear, it was also limited (average ratio 1.3, range 0.7 to 2.2). The standard deviation of the pollen ratio was highly variable when the lower station was located close to the ground level (below 10 m AGL). We show that pollen concentrations measured at >10m are representative for background near-ground levels.

Technical University of Munich, Zentrum Allergie und Umwelt (ZAUM)
Biedersteinerstrasse 29, 80802 Munich, Germany

Dr. Jesus Rojo
Email: jesus.rojo.ubeda@gmail.com

Munich 9th January 2019

Dear Editor,

Find enclosed the manuscript entitled "Near-ground effect of height on pollen exposure" which represents the first global study that analyzes the real estimated near-ground vertical profile of pollen exposure. This study used a big data approach based on a global study of 59 stations around the world (25 different countries). Therefore, we think it accomplishes the objectives of the journal "Environmental Research" because it is based on the estimation of the real allergen exposure at ground level from pollen measurements registered by the monitoring networks for biological air, an important research field related with the control of the environmental risks associated to airborne biological pollutants. We hope it will be accepted for publication in your journal.

This manuscript is an original research article. All results are original and have not been previously published elsewhere. In the same way, the figures and graphics were created by the authors of this manuscript and have never been published. All authors are aware of and accept responsibility for the manuscript and this study does not involve human subjects.

Best regards

Dr. Jesus Rojo

Highlights

A big data approach was used to estimate the near-ground vertical profile of pollen exposure

The effect of sampling pollen at different heights is clear but limited

The influence of the height on pollen sampling is getting smaller above 10m AGL

Local emissions near the pollen stations will intensify the effect between paired stations

Near-ground effect of height on pollen exposure

Jesús Rojo[1,2*], Jose Oteros[1], Rosa Pérez-Badia[2], Patricia Cervigón[3], Zuzana Ferencova[3], A. Monserrat Gutiérrez-Bustillo[3], Karl-Christian Bergmann[4], Gilles Oliver[5], Michel Thibaudon[5], Roberto Albertini[6], David Rodríguez-De la Cruz[7], Estefanía Sánchez-Reyes[7], José Sánchez-Sánchez[7], Anna-Mari Pessi[8], Jukka Reiniharju[9], Annika Saarto[8], M. Carmen Calderón[10], César Guerrero[10], Daniele Berra[11], Maira Bonini[12], Elena Chiodini[11], Delia Fernández-González[13], José García[14], M. Mar Trigo[14], Dorota Myszkowska[15], Santiago Fernández-Rodríguez[16], Rafael Tormo-Molina[16], Athanasios Damialis[17], Franziska Haering[17], Claudia Traidl-Hoffmann[17,18], Elena Severova[19], Elsa Caeiro[20], Helena Ribeiro[21], Donat Magyar[22], László Makra[23], Orsolya Udvardy[22], Purificación Alcázar[24], Carmen Galán[24], Katarzyna Borycka[25], Idalia Kasprzyk[25], Ed Newbigin[26], Beverley Adams-Groom[27], Godfrey P. Apangu[27], Carl A. Frisk[27], Carsten Skjøth[27], Predrag Radišič[28], Branko Šikoparija[28], Sevcan Celenk[29], Carsten Schmidt-Weber[1] & Jeroen Buters[1]

[1]Technical University of Munich, Zentrum Allergie und Umwelt (ZAUM), Germany; [2]University of Castilla-La Mancha, Spain; [3]Complutense University of Madrid, Spain; [4]Charité Universitätsmedizin Berlin, Germany; [5]Réseau National de Surveillance Aérobiologique, France; [6]University of Parma, Italy; [7]University of Salamanca, Spain; [8]Turun yliopisto, Aerobiology Unit, Finland; [9]University of Turku, Finland; [10]National Autonomous University of Mexico, Mexico; [11]Ospedale di Circolo, ASST Valle Olona, Italy; [12]Local Health Authority ATS della Città Metropolitana di Milano, Italy; [13]University of León, Spain; [14]University of Malaga, Spain; [15]Jagiellonian University Medical College, Poland; [16]University of Extremadura, Spain; [17]Chair and Institute of Environmental Medicine, UNIKA-T, Technical University of Munich, Research Center for Environmental Health, Augsburg, Germany; [18]CK CARE Crhistine Kühne Center for Allergy Research and Education, Switzerland; [19]Lomonosov Moscow State University, Russia; [20]Sociedade Portuguesa de Alergologia e Imunologia Clínica, Lisboa, Portugal; [21]Universidade do Porto, Portugal; [22]National Public Health Institute, Hungary; [23]University of Szeged, Hungary; [24]University of Córdoba, Spain; [25]University of Rzeszów, Poland; [26]University of

Melbourne, Australia; [27]University of Worcester, UK; [28]BioSense Institute, University of Novi Sad, Serbia; [29]Uludag University, Turkey.

* Corresponding author: jesus.rojo.ubeda@gmail.com, Biedersteinerstrasse 29, 80802 Munich, Germany

ABSTRACT

The effect of height on pollen concentration is not well documented and little is known about the near-ground vertical profile of airborne pollen. This is important as most measuring stations are on roofs, but patient exposure is at ground level. Our study used a big data approach to estimate the near-ground vertical profile of pollen concentrations based on a global study of paired stations located at different heights. We analyzed paired sampling stations located at different heights between 1.5 and 50 m above ground level (AGL). This provided pollen data from 59 Hirst-type volumetric traps from 25 different areas, mainly in Europe, but also covering North America and Australia, resulting in about 2,000,000 daily pollen concentrations analyzed. The daily ratio of the amounts of pollen from different heights per location was used, and the values of the lower station were divided by the higher station. The lower station of paired traps recorded more pollen than the higher trap. However, while the effect of height on pollen concentration was clear, it was also limited (average ratio 1.3, range 0.7 to 2.2). The standard deviation of the pollen ratio was highly variable when the lower station was located close to the ground level (below 10 m AGL). We show that pollen concentrations measured at >10m are representative for background near-ground levels.

Keywords: Height, pollen, aerobiology, monitoring network, big data.

Funding Sources

The work was funded by ZAUM- Center of Allergy & Environment of the Technical University Munich/ Helmholtzzentrum Munich.

Introduction

Respiratory diseases related to allergy are considered as one of the most important health public problem for the XXI century, according to the World Allergy Organization (Pawankar et al., 2013). Bioaerosols such as pollen grains or spores are the main cause of allergic diseases and their incidence is rising also due to climate change and urban pollution (Cecchi et al., 2010; Lake et al., 2017; Reinmuth-Selzle et al., 2017). According to the European Academy of Allergy and Clinical Immunology around 30% of the population from industrialized areas suffers from allergic diseases (European Academy of Allergy and Clinical & Immunology, 2015). For this reason the interest in aeroallergens has increased and in addition to measuring air quality from inorganic pollutants (Zhang et al., 2016; Fugiel et al., 2017), monitoring networks for biological air components like pollen were installed during the last decades of the XX century (Hertel et al., 2013). Moreover, monitoring of biological particulate matter also provides relevant information for agronomic or ecological purposes (Jarosz et al., 2005; Fernandez-Gonzalez et al., 2013; Charalampopoulos et al., 2018; Romero-Morte et al., 2018).

Around the world, airborne pollen monitoring is mainly done by samplers located at higher locations (Buters et al., 2018), such as rooftops of buildings, following the recommendations of the standard methodology agreed by the international aerobiology associations (Galán et al., 2014; Jäger et al., 1995). The reason of sampling at rooftops is that pollen concentrations should be sampled at homogeneous conditions, enabling a single trap to cover a large area around the sampling station, e.g. the area of a city. However, measured airborne pollen at rooftop levels could be different from those at ground level, where patient outdoor pollen exposure occurs (Peel et al., 2013; Penel et al., 2017; Fernández-Rodríguez et al., 2018). Although many stations are at variable heights above ground, the effect of height on pollen sampling is not well documented, although the subject has been addressed at a local scale in numerous papers (See Supplementary Material Table S1). To estimate the near-ground level of pollen from rooftop measurements we analyzed all the available data from paired traps across the world.

The vertical profile of the bioaerosol concentrations was analyzed in the lower atmosphere using aircrafts or tethered balloons (Gregory, 1978; Gruber et al., 1998; Comtois et al., 2000; Damialis et al., 2017). Although in general terms, Gregory (1978) demonstrated that the concentration of bioaerosols decreases logarithmically with height from ground level up to the upper layers of the troposphere, certain types of biological particles can show higher concentrations in higher heights above ground level (Comtois et al., 2000; Damialis et al., 2017) due to the long-distance transport of particulate matter below the atmospheric boundary layer (Makra et al., 2016, 2010; Rojo et al., 2018). Above or below tens of meters AGL different processes of the atmospheric dynamic determine the vertical profile (Orlanski, 1975). In this study we focused on the processes determining the vertical profile within the first tens of meters above ground level.

