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Near-ground effect of height on pollen exposure

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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.

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Introduction

Respiratory diseases related to allergy are considered as one of the most important public health problem for the 21st 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 20th century (Hertel et al., 2013). The interest increased since recent studies revealed the effects of the interaction between the inorganic pollutants and aeroallergens on allergies and respiratory diseases (Sénéchal et al., 2015; Reinmuth-Selzle et al., 2017; Cole-Hunter et al., 2018). 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).

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). Different processes of the atmospheric dynamic determine changes on the vertical profile of bioaerosols between tropospheric vertical profile and the near-ground vertical profile (Orlanski, 1975) i.e. only reaching tens of meters above ground level (AGL).

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 study of the near-ground vertical profile on pollen concentration is complex and rarely more than two samplers at the same location are 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). Representative examples considering the near-ground vertical profile of pollen are the study of Raynor et al. (1973) on a meteorological tower in USA up to 108 m AGL or the study by Barbosa et al. (2018), at the Amazon Tall Tower Observatory (ATTO) in Brazil up to 300 m AGL, reaching the maximum studied height for a static sampler. Few other heights 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 estimated the near-ground vertical profile of pollen concentrations using a big data approach based on a global study of paired stations located at different heights within the first tens of meters above ground level. The study used data from 59 pollen stations around the world (about 2,000,000 daily pollen concentrations) and yields important conclusions that can be generalized to different areas across the world for most pollen types.

Materials and Methods

Pollen data

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.

Availability of pollen data from paired station fulfilling our criteria was obtained with the help of the Worldwide Map of Pollen Monitoring Stations (Buters et al., 2018).

Calculation of the pollen ratio between paired stations

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 March 2019). The height of selected stations was between 1.5 and 50 m AGL (Supplementary Material, Figure S2).

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.

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

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 (this threshold has been used to reduce sources of error due to very low pollen concentrations, see below).

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.

Data quality assessment

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 concentrations, 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 (Pedersen and Moseholm, 1993; Comtois et al., 1999; Oteros et al., 2013). 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.

Statistical analysis

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 S3, and online at https://modeling-jesus-rojo.shinyapps.io/result_app2/, accessed March 2019). Pollen types considered from woody plants were *Alnus* (alder), *Betula* (birch), Cupressaceae/Taxaceae (cypress/yew), *Fraxinus* (ash), *Olea* (olive), Pinaceae (pines and cedars), *Platanus* (plane tree) and *Quercus* (oak and holm-oak). Herbaceous plants included were *Ambrosia* (ragweed), *Plantago* (plantain), Poaceae (grass) and Urticaceae (nettle and pellitory). 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). The management of the pollen database and all analyses were carried out using the statistical software R (R Development Core Team, 2017).

Results and Discussion

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 (Figures 1A-C). 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). The increasing of the ratio with the height difference was more evident in the first 10 m of difference between pollen traps, as observed in Figure 2 showing more detailed information for this lower range (0-10 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 (Supplemental Material, Figure S3). 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 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 1A-C). Above this level, standard deviation showed a strong reduction and a marked stabilization (Figure 3). 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). Our 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 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). Thus, local building structure can demand placements of a trap substantially above 10 m AGL. Supporting our results, similar considerations are followed by the World Meteorological Organisation to locate anemometers for measuring wind speed and direction, including an optimal height above 10 m AGL (WMO, 2017). However, our results show that the influence of the height on pollen sampling is getting smaller above 10 m 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 sources (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 S3). Only pollen types such as *Platanus*, Cupressaceae or *Olea* showed a different pattern which can also be observed in Figure 4A and Supplementary Material. In Figure 4A, these pollen types showed higher pollen ratio when the height difference of the paired-stations decreased, contrary to other pollen types.

We expected relevant differences between herbaceous and woody species whose lifeform determines the height from which pollen is released (Fernández-Illescas et al., 2010). However, no clear differences are reported in our work with respect to the near-ground vertical profile of pollen concentrations (Fig. 1A-C). Herbaceous species showed a much lower standard deviation below 10 m AGL than woody pollen types (Figure 3), and these results could be related to the different phenomena of pollen release, which is upward from the ground level in herbaceous plants while for woody species the pollen are dropped from trees. Ranta et al. (2008) reported that the percentage of the tree pollen was higher in the atmosphere than at ground level deposition, and pollen coming from herbaceous plant and other low-growing plants are more represented in deposition samples. Thus, the presence of tree pollen below 10 m AGL depends more of dynamics that influence the deposition or dispersal (wind) of pollen.