The study of the near-ground vertical profile on pollen concentration is complex and rarely more than two samplers at the same location were analyzed (Galán et al., 1995; Myszkowska et al., 2012; Fernández-Rodríguez et al., 2014; Rodríguez de la Cruz et al., 2016; Borycka and Kasprzyk, 2018) (Supplementary Material Table S1). As a consequence, up to date few researches have considered a vertical profile using more than two sampling heights simultaneous at one location (Raynor et al., 1973; Bryant et al., 1989; Fiorina et al., 1999; Alcazar and Comtois, 2000; Jarosz et al., 2005; Chakraborty et al., 2001; Xiao et al., 2013). A representative example considering the near-ground vertical profile of pollen is the study of Raynor et al. (1973) on a meteorological tower in USA up to 108 m AGL or the Amazon Tall Tower Observatory (ATTO) in Brazil up to 300 m AGL, reaching the maximum studied height for a static sampler (Barbosa et al., 2018). Few other heights points were analyzed for the near-ground vertical profile of airborne pollen and it is also difficult to find studies that were maintained over a longer period of time.

Our study used a big data approach to estimate the near-ground vertical profile of pollen concentrations based on a global study of paired stations located at different heights. The study of 59 pollen stations around the world provided a dataset of about 2,000,000 daily pollen concentrations, and yields important conclusions that can be generalized to different areas across the world for the most pollen types.

Materials and Methods

We studied the effect of height of air sampling on pollen concentrations in 25 areas around the world from 99.28º west to 145.13º east and from 60.46º north to 3.83º south, mainly in Europe, but also covering North America and Australia (Table 1; Supplementary Material Fig. S1).

Pollen data from 2-5 monitoring stations were considered from each area and analyzed, yielding a total of 59 pollen stations (Table 1). The same type of sampling device (Hirst-type volumetric trap (Hirst, 1952)) was used in all studied stations. The standard methodology agreed by the International Association for Aerobiology (IAA) (Jäger et al., 1995) or the European Aerobiology Society (EAS) (Galán et al., 2014; Šikoparija et al., 2017) was followed.

After pairing pollen monitoring stations, a total of 47 paired stations was obtained. For instance, an area provided only one pair when two stations were combined for that area e.g. Augsburg (Germany). Other areas with more concomitant stations could provide more pairs, like ten pairs of stations when five stations available for that area, e.g. Munich (Germany) (Table 1). Stations within 10km of each other were considered a pair (this criterium can be changed in the online analysis program: https://modeling-jesus-rojo.shinyapps.io/result_app2/, accessed October 2018). The height of selected stations was between 1.5 and 50 m above ground level (AGL).

Daily ratios of pollen concentrations were used to study the effect of height, and the mean pollen ratio (MPR) between two paired stations was calculated using equation 1. The standard deviation was estimated from daily pollen ratios.

$$\text{Mean Pollen Ratio (MPR)} = \frac{\sum^{n} PC_{lower}/\, PC_{higher}}{n} \qquad \text{(equ. 1)}$$

where, MPR is the mean of the daily pollen ratio, PC_{lower} is the pollen concentration from the lower pollen trap, PC_{higher} the pollen concentration from the higher pollen trap, and n is the number of days with pollen concentrations > 10 grains/m^3 for both traps.

Equation 1 exemplifies that if MPR > 1 then the lower pollen trap measured higher pollen concentrations. Alternatively, if MPR < 1, the higher pollen trap measured more pollen than the lower trap. The management of the pollen database and all analyses were carried out using the statistical software R (R Development Core Team, 2017).

To assess data quality, only years where the pollen data series from the paired stations were significantly correlated (R > 0.8) were included. Additionally, only days with pollen concentrations > 10 grains/m^3 for both traps of a pair were considered (Buters et al., 2015). The aim of these inclusion criteria was to minimize errors in the measurements of very low pollen counts, inherent to the aerobiological methods and documented by previous studies (Cotos-Yáñez et al., 2013; Šikoparija et al., 2017). This threshold of 10 grains/m^3 was used for all different pollen types and was a compromise value between reducing possible sources of error due to inaccurate pollen measurements and the largest possible number of data and number of stations for the analysis of each pollen type.

Pollen concentrations between sites can vary independent of the effects of height on air sampling (Tormo-Molina et al., 2013). Sources of variability may be instrumental (Oteros et al., 2017), environmental or human (Comtois et al., 1999; Oteros et al., 2013; Pedersen and Moseholm, 1993). To assess the effect of height-independent sources of variability (e.g. variations due to instrumental or human errors), pollen concentration from paired stations located at the same height and at the same location were analyzed as special cases. The areas selected for this comparison were: Munich (Germany), where three pollen stations were located at 8 m AGL (Buters et al., 2012) and Zrenjanin (Serbia) where two pollen stations were located at 20 m AGL. In these special cases, the mean pollen ratio was represented as a range of values around one, since either pollen stations could be used as the numerator when calculating the pollen ratio.

Although a great number of woody and herbaceous pollen types were analyzed, only the total pollen sum for all pollen types and total for the woody and for the herbaceous pollen types are shown in the results about the vertical profile of airborne pollen, ensuring an adequate number of cases to be studied. More detailed information on individual pollen types is given in Supplementary Material (Figure S2, and online at https://modeling-jesus-rojo.shinyapps.io/result_app2/, accessed October 2018). Pollen types considered from woody plants were *Alnus*, *Betula*, Cupressaceae/Taxaceae, *Fraxinus*, *Olea*, Pinaceae, *Platanus* and *Quercus*. Herbaceous plants included were *Ambrosia*, *Plantago*, Poaceae and Urticaceae. Again, the analysis can be adjusted to individual preferences online (see above).

Differences in ratios between pollen types were analyzed using a one-way analysis of variance (ANOVA) to determine whether the daily ratios of one pollen type deviated from other pollen types, i.e. whether some pollen type behaved differently to other pollen types. If ANOVA detected a significant difference among pollen, a Tukey test was then applied to determine exactly which pollen differed significantly from the others (see Table 2).

Results and Discussion

In this study, a dataset of about 2,000,000 daily pollen concentrations was used from a total of 59 pollen stations across the world, mainly in Europe, but also North America, and Australia. Our original hypothesis that pollen concentrations would vary vertically between near-ground and 50m was supported by the results. However, the effect of height on pollen concentrations was limited, and was mainly determined by differences within the first ten meters above ground.

The results show that as the height difference increases, the pollen ratio increased (i.e. pollen concentrations were lower at increased height). Above a certain height difference the ratio stabilizes at around 1.5. Thus, the difference in pollen concentrations registered by the lower station was maximally 50% higher than observed at higher height (the maximum height difference considered, Δheight = 33 m). This general behavior is shown for total pollen amounts (Figures 1A-C) and for the most pollen types studied such as *Betula*, *Fraxinus*, Poaceae, *Quercus* or Urticaceae (Supplementary Material, Figure S2). Chan and Kwok (2000) reported a similar pattern of vertical distribution in suspended particulate matter, with a decrease in airborne particle concentrations occurring mainly within the first meters of increase in height.

Our study on the height on pollen sampling showed that most of the paired stations for most of the pollen types yielded values of mean pollen ratio higher than 1. Therefore, the pollen traps at lower height registered generally higher pollen concentrations. Pollen ratio higher than 1 were expected according to the reviewed literature (Alcázar et al., 1999; Xiao et al., 2013), as pollen concentrations decrease with height. However, this behavior was not observed for all reviewed cases, possibly due to the influence of other factors than height as discussed below (Borycka and Kasprzyk, 2018; Bryant et al., 1989; Khattab and Levetin, 2008).

Not only the height difference between paired pollen stations is important. The height above ground level of the lower station (minimum height) plays a crucial role on the effect of height on pollen concentrations. Figure 1 (D-F) showed that the standard deviation of the pollen ratio is highly variable when the lower station is located close to the ground level reaching standard deviations above 3 when the minimum height of the lower station was below 10 m AGL. Similar to pollen grains, also concentrations of other particulate matter (Brady et al., 2016) and gases (that have no sedimentation) at ground level showed more daily fluctuations in concentrations than those registered at higher levels of the troposphere, where concentrations are more stable (Salmond et al., 2013; Zhang and Rao, 1999).

In general, a greater pollen ratio between paired stations was observed when the lower station was located below 10 m AGL (Figure 1 A-C). Above this level, standard deviation showed a strong reduction and a marked stabilization (Fig. 2). These results could be interpreted as showing that airborne pollen sampled in the first few meters from ground level (emission source) is dependent on the height of the trap but their concentrations are also highly fluctuating over time due to local pollen emission, deposition or resuspension, or phenomena of atmospheric dynamics produced at microscale . Then, pollen concentrations from a certain height tend to stabilize and the height effect loses relevance (Raynor et al., 1973), as for other aerosols (Brady et al., 2016).

The results indicate that the pollen concentrations are much more homogenous above 10 m AGL, where most pollen stations in urban areas are localized. This suggest, that if the purpose of a pollen trap is to provide representative data for a relatively large geographical region in an urbanized area (Velasco-Jiménez et al., 2013), then it should be placed on a building at least 10 m AGL, i.e. this height could be considered as the minimum optimal height to locate stations for pollen sampling. A consequence of such a placement is that local effects are less likely to be detected by the trap and thus pollen stations above this height analyze airborne pollen in more homogeneous conditions. The optimal height for the location of a sampler also depends on the urban design (Galán et al., 2014). Therefore the sampler should be located away from the edge of a building and away from higher surrounding buildings avoiding the effect of turbulence due to urban canyon influence (Peel et al., 2014). Therefore, local building structure can demand placements of a trap substantially above 10 m AGL. However, our results show that the influence of the height on pollen sampling is getting smaller above 10m AGL. On the other hand, traps used for other purposes could be placed near the surface where airborne particles are emitted for the assessment of the spatial distribution of the allergenic flora (Hjort et al., 2016; Werchan et al., 2018), the control of the levels of pathogens in agriculture (Fernandez-Gonzalez et al., 2013) or the study of the fluxes of pollen emission and deposition near the pollen sourcesn(Jarosz et al., 2005).

The results also show that the effect of height on pollen sampling is independent of the pollen type considered. Most woody and herbaceous pollen types showed a similar pattern in the relationships between the mean pollen ratio or the standard deviation and the differences in height on sampling (Supplementary Material, Figure S2). Only pollen types such as *Platanus*, Cupressaceae or *Olea* showed a different pattern which can also be observed in Figure 3A and Supplementary Material. In Figure 3A, these pollen types showed higher pollen ratio when the height difference of the paired-stations decreased, contrary to other pollen types. Furthermore, *Platanus* and Cupressaceae were the pollen types that showed the greatest number of differences in pollen ratio, compared to the other types (Table 2).

It is remarkable that pollen types showing the highest differences in ratio represent the main pollen grains coming from ornamental plants in many urban green zones of the cities. *Platanus* trees and Cupressaceae species are important urban planted ornamental species especially in the western Mediterranean region (Cariñanos et al., 2017; Cariñanos and Casares-Porcel, 2011; Sánchez-Reyes et al., 2009), and therefore, the pollen sources in this case would be near to the urban pollen. Pollen types coming from species that grow abundantly could exhibit different vertical distribution profiles than sporadic planted species.

These results also indicate the importance of the distance from the pollen source to be considered on the effect of height on air sampling. Local emissions near the pollen stations will intensify the effect between paired stations and probably an increased pollen concentration can be expected at ground level (Šikoparija et al., 2018). Adams-Groom et al. (2017) indicated that most pollen was deposited at the first few meters from the pollen sources. In a same way, air in the first few meters above ground level from the pollen source would contain much greater quantities of pollen than higher heights resulting in severe differences in height ratios for places close to the pollen sources (Jarosz et al., 2005; Katz and Carey, 2014; Raynor et al., 1968). Therefore, the distance from the pollen source is an important factor influencing the pollen ratio, and will overlap with the effect of height on pollen sampling (Spieksma et al., 2000).

Apart from height or distance to a local source like ornamental plants, other factors can influence the ratio of pollen concentrations between stations too. These factors are topography, hour of day (Rantio-Lehtimäki et al. 1991; Alcazar et al. 1999; Noh et al. 2013), period of season considered (R. G. Peel et al., 2014), or meteorological conditions of the atmosphere (Ríos et al., 2016; Skjøth et al., 2013), specially wind direction and speed, ambient humidity or rainfall which determines the pollen dispersal capacity in the air (Pérez et al., 2009; Rojo et al., 2015).

We also assessed the error of the Hirst-type pollen trap by using side by side stations located at the same height, as documented by other authors in previous works (Buters et al., 2012; Tormo-Molina et al., 2013; Buters et al., 2015). Although pollen concentrations between pollen traps located at the same height were not significantly different (Giorato et al., 2003; Irdi et al., 2002; Velasco-Jiménez et al., 2013), certain level of variability for daily pollen data was observed in our results (Fig. 4). Therefore, the standard deviation of Hirst-type traps in the analysis of Munich (Germany) and Zrenjanin (Serbia) was 0.34 (34%) on average, being the maximum uncertainty estimated by (Pedersen and Moseholm, 1993) in a similar approach. This value of the standard deviation from daily pollen ratio showed an important daily variation despite that the mean pollen ratio was near to 1 (0.83-1.17) i.e. the mean pollen concentrations were similar for both paired stations. This explains why no significant differences were found in previous works (Tormo-Molina et al., 2013). This daily variability could be explained by random variations caused by instrumental error but could also be influenced again by meteorological conditions (Pedersen and Moseholm, 1993). This error is independent of the interlaboratory variability, as all samples between paired stations were processes and counted at the same laboratory.

In conclusion, the effect of height of air sampling between stations is only one of the factors which influences the pollen ratio between paired stations, together with other factors such as the minimum height of the lower station or the distance between the stations. At a local scale, other factors such as distance from the local sources, topography, meteorological conditions, hour of day and period of season could play a role too. The data shows that the effect of sampling pollen at different heights is clear but limited, and that pollen concentrations are much more homogenous above 10 m AGL. Thus, depending on the purpose of the trap, the optimal height of a pollen monitor could be >10 m AGL. These findings reveal the importance of the vertical distribution of bioaerosols and further contribute to the definition of the real pollen exposure at ground level and, hence, are highly relevant to clinical practice.

Acknowledgment

Ingrid Weichenmeier, Christine Weil and Gudrun Pusch are greatly acknowledged for their help in counting pollen for so many years. Also the acknowledgment to the personnel responsible of the rest of research groups.

Funding Sources

The work was funded by ZAUM- Center of Allergy & Environment of the Technical University Munich/ Helmholtzzentrum Munich.

Declaration of competing financial interests (CFI)

The authors declare they have no actual or potential competing financial interests.

References

Adams-Groom, B., Skjøth, C.A., Baker, M., Welch, T.E., 2017. Modelled and observed surface soil pollen deposition distance curves for isolated trees of Carpinus betulus, Cedrus atlantica, Juglans nigra and Platanus acerifolia. Aerobiologia 33, 407–416. https://doi.org/10.1007/s10453-017-9479-1

Alcazar, P., Comtois, P., 2000. The influence of sampler height and orientation on airborne Ambrosia pollen counts in Montreal. Grana 39, 303–307. https://doi.org/10.1080/00173130052504342

Alcázar P, Galán C, Cariñanos P, Domínguez-Vilches E. 1999. Effects of sampling height and climatic conditions in aerobiological studies. J Investig Allergol Clin Immunol 9: 253–261.

Alcázar P, Galán C, Cariñanos P, Domínguez-Vilches E. 1999. Diurnal variation of airborne pollen at two different heights. J Investig Allergol Clin Immunol 9: 89–95.

Barbosa, C.G.G., Taylor, P.E., de Souza, R.A.F., Pöhlker, C., Andreae, M.O., Godoi, R.H.M., 2018. Vertical transport of primary biological aerosols emitted from the Amazon rainforest, in: 14th Quadrennial Symposium ICACGP and 15th Science Conference IGAC. Takamatsu Kagawa, Japan.

Borycka, K., Kasprzyk, I., 2018. Hourly pattern of allergenic alder and birch pollen concentrations in the air: Spatial differentiation and the effect of meteorological conditions. Atmos. Environ. 182, 179–192. https://doi.org/10.1016/j.atmosenv.2018.03.048

Brady, J.M., Stokes, M.D., Bonnardel, J., Bertram, T.H., 2016. Characterization of a Quadrotor Unmanned Aircraft System for Aerosol-Particle-Concentration Measurements. Environ. Sci. Technol. 50, 1376–1383. https://doi.org/10.1021/acs.est.5b05320

Bryant, R.H., Emberlin, J.C., Norris-Hill, J., 1989. Vertical variation in pollen abundance in North-Central London. Aerobiologia 5, 123–137. https://doi.org/10.1007/BF02486510

Buters, J., Prank, M., Sofiev, M., Pusch, G., Albertini, R., Annesi-Maesano, I., Antunes, C., Behrendt, H., Berger, U., Brandao, R., Celenk, S., Galan, C., Grewling, Ł., Jackowiak, B., Kennedy, R., Rantio-Lehtimäki, A., Reese, G., Sauliene, I., Smith, M., Thibaudon, M., Weber, B., Cecchi, L., 2015. Variation of the group 5 grass pollen allergen content of airborne pollen in relation to geographic location and time in season. J. Allergy Clin. Immunol. 136, 87-95.e6. https://doi.org/10.1016/j.jaci.2015.01.049

Buters J, Antunes C, Galveias A, Bergmann KC, Thibaudon M, Galán C, et al. 2018. Pollen and spore monitoring in the world. Clin Transl Allergy 8; doi:10.1186/s13601-018-0197-8.

Buters J, Thibaudon M, Smith M, Kennedy R, Rantio-Lehtimäki A, Albertini R, et al. 2012. Release of Bet v 1 from birch pollen from 5 European countries. Results from the HIALINE study. Atmos Environ 55:496–505; doi:10.1016/j.atmosenv.2012.01.054.