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 in the western Mediterranean region (Cariñanos et al., 2017; Cariñanos and Casares-Porcel, 2011; Sánchez-Reyes et al., 2009), and thus, the pollen sources in this case would be near to the urban stations. Pollen types coming from species that grow abundantly in urban and natural environments, and thus more widespread, could exhibit different vertical distribution profiles than species planted predominantly near urban areas.

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 is 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 (Raynor et al., 1968; Jarosz et al., 2005; Katz and Carey, 2014). Otherwise, long-distance transport of pollen can be important in specific situations being responsible of high proportions of allergenic pollen from external sources (Izquierdo et al., 2011). We expect that the amounts of pollen coming from distant pollen sources would reduce the effect of the height on pollen measurements because long-range wind-transported pollen would come from high elevations (Makra et al., 2016), on the contrary as could be thought from local sources. 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 (Peel et al., 2014), or meteorological conditions of the atmosphere (Ríos et al., 2016; Skjøth et al., 2013), especially 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).

It is remarkable that side by side stations located at the same height (Δheight = 0 m), such as in Munich, Germany or Zrenjanin, Serbia (Table 1) showed pollen ratios different to 1 (Figure 1A-C). 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. 5). 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. The 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 fact explains why no significant differences were found in previous works (Tormo-Molina et al., 2013). The daily variability observed could be explained by random variations caused by instrumental error but could also be influenced again by meteorological conditions (Pedersen and Moseholm, 1993). All samples between paired stations were processes and counted at the same laboratory and the error is independent of the interlaboratory variability.

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 height of the lower station or the distance between the stations. 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 study of the general pattern of pollen exposure at ground level and, hence, are highly relevant to clinical practice. Until now, the results of our study constitute the most complete estimation of the variability of the near-ground vertical profile of airborne pollen.

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Declaration of competing financial interests (CFI)

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

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Supplementary Material

- Supplementary Material Figure S1
- Supplementary Material Figure S2
- Supplementary Material Figure S3
- 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 March 2019.

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 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 minimum height proposed for the lower station. The plots for the individual pollen types are given in Supplemental Material.

Figure 2. Relationship between the mean pollen ratio and the height difference between paired-stations, only for the lower range of height difference (0-10 m).

Figure 3. Relationship between the standard deviation of the standard deviation (SD) of the mean pollen ratio and the 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 for the lower station of >10 m AGL as this reduces the variability of the measurements.

Figure 4. Boxplots comparing the mean pollen ratio depending on: (A) Δheight or (B) height of the lower station.

Figure 5. 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% on average. 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%). The highlighted cells show the greater number of significant differences.