Cariñanos, P., Casares-Porcel, M., 2011. Urban green zones and related pollen allergy: A review. Some guidelines for designing spaces with low allergy impact. Landsc. Urban Plan. 101, 205–214. https://doi.org/10.1016/j.landurbplan.2011.03.006

Cariñanos, P., Casares-Porcel, M., Díaz de la Guardia, C., Aira, M.J., Belmonte, J., Boi, M., Elvira-Rendueles, B., De Linares, C., Fernández-Rodriguez, S., Maya-Manzano, J.M., Pérez-Badía, R., Rodriguez-de la Cruz, D., Rodríguez-Rajo, F.J., Rojo-Úbeda, J., Romero-Zarco, C., Sánchez-Reyes, E., Sánchez-Sánchez, J., Tormo-Molina, R., Vega

Maray, A.M., 2017. Assessing allergenicity in urban parks: A nature-based solution to reduce the impact on public health. Environ. Res. 155, 219–227. https://doi.org/10.1016/j.envres.2017.02.015

Cecchi L, D'Amato G, Ayres JG, Galán C, Forastiere F, Forsberg B, et al. 2010. Projections of the effects of climate change on allergic asthma: the contribution of aerobiology: Climate change and aerobiology. Allergy 65:1073–1081; doi:10.1111/j.1398-9995.2010.02423.x.

Chakraborty, P., Gupta-Bhattacharya, S., Chowdhury, I., Majumdar, M.R., Chanda, S., 2001. Differences in concentrations of allergenic pollens and spores at different heights on an agricultural farm in West Bengal, India. Ann. Agric. Environ. Med. 8, 123–130.

Chan, L.., Kwok, W.., 2000. Vertical dispersion of suspended particulates in urban area of Hong Kong. Atmos. Environ. 34, 4403–4412. https://doi.org/10.1016/S1352-2310(00)00181-3

Charalampopoulos, A., Lazarina, M., Tsiripidis, I., Vokou, D., 2018. Quantifying the relationship between airborne pollen and vegetation in the urban environment. Aerobiologia 34, 285–300. https://doi.org/10.1007/s10453-018-9513-y

Comtois P, Alcázar P, Néron D. 1999. Pollen counts statistics and its relevance to precision. Aerobiologia 15:19–28; doi:10.1023/A:1007501017470.

Comtois, P., Fernández-González, D., Valencia-Barrera, R.M., Sánchez, J.L., Fraile, R., Rodier, S., 2000. Pollen content study of the lower atmosphere in León (Spain) by use of a tethered balloon. Aerobiologia 16, 187–191. https://doi.org/10.1023/A:1007685513925

Cotos-Yáñez, T.R., Rodríguez-Rajo, F.J., Pérez-González, A., Aira, M.J., Jato, V., 2013. Quality control in aerobiology: comparison different slide reading methods. Aerobiologia 29, 1–11. https://doi.org/10.1007/s10453-012-9263-1

Damialis A, Kaimakamis E, Konoglou M, Akritidis I, Traidl-Hoffmann C, Gioulekas D. 2017. Estimating the abundance of airborne pollen and fungal spores at variable elevations using an aircraft: how high can they fly? Sci Rep 7: 44535; doi:https://doi.org/10.1038/srep44535

Di-Giovanni, F., Kevan, P.G., 1991. Factors affecting pollen dynamics and its importance to pollen contamination: a review. Can. J. For. Res. 21, 1155–1170.

European Academy of Allergy and Clinical & Immunology, 2015. Advocacy Manifesto Tackling the Allergy Crisis in Europe - Concerted Policy Action Needed. Brussels, Belgium.

Fernandez-Gonzalez, M., Rodriguez-Rajo, F.J., Escuredo, O., Aira, M.J., 2013. Optimization of integrated pest management for powdery mildew (Unincula necator) control in a vineyard based on a combination of phenological, meteorological and aerobiological data. J. Agric. Sci. 151, 648–658. https://doi.org/10.1017/S0021859612000743

Fernández-Rodríguez, S., Durán-Barroso, P., Silva-Palacios, I., Tormo-Molina, R., Maya-Manzano, J.M., Gonzalo-Garijo, Á., Monroy-Colin, A., 2018. Environmental assessment of allergenic risk provoked by airborne grass pollen through forecast model in a Mediterranean region. J. Clean. Prod. 176, 1304–1315. https://doi.org/10.1016/j.jclepro.2017.11.226

Fernández-Rodríguez S, Tormo-Molina R, Maya-Manzano JM, Silva-Palacios I, Gonzalo-Garijo Á. 2014. A comparative study on the effects of altitude on daily and hourly airborne pollen counts. Aerobiologia 30: 257–268; doi: doi.org/10.1007/s10453-014-9325-7

Fiorina, A., Mincarini, M., Sivori, M., Scordamaglia, A., Canonica, G.W., Brichetto, L., 1999. Aeropollinic sampling at three different heights by personal volumetric collector (Partrap FA 52). Allergy 54, 1309–1315.

Fugiel, A., Burchart-Korol, D., Czaplicka-Kolarz, K., Smoliński, A., 2017. Environmental impact and damage categories caused by air pollution emissions from mining and quarrying sectors of European countries. J. Clean. Prod. 143, 159–168. https://doi.org/10.1016/j.jclepro.2016.12.136

Galán, C., Alcázar-Teno, P., Domínguez-Vilches, E., de la Torre, F.V., Garcia-Pantaleon, F.I., 1995. Airborne pollen grain concentrations at two different heights. Aerobiologia 11, 105–109.

Galán, C., Smith, M., Thibaudon, M., Frenguelli, G., Oteros, J., Gehrig, R., Berger, U., Clot, B., Brandao, R., EAS QC Working Group, 2014. Pollen monitoring: minimum requirements and reproducibility of analysis. Aerobiologia 30, 385–395. https://doi.org/10.1007/s10453-014-9335-5

Giorato, M., Bordin, A., Gemignani, C., Turatello, F., Marcer, G., 2003. Airborne pollen in Padua (NE-Italy): A comparison between two pollen samplers. Aerobiologia 19, 129–131.

Gregory, P.H., 1978. Distribution of airborne pollen and spores and their long distance transport. Pure Appl. Geophys. PAGEOPH 116, 309–315. https://doi.org/10.1007/BF01636888

Gruber, S., Matthias-Maser, S., Brinkmann, J., Jaenicke, R., 1998. Vertical distribution of biological aerosol particles above the North Sea. J. Aerosol Sci. S771–S772.

Hertel, O., Jensen, S.S., Ketzel, M., Becker, T., Peel, R.G., Orby, P.V., Skjoth, C.A., Ellermann, T., Raaschou-Nielsen, O., Sorensen, M., Brauner, E.V., Andersen, Z.J., Loft, S., Schlunssen, V., Bonlokke, J.H., Sigsgaard, T., 2013. Utilizing Monitoring Data and Spatial Analysis Tools for Exposure Assessment of Atmospheric Pollutants in Denmark, in: McConnell, L.L., Dachs, J., Hapeman, C.J. (Eds.), Occurrence, Fate and Impact of Atmospheric Pollutants on Environmental and Human Health. Amer Chemical Soc, Washington, pp. 95–122.

Hirst, J.M., 1952. An automatic volumetric spore trap. Ann. Appl. Biol. 39, 257–265. https://doi.org/10.1111/j.1744-7348.1952.tb00904.x

Hjort, J., Hugg, T.T., Antikainen, H., Rusanen, J., Sofiev, M., Kukkonen, J., Jaakkola, M.S., Jaakkola, J.J.K., 2016. Fine-Scale Exposure to Allergenic Pollen in the Urban Environment: Evaluation of Land Use Regression Approach. Environ. Health Perspect. 124, 619–626. https://doi.org/10.1289/ehp.1509761

Irdi, G.A., Jones, J.R., White, C.M., 2002. Pollen and fungal spore sampling and analysis. Statistical evaluations. Grana 41, 44–47.

Jäger, S., Mandrioli, P., Spieksma, F., Emberlin, J., Hjelmroos, M., Rantio-Lehtimäki, A., Domínguez-Vilches, E., Ickovic, M.-R., 1995. Methodology for routinely performed monitoring of airborne pollen recommendations. Aerobiologia 11, 69. https://doi.org/10.1007/BF02136148

Jarosz, N., Loubet, B., Durand, B., Foueillassar, X., Huber, L., 2005. Variations in Maize Pollen Emission and Deposition in Relation to Microclimate. Environ. Sci. Technol. 39, 4377–4384. https://doi.org/10.1021/es0494252

Katz, D.S.W., Carey, T.S., 2014. Heterogeneity in ragweed pollen exposure is determined by plant composition at small spatial scales. Sci. Total Environ. 485–486, 435–440. https://doi.org/10.1016/j.scitotenv.2014.03.099

Khattab, A., Levetin, E., 2008. Effect of sampling height on the concentration of airborne fungal spores. Ann. Allergy. Asthma. Immunol. 101, 529–534.