	*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

Figure 1

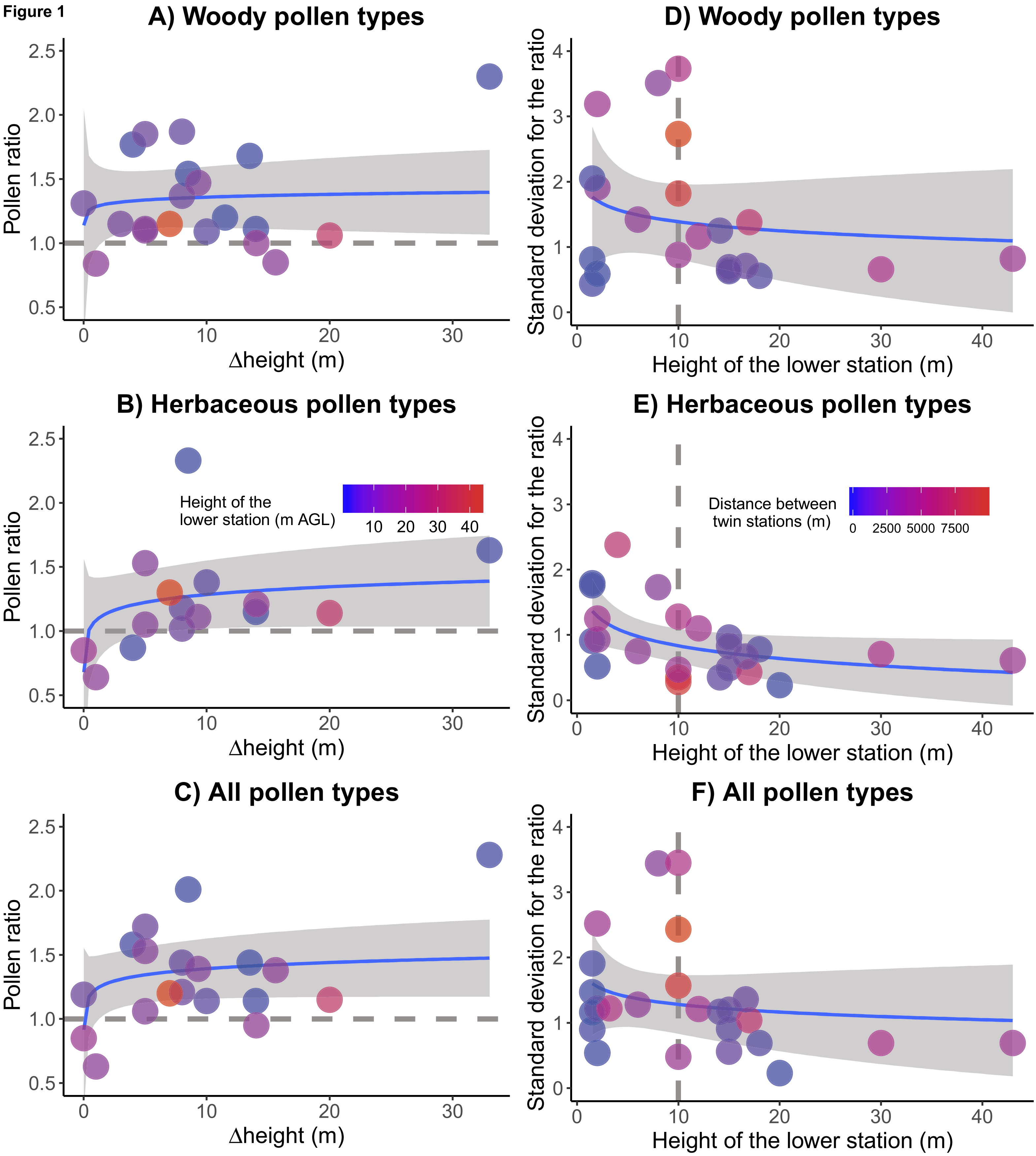

A) Woody pollen types
Pollen ratio
2.5
2.0
1.5
1.0
0.5
0
10
20
30
Δheight (m)
D) Woody pollen types
Standard deviation for the ratio
4
3
2
1
0
0
10
20
30
40
Height of the lower station (m)
B) Herbaceous pollen types
Pollen ratio
Height of the lower station (m AGL)
10 20 30 40
Δheight (m)
E) Herbaceous pollen types
Standard deviation for the ratio
Distance between twin stations (m)
0 2500 5000 7500
Height of the lower station (m)
C) All pollen types
Pollen ratio
Δheight (m)
F) All pollen types
Standard deviation for the ratio
Height of the lower station (m)