Lake, I.R., Jones, N.R., Agnew, M., Goodess, C.M., Giorgi, F., Hamaoui-Laguel, L., Semenov, M.A., Solomon, F., Storkey, J., Vautard, R., Epstein, M.M., 2017. Climate Change and Future Pollen Allergy in Europe. Environ. Health Perspect. 125, 385–391. https://doi.org/10.1289/EHP173

Makra, L., Matyasovszky, I., Tusnády, G., Wang, Y., Csépe, Z., Bozóki, Z., Nyúl, L.G., Erostyák, J., Bodnár, K., Sümeghy, Z., Vogel, H., Pauling, A., Páldy, A., Magyar, D., Mányoki, G., Bergmann, K.-C., Bonini, M., Šikoparija, B., Radišić, P., Gehrig, R., Seliger, A.K., Stjepanović, B., Rodinkova, V., Prikhodko, A., Maleeva, A., Severova, E., Ščevková, J., Ianovici, N., Peternel, R., Thibaudon, M., 2016. Biogeographical estimates of allergenic pollen transport over regional scales: Common ragweed and Szeged, Hungary as a test case. Agric. For. Meteorol. 221, 94–110. https://doi.org/10.1016/j.agrformet.2016.02.006

Makra, L., Santa, T., Matyasovszky, I., Damialis, A., Karatzas, K., Bergmann, K.-C., Vokou, D., 2010. Airborne pollen in three European cities: Detection of atmospheric circulation pathways by applying three-dimensional clustering of backward trajectories. J. Geophys. Res.-Atmospheres 115, D24220. https://doi.org/10.1029/2010JD014743

Myszkowska, D., Stepalska, D., Dyga, W., Bokalska-Rajba, J., Czarnobilska, E., 2012. Survey of biological particles in the atmosphere of the Cracow center (southern Poland) in 2011. Preliminary study. Przegl. Lek. 69, 1254–1260.

Noh, Y.M., Lee, H., Mueller, D., Lee, K., Shin, D., Shin, S., Choi, T.J., Choi, Y.J., Kim, K.R., 2013. Investigation of the diurnal pattern of the vertical distribution of pollen in the lower troposphere using LIDAR. Atmospheric Chem. Phys. 13, 7619–7629. https://doi.org/10.5194/acp-13-7619-2013

Orlanski, I., 1975. A rational subdivision of scales for atmospheric processes. Bull. Am. Meteorol. Soc. 56, 527–530. https://doi.org/www.jstor.org/stable/26216020

Oteros, J., Buters, J., Laven, G., Röseler, S., Wachter, R., Schmidt-Weber, C., Hofmann, F., 2017. Errors in determining the flow rate of Hirst-type pollen traps. Aerobiologia 33, 201–210. https://doi.org/10.1007/s10453-016-9467-x

Oteros, J., Galán, C., Alcázar, P., Domínguez-Vilches, E., 2013. Quality control in bio-monitoring networks, Spanish Aerobiology Network. Sci. Total Environ. 443, 559–565. https://doi.org/10.1016/j.scitotenv.2012.11.040

Pawankar, R., Canonica, G.W., Holgate, S.T., Lockey, R.F., Blaiss, M., 2013. World Allergy Organisation (WAO) white book on allergy: update 2013. Milwaukee World Allergy Organ.

Pedersen, B.V., Moseholm, L., 1993. Precision of the daily pollen count. Identifying sources of variation using variance component models. Aerobiologia 9, 15–26.

Peel, R.G., Hertel, O., Smith, M., Kennedy, R., 2013. Personal exposure to grass pollen: relating inhaled dose to background concentration. Ann. Allergy. Asthma. Immunol. 111, 548–554. https://doi.org/10.1016/j.anai.2013.09.002

Peel, Robert George, Kennedy, R., Smith, M., Hertel, O., 2014. Do urban canyons influence street level grass pollen concentrations? Int. J. Biometeorol. 58, 1317–1325. https://doi.org/10.1007/s00484-013-0728-x

Peel, R. G., Ørby, P.V., Skjøth, C.A., Kennedy, R., Schlünssen, V., Smith, M., Sommer, J., Hertel, O., 2014. Seasonal variation in diurnal atmospheric grass pollen concentration profiles. Biogeosciences 11, 821–832. https://doi.org/10.5194/bg-11-821-2014

Penel, V., Calleja, M., Pichot, C., Charpin, D., 2017. Static and elevated pollen traps do not provide an accurate assessment of personal pollen exposure. Eur. Ann. Allergy Clin. Immunol. 49, 59–65.

Pérez, C.F., Gassmann, M.I., Covi, M., 2009. An evaluation of the airborne pollen–precipitation relationship with the superposed epoch method. Aerobiologia 25, 313–320. https://doi.org/10.1007/s10453-009-9135-5

R Development Core Team, 2017. R: A Language and Environment for Statistical Computing. The R Foundation for Statistical Computing, Vienna, Austria.

Rantio-Lehtimäki, A, Helander, M.L., Pessi, A.-M., 1991. Circadian periodicity of airborne pollen and spores; significance of sampling height. Aerobiologia 7, 129–135. https://doi.org/10.1007/BF02270681

Raynor, G.S., Ogden, E.C., Hayes, J.V., 1973. Variation in ragweed pollen concentration to a height of 108 meters. J. Allergy Clin. Immunol. 51, 199–207.

Raynor, G.S., Ogden, E.C., Hayes, J.V., 1968. Effect of a local source on ragweed pollen concentrations from background sources. J. Allergy 41, 217–225.

Reinmuth-Selzle, K., Kampf, C.J., Lucas, K., Lang-Yona, N., Fröhlich-Nowoisky, J., Shiraiwa, M., Lakey, P.S.J., Lai, S., Liu, F., Kunert, A.T., Ziegler, K., Shen, F., Sgarbanti, R., Weber, B., Bellinghausen, I., Saloga, J., Weller, M.G., Duschl, A., Schuppan, D., Pöschl, U., 2017. Air Pollution and Climate Change Effects on Allergies in the Anthropocene: Abundance, Interaction, and Modification of Allergens and Adjuvants. Environ. Sci. Technol. 51, 4119–4141. https://doi.org/10.1021/acs.est.6b04908

Ríos, B., Torres-Jardón, R., Ramírez-Arriaga, E., Martínez-Bernal, A., Rosas, I., 2016. Diurnal variations of airborne pollen concentration and the effect of ambient temperature in three sites of Mexico City. Int. J. Biometeorol. 60, 771–787. https://doi.org/10.1007/s00484-015-1061-3

Rodríguez de la Cruz, D., Dávila, I., Sánchez-Reyes, E., Lorente, F., Sánchez, J.S., 2016. Comparison of Pollen Levels Between 2 Pollen Traps in Salamanca, Spain. J Investig Allergol Clin Immunol 26, 111–143.

Rojo, J., Rapp, A., Lara, B., Fernández-González, F., Pérez-Badia, R., 2015. Effect of land uses and wind direction on the contribution of local sources to airborne pollen. Sci. Total Environ. 538, 672–682. https://doi.org/10.1016/j.scitotenv.2015.08.074

Rojo J, Serrano-Bravo MD, Lara B, Fernández-González F, Pérez-Badia R. 2018. Halo-nitrophilous scrub species and their relationship to the atmospheric concentration of allergenic pollen: case study of the Mediterranean saltbush (Atriplex halimus L., Amaranthaceae). Plant Biosyst - Int J Deal Asp Plant Biol 1–10; doi:10.1080/11263504.2018.1461699.

Romero-Morte, J., Rojo, J., Rivero, R., Fernández-González, F., Pérez-Badia, R., 2018. Standardised index for measuring atmospheric grass-pollen emission. Sci. Total Environ. 612, 180–191. https://doi.org/10.1016/j.scitotenv.2017.08.139

Salmond, J.A., Williams, D.E., Laing, G., Kingham, S., Dirks, K., Longley, I., Henshaw, G.S., 2013. The influence of vegetation on the horizontal and vertical distribution of pollutants in a street canyon. Sci. Total Environ. 443, 287–298. https://doi.org/10.1016/j.scitotenv.2012.10.101

Sánchez-Reyes, E., de la Cruz, D.R., Sanchís-Merino, M.E., Sánchez-Sánchez, J., 2009. First results of Platanus pollen airborne content in the middle-west of the Iberian Peninsula. Aerobiologia 25, 209.

Šikoparija, B., Galán, C., Smith, M., EAS QC Working Group, 2017. Pollen-monitoring: between analyst proficiency testing. Aerobiologia 33, 191–199. https://doi.org/10.1007/s10453-016-9461-3

Šikoparija, B., Mimić, G., Panić, M., Marko, O., Radišić, P., Pejak-Šikoparija, T., Pauling, A., 2018. High temporal resolution of airborne Ambrosia pollen measurements above the source reveals emission characteristics. Atmos. Environ. 193, 13–23. https://doi.org/10.1016/j.atmosenv.2018.08.040

Skjøth, C.A., Ørby, P.V., Becker, T., Geels, C., Schlünssen, V., Sigsgaard, T., Bønløkke, J.H., Sommer, J., Søgaard, P., Hertel, O., 2013. Identifying urban sources as cause of elevated grass pollen concentrations using GIS and remote sensing. Biogeosciences 10, 541–554.

Spieksma, F.T.M., van Noort, P., Nikkels, H., 2000. Influence of nearby stands of Artemisia on street-levelversus roof-top-level ratio's of airborne pollen quantities. Aerobiologia 16, 21–24.