Figure 2

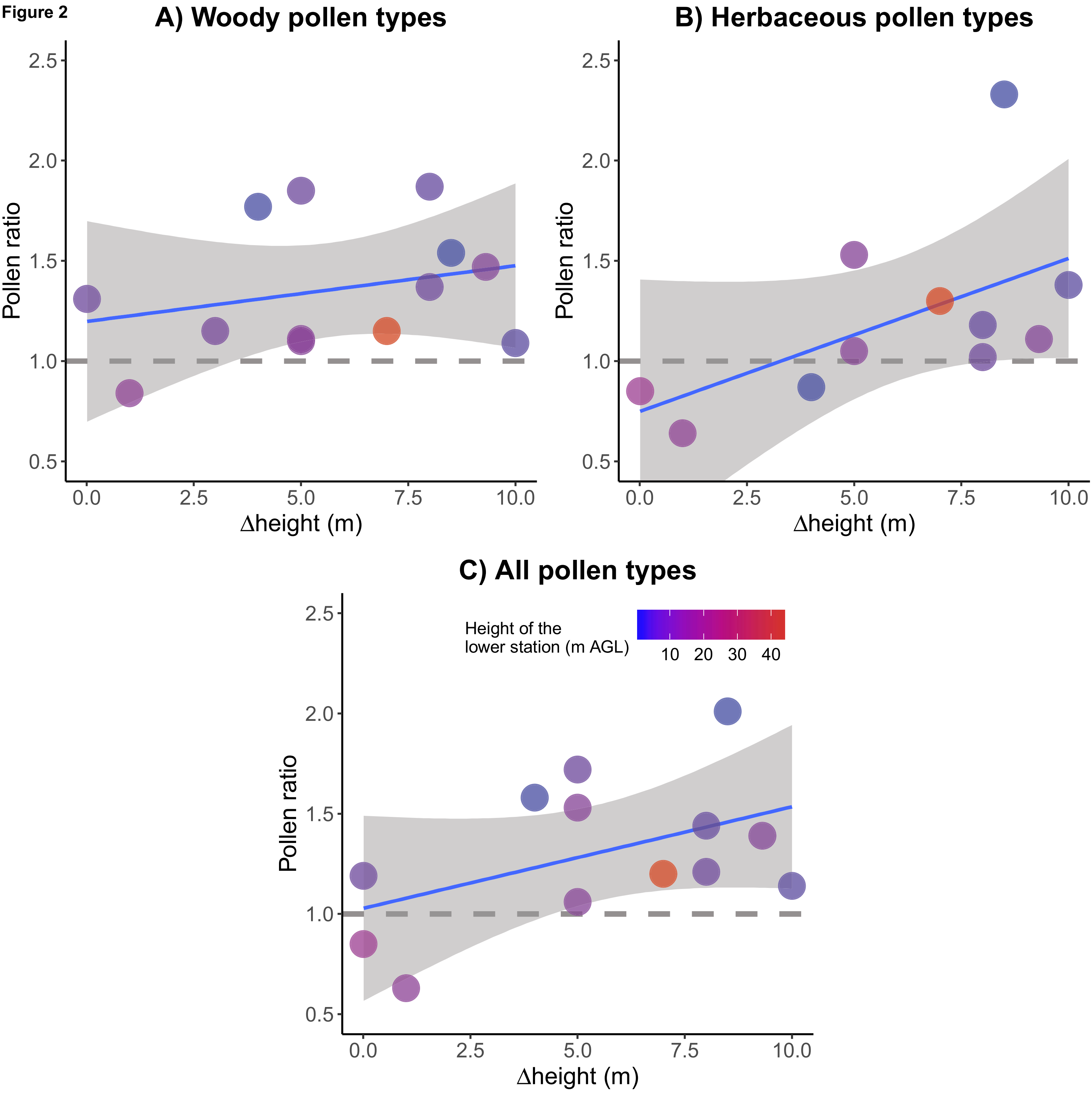

A) Woody pollen types
B) Herbaceous pollen types
C) All pollen types
Pollen ratio
2.5
2.0
1.5
1.0
0.5
Δheight (m)
0.0
2.5
5.0
7.5
10.0
Height of the
lower station (m AGL)
10
20
30
40