Tormo-Molina, R., Maya Manzano, J.M., Fernandez Rodriguez, S., Gonzalo Garijo, Á., Silva Palacios, I., 2013. Influence of environmental factors on measurements with Hirst spore traps. Grana 52, 59–70. https://doi.org/10.1080/00173134.2012.718359

Velasco-Jiménez, M.J., Alcázar, P., Domínguez-Vilches, E., Galán, C., 2013. Comparative study of airborne pollen counts located in different areas of the city of Córdoba (south-western Spain). Aerobiologia 29, 113–120. https://doi.org/10.1007/s10453-012-9267-x

Werchan, B., Werchan, M., Mücke, H.-G., Bergmann, K.-C., 2018. Spatial distribution of pollen-induced symptoms within a large metropolitan area—Berlin, Germany. Aerobiologia. https://doi.org/10.1007/s10453-018-9529-3

Xiao, X., Fu, A., Xie, X., Kang, M., Hu, D., Yang, P., Liu, Z., 2013. An investigation of airborne allergenic pollen at different heights. Int. Arch. Allergy Immunol. 160, 143–151.

Zhang, H., Wang, Shuxiao, Hao, J., Wang, X., Wang, Shulan, Chai, F., Li, M., 2016. Air pollution and control action in Beijing. J. Clean. Prod. 112, 1519–1527. https://doi.org/10.1016/j.jclepro.2015.04.092

Zhang, J., Rao, S.T., 1999. The role of vertical mixing in the temporal evolution of ground-level ozone concentrations. J. Appl. Meteorol. 38, 1674–1691.

Supplementary Material

- Supplementary Material Figure S1
- Supplementary Material Figure S2
- Supplementary Material Table S1
- Supporting data evaluation: all parameters leading to our conclusions can be individually adjusted to the user needs with a supplemental data evaluation tool available at https://modeling-jesus-rojo.shinyapps.io/result_app2/, accessed October 2018.

Figure legends

Figure 1. Relationship between the mean pollen ratio and the height difference between paired-stations (A-C). Relationship between the standard deviation of the mean pollen ratio and the minimum height of the lower station (D-F). A logarithmic function was fitted and the 99% confidence intervals are shown. The vertical dashed line in D-F is the proposed minimum height of the lower station. The plots for the individual pollen types are given in supplementary material.

Figure 2. Relationship between the standard deviation of the standard deviation (SD) of the mean pollen ratio and the minimum height of the lower station for (A) woody, (B) herbaceous and (C) all pollen types. This figure shows the SD of the figure 1 (D-F) and supports the minimum height of the lower station of >10 m AGL as this reduces the variability of the measurements.

Figure 3. Boxplots comparing the mean pollen ratio depending on: (A) ∆height or (B) height of the lower station.

Figure 4. Mean pollen ratio and standard deviation calculated for the pollen concentrations registered by pollen traps located at the same height and location. This special case was studied for three stations in Munich (Germany) (A, B) and two stations in Zrenjanin (Serbia) (C). The standard deviation of Hirst-type traps in this analysis was 34%. Values of <10 pollen/m^3 were not considered.

Tables

Table 1. Detailed information about the pollen stations located in the studied areas. *Latitude and longitude values show a geographical range when pollen stations are separated from each other.

City of the studied area (country)	Sampling heights (m AGL)	Latitude (decimal degrees)*	Longitude (decimal degrees)*
Augsburg (Germany)	1.5, 13	48.32 – 48.33	10.90
Badajoz (Spain)	2, 6, 16	38.88 – 38.90	-7.00 – -6.97
Budapest (Hungary)	12, 23	47.48	19.08 – 19.09
Bursa (Turkey)	20, 20	40.22	28.88
Copenhagen (Denmark)	15, 20	55.70 – 55.72	12.55
Cordoba (Spain)	1.5, 15	37.87	-4.80
Krakow (Poland)	15, 20	50.06	19.94 – 19.95
Leon (Spain)	15, 20	42.60 – 42.61	-5.57 – -5.56
Madrid (Spain)	8, 10, 16, 18	40.31 – 40.45	-3.76 – -3.70
Malaga (Spain)	12, 15	36.72 – 36.73	-4.47 – -4.42
Melbourne (Australia)	3, 4, 14	-37.82 – -37.80	144.90 – 145.13
Mexico City (Mexico)	10, 10, 15	19.33 – 19.41	-99.28 – -99.18
Milan (Italy)	17, 18	45.60 – 45.61	8.84 – 8.92
Moscow (Russia)	1.5, 10	55.70	37.53
Munich (Germany)	2, 8, 8, 8, 35	48.13 – 48.22	11.56 – 11.60
Paris (France)	30, 43, 50	48.84 – 48.89	2.31 – 2.37
Parma (Italy)	18, 32	44.80	10.31 – 10.32
Porto (Portugal)	10, 18	41.15 – 41.18	-8.64 – -8.60
Rzeszow (Poland)	1.5, 12	50.00	22.02
Salamanca (Spain)	14, 23	40.97	-5.68 – -5.66
Szeged (Hungary)	18, 20	46.24 – 46.25	20.14 – 20.17

Turku (Finland)	1.5, 15	60.46	22.29
Valladolid (Spain)	17, 32	41.64 – 41.66	-4.73
Worcester (United Kingdom)	4, 10	52.20 – 52.25	-2.25 – -2.24
Zrenjanin (Serbia)	20, 20	45.38	20.40

Table 2. Number of significant differences in ratio per pollen type ($p < 0.05$, Tukey post hoc test). The height effect is not pollen dependent, except for *Platanus* and Cupressaceae in some stations. The rest of paired stations did not display differences (70%).

	*Paired-station	Alnu	Ambr	Betu	Cupr	Frax	Olea	Pina	Plan	Plat	Poac	Popu	Urti
1	Badajoz (2/16)						2	2	1	1			
2	Badajoz (2/6)						1		2		1		
3	Badajoz (6/16)						2		2		2		
4	Copenhagen (15/20)			1		3		2			1		1
5	Cordoba (1.5/15)				1		2				1		
6	Madrid (10/18)				1	1	1	1	1	7	1	1	
7	Madrid (8/16)				4	1	2	1	2	7	2	1	
8	Milan (17/18)	1		2	1			2		6	3		1
9	Munich (2/35)	1		2	7	3		1			1	1	2
10	Parma (18/32)									2	1	1	
11	Salamanca (14/23)					1	1						
12	Turku (1.5/15)			1				1					

*Stations per city (x/y): x height of the lower station, y height of the higher station, given in m AGL

Pollen types: Alnu Alnus, Ambr Ambrosia, Betu Betula, Cupr Cupressaceae/Taxaceae, Frax Fraxinus, Olea Olea, Pina Pinaceae, Plan Plantago, Plat Platanus, Poac Poaceae, Popu Populus, Urti Urticaceae

Graphical Abstract

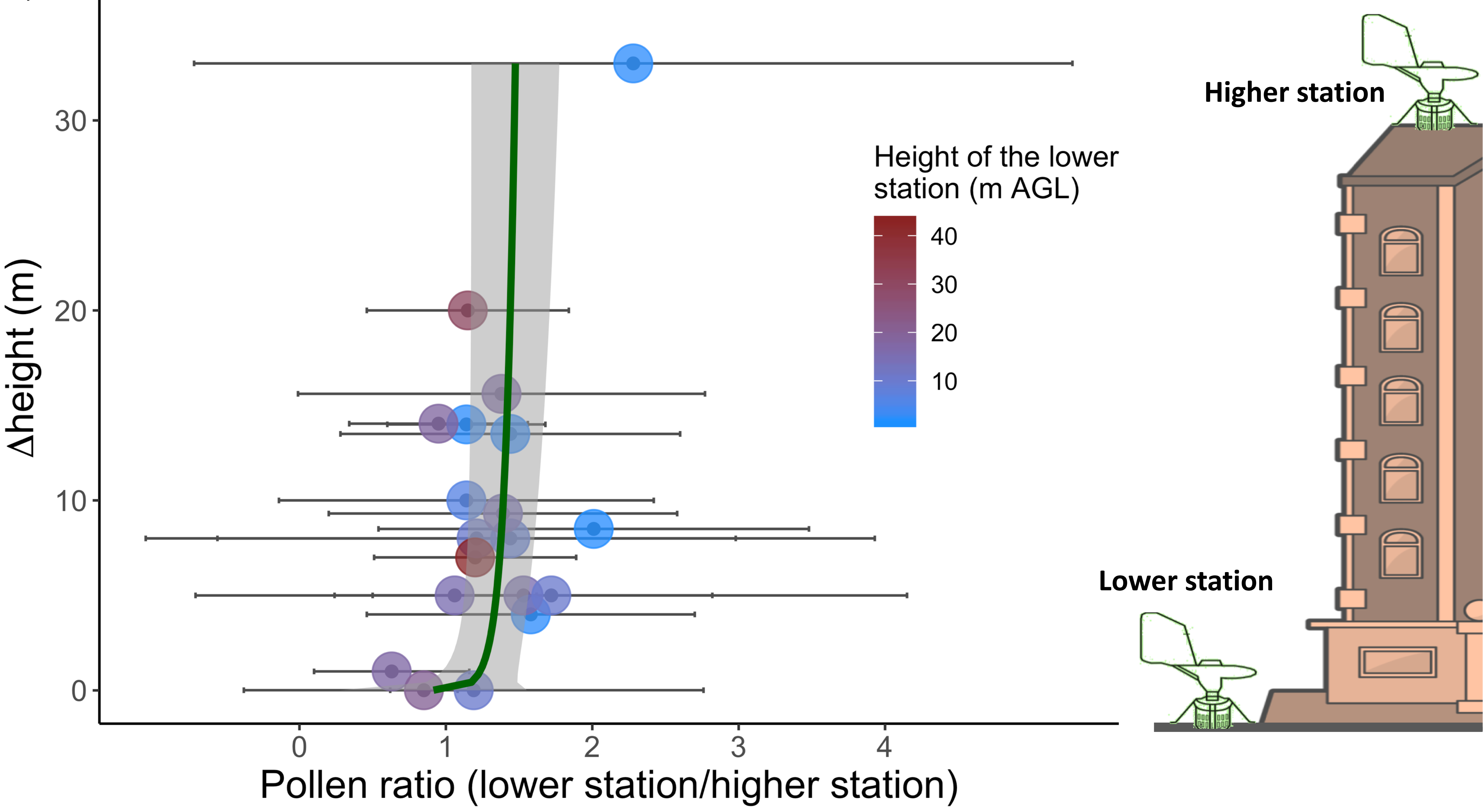


Figure 1

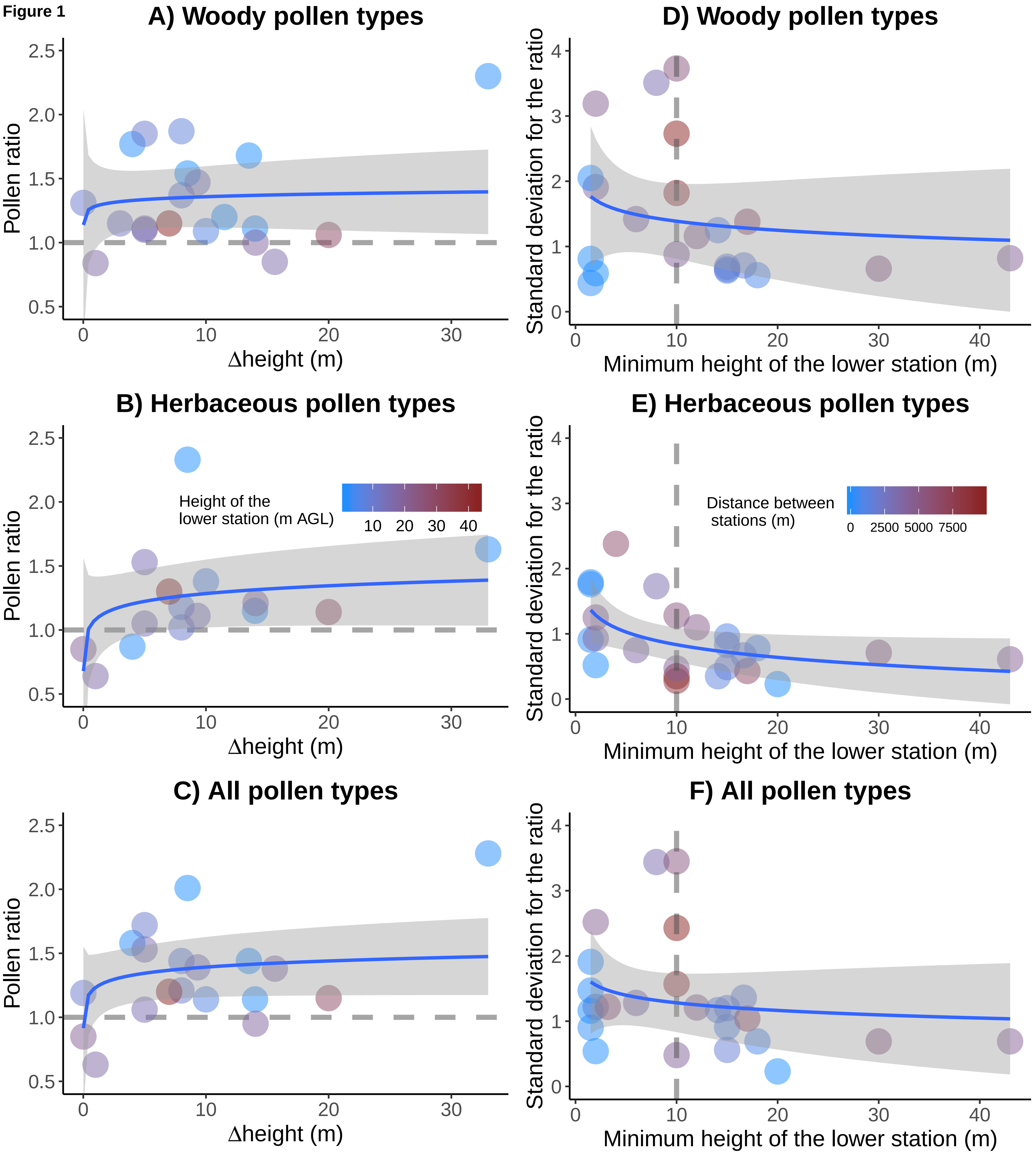

A) Woody pollen types
Pollen ratio
Δheight (m)
B) Herbaceous pollen types
Height of the
lower station (m AGL)
10 20 30 40
C) All pollen types
D) Woody pollen types
Standard deviation for the ratio
Minimum height of the lower station (m)
E) Herbaceous pollen types
Distance between
stations (m)
0 2500 5000 7500
F) All pollen types

Figure 2

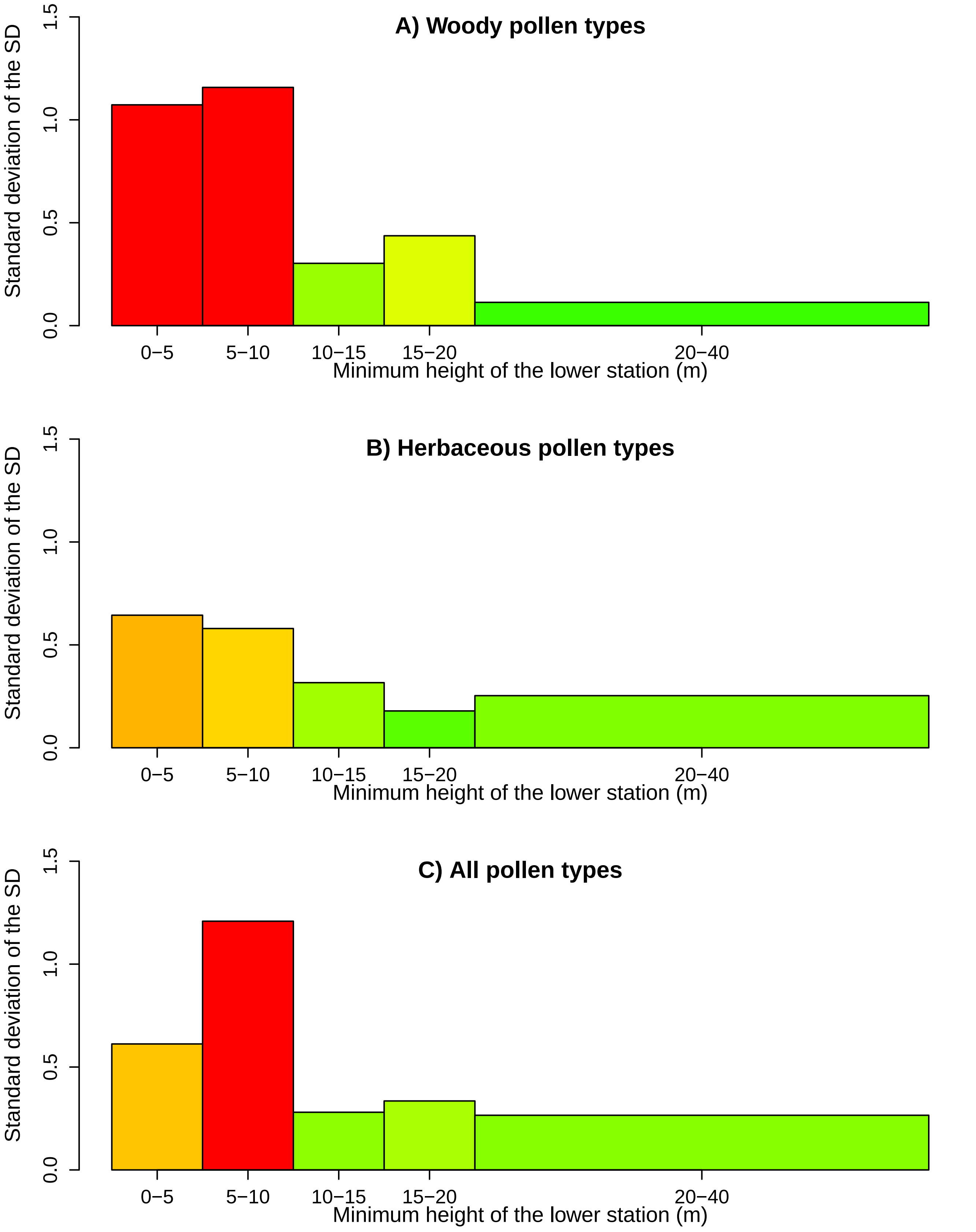

A) Woody pollen types
B) Herbaceous pollen types
C) All pollen types
Standard deviation of the SD
0.0
0.5
1.0
1.5
0−5
5−10
10−15
15−20
20−40
Minimum height of the lower station (m)