Figure 3

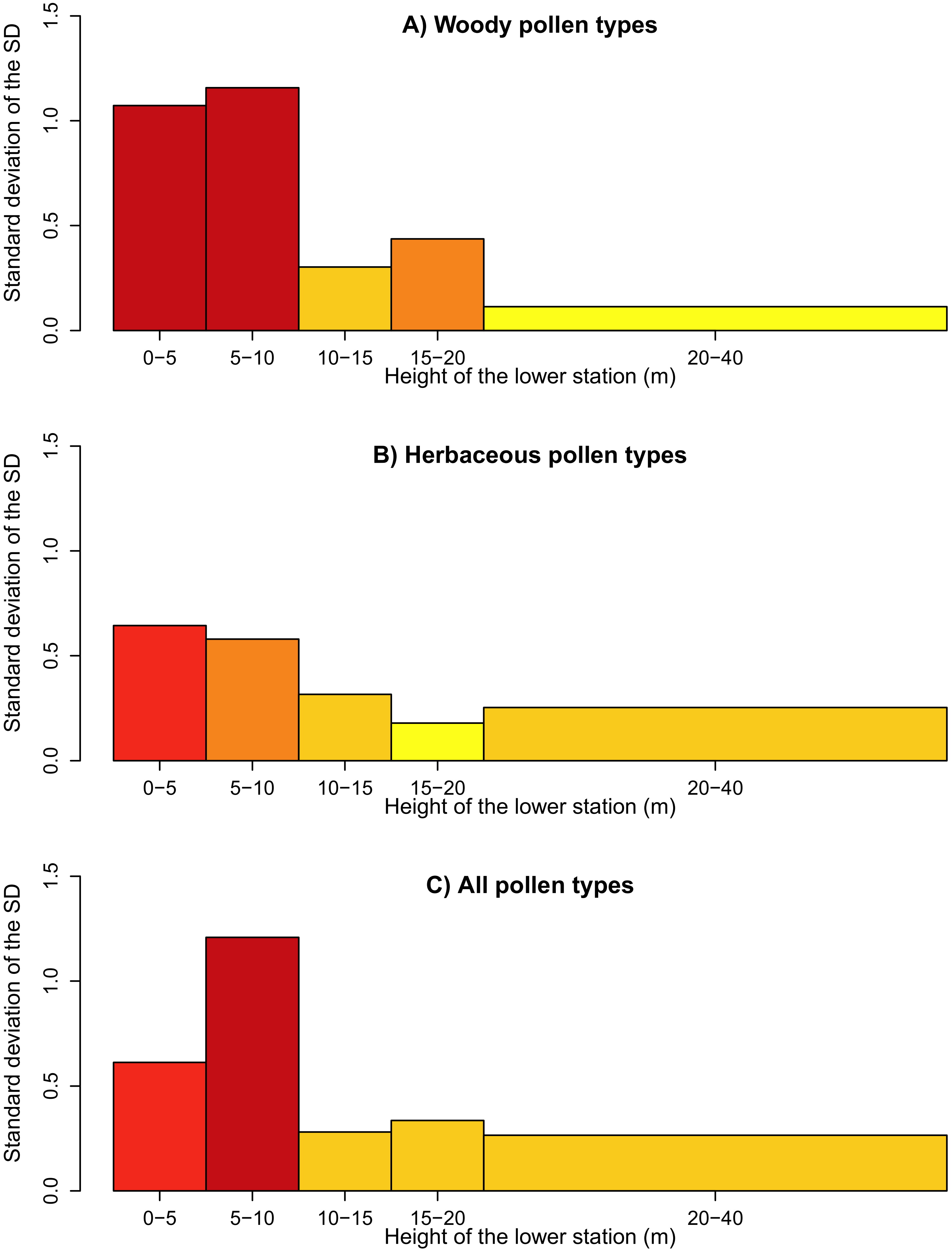

A) Woody pollen types
B) Herbaceous pollen types
C) All pollen types
Standard deviation of the SD
Height of the lower station (m)
0.0
0.5
1.0
1.5
0−5
5−10
10−15
15−20
20−40

Figure 4

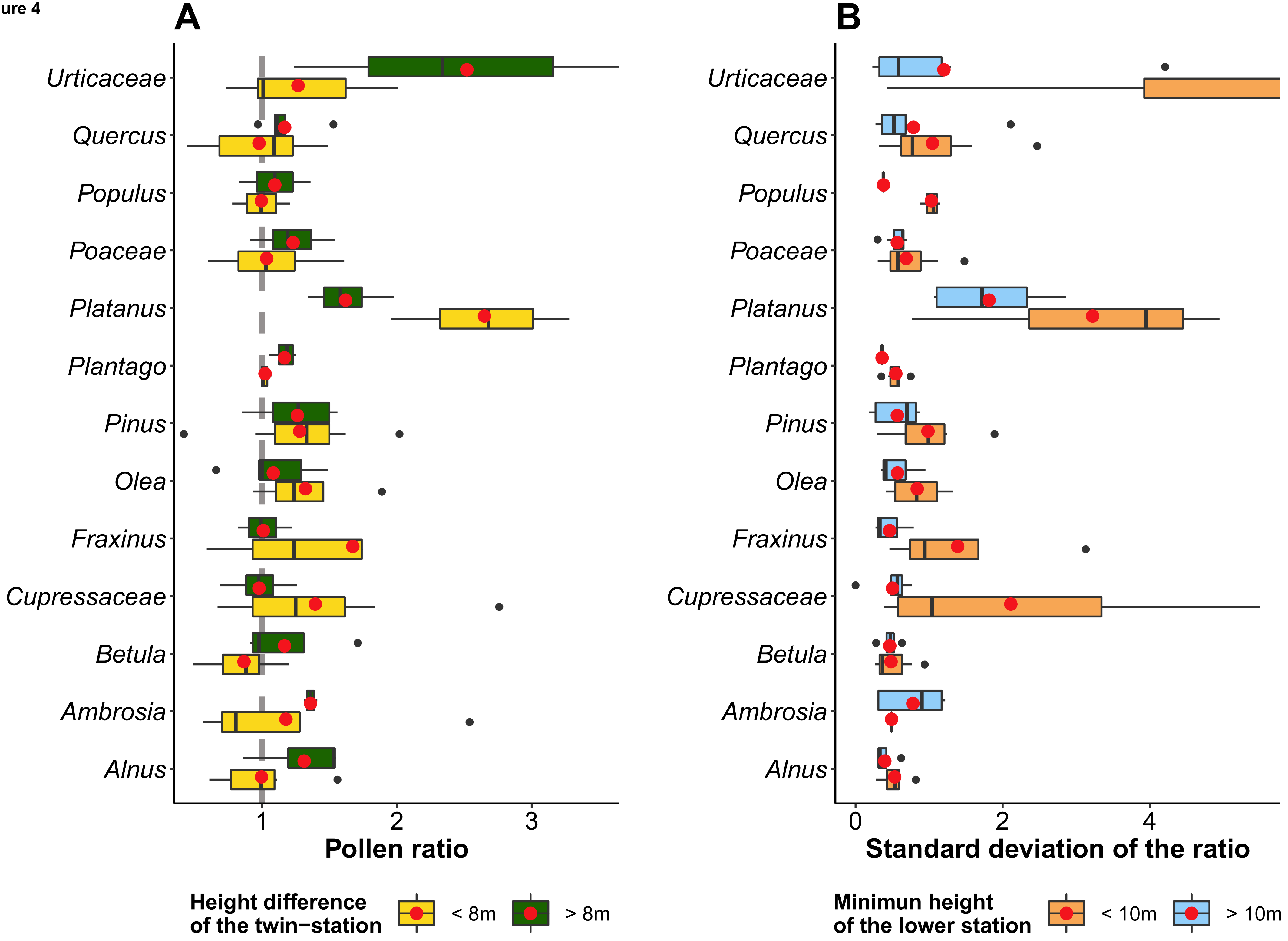
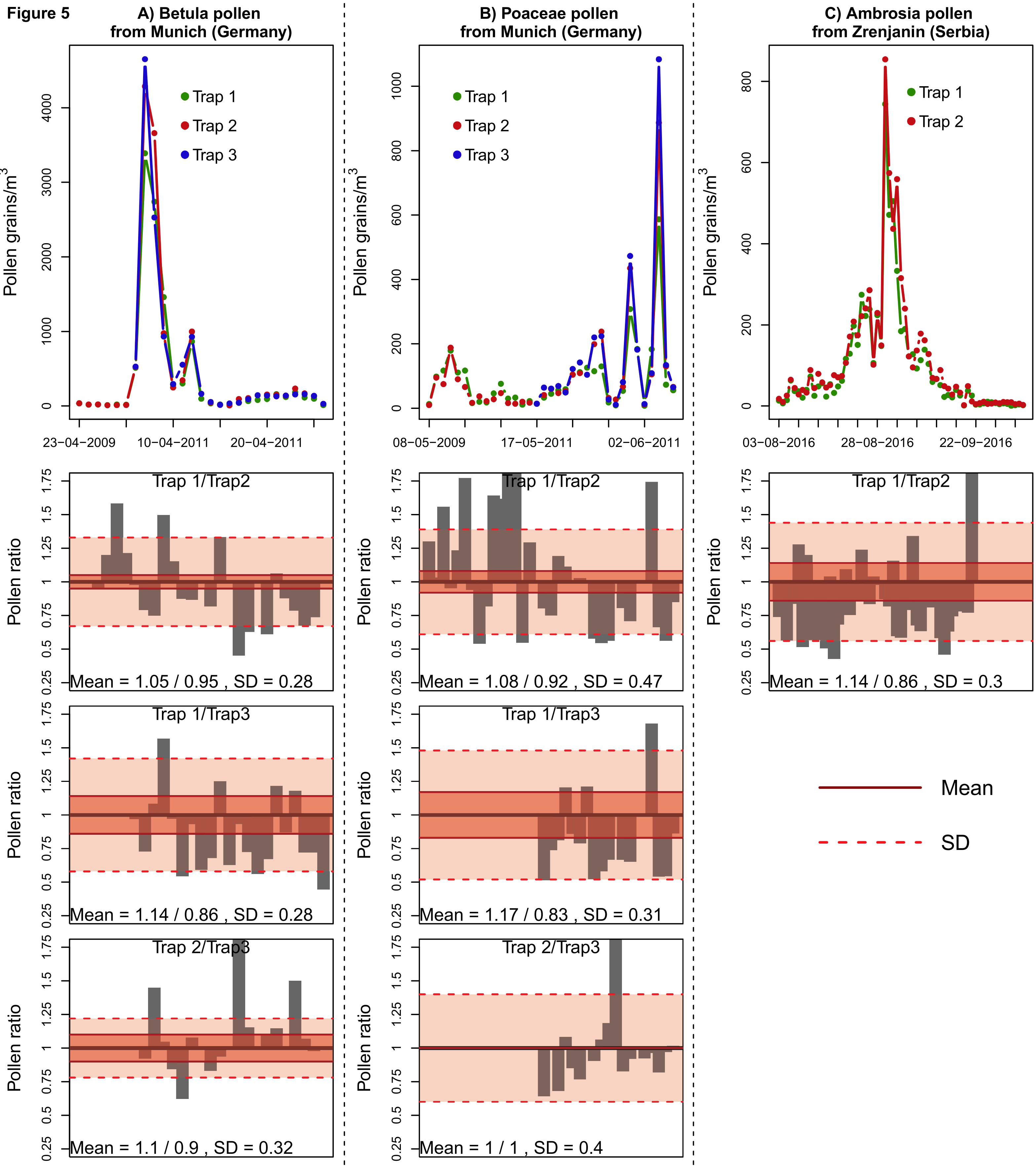