Figure 3

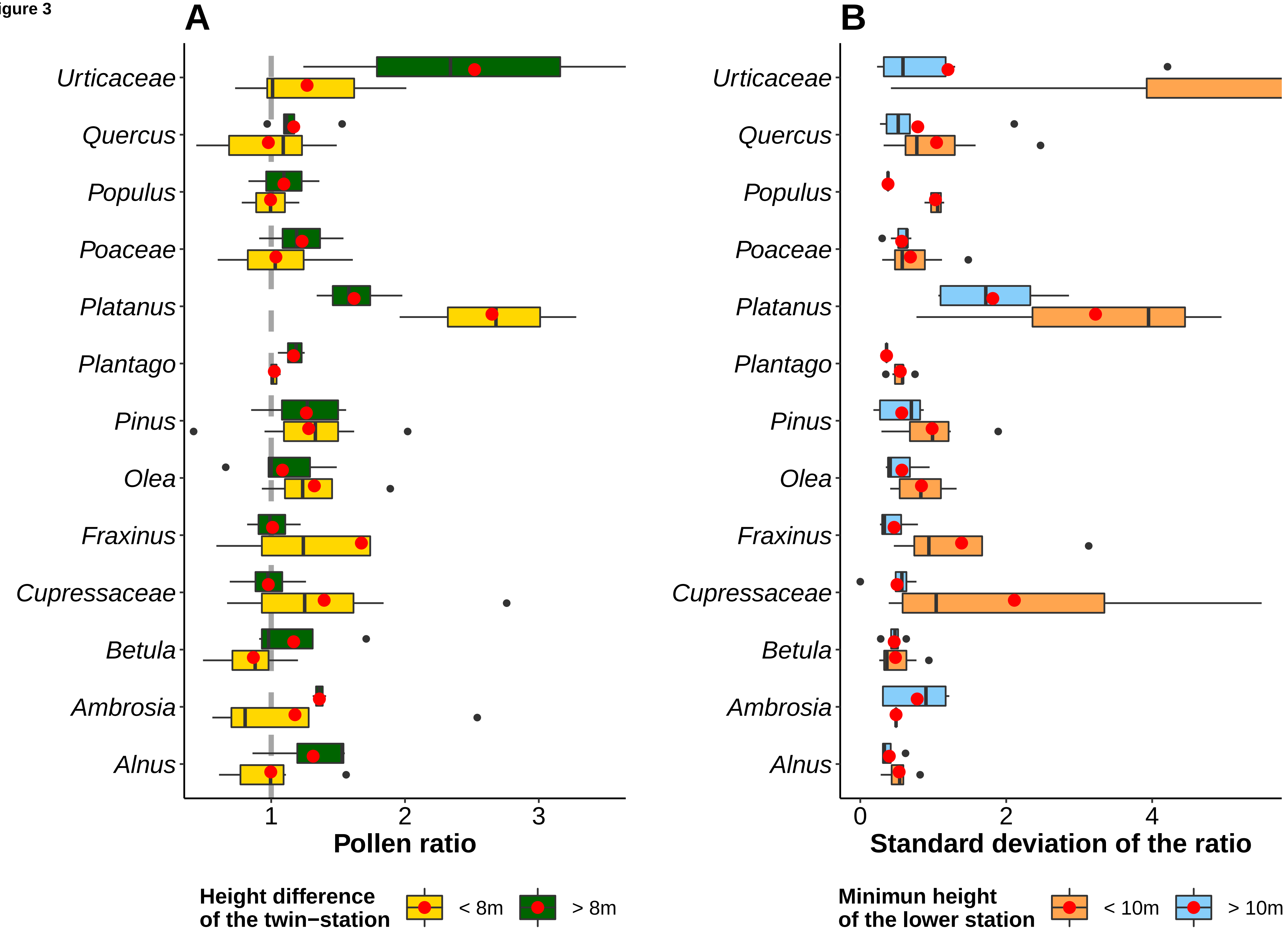
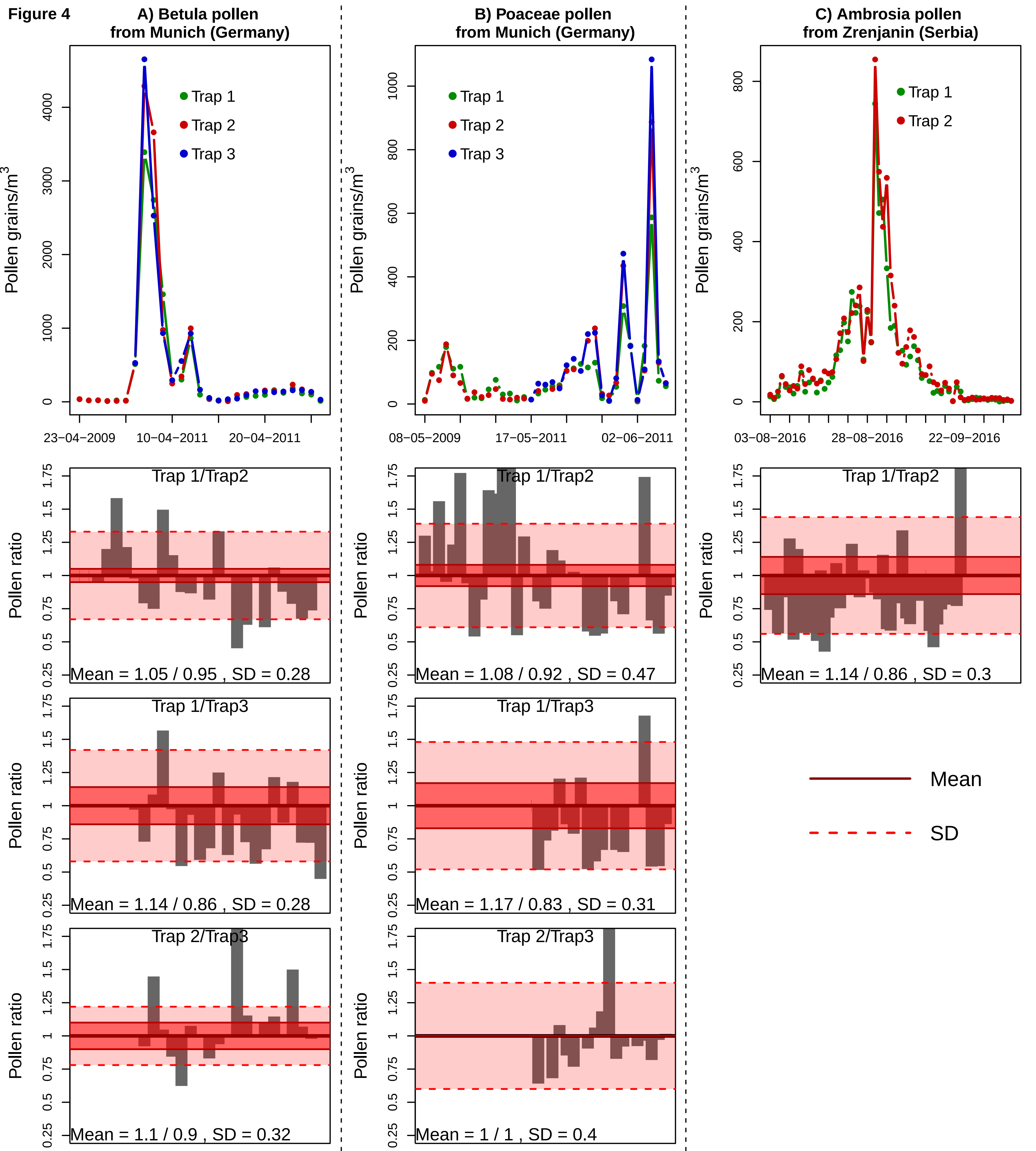

A
B
Urticaceae
Quercus
Populus
Poaceae
Platanus
Plantago
Pinus
Olea
Fraxinus
Cupressaceae
Betula
Ambrosia
Alnus
1
2
3
Pollen ratio
0
2
4
Standard deviation of the ratio
Height difference of the twin−station
< 8m
> 8m
Minimun height of the lower station
< 10m
> 10m

Figure 4



A) Betula pollen
from Munich (Germany)
B) Poaceae pollen
from Munich (Germany)
C) Ambrosia pollen
from Zrenjanin (Serbia)
Pollen grains/m3
Trap 1
Trap 2
Trap 3
23−04−2009
10−04−2011
20−04−2011
08−05−2009
17−05−2011
02−06−2011
03−08−2016
28−08−2016
22−09−2016
Pollen ratio
Trap 1/Trap2
Trap 1/Trap3
Trap 2/Trap3
Mean = 1.05 / 0.95 , SD = 0.28
Mean = 1.08 / 0.92 , SD = 0.47
Mean = 1.14 / 0.86 , SD = 0.3
Mean = 1.14 / 0.86 , SD = 0.28
Mean = 1.17 / 0.83 , SD = 0.31
Mean = 1.1 / 0.9 , SD = 0.32
Mean = 1 / 1 , SD = 0.4
Mean
SD

Supplementary Material

Click here to download Supplementary Material: Supplementary Material_20-12-18.pdf