A
B
Urticaceae
Quercus
Populus
Poaceae
Platanus
Plantago
Pinus
Olea
Fraxinus
Cupressaceae
Betula
Ambrosia
Alnus
1
2
3
Pollen ratio
Height difference
of the twin−station
< 8m
> 8m
0
2
4
Standard deviation of the ratio
Minimun height
of the lower station
< 10m
> 10m

Figure 5


A) Betula pollen
from Munich (Germany)
B) Poaceae pollen
from Munich (Germany)
C) Ambrosia pollen
from Zrenjanin (Serbia)
Pollen grains/m^3
Trap 1
Trap 2
Trap 3
0
1000
2000
3000
4000
200
400
600
800
1000
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
0.25
0.5
0.75
1
1.25
1.5
1.75
Trap 1/Trap2
Mean = 1.05 / 0.95 , SD = 0.28
Trap 1/Trap2
Mean = 1.08 / 0.92 , SD = 0.47
Trap 1/Trap2
Mean = 1.14 / 0.86 , SD = 0.3
Trap 1/Trap3
Mean = 1.14 / 0.86 , SD = 0.28
Trap 1/Trap3
Mean = 1.17 / 0.83 , SD = 0.31
Trap 2/Trap3
Mean = 1.1 / 0.9 , SD = 0.32
Trap 2/Trap3
Mean = 1 / 1 , SD = 0.4
Mean
SD