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# Near-ground effect of height on pollen exposure

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

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

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31 Melbourne, Australia; <sup>27</sup>University of Worcester, UK; <sup>28</sup>BioSense Institute, University of Novi  
32 Sad, Serbia; <sup>29</sup>Uludag University, Turkey.

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34 \* Corresponding author: [jesus.rojo.ubeda@gmail.com](mailto:jesus.rojo.ubeda@gmail.com), Biedersteinerstrasse 29, 80802 Munich,  
35 Germany

36  
37 **ABSTRACT**

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

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

57  
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61 ePIN-Valid.

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4 **64 Introduction**  
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8 66 Respiratory diseases related to allergy are considered as one of the most important public health  
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10 67 problem for the 21st century, according to the World Allergy Organization (Pawankar et al.,  
11  
12 68 2013). Bioaerosols such as pollen grains or spores are the main cause of allergic diseases and  
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14 69 their incidence is rising also due to climate change and urban pollution (Cecchi et al., 2010; Lake  
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16 70 et al., 2017; Reinmuth-Selzle et al., 2017). According to the European Academy of Allergy and  
17  
18 71 Clinical Immunology around 30% of the population from industrialized areas suffers from  
19  
20 72 allergic diseases (European Academy of Allergy and Clinical & Immunology, 2015). For this  
21  
22 73 reason the interest in aeroallergens has increased and in addition to measuring air quality from  
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24 74 inorganic pollutants (Zhang et al., 2016; Fugiel et al., 2017), monitoring networks for biological  
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26 75 air components like pollen were installed during the last decades of the 20th century (Hertel et  
27  
28 76 al., 2013). The interest increased since recent studies revealed the effects of the interaction  
29  
30 77 between the inorganic pollutants and aeroallergens on allergies and respiratory diseases  
31  
32 78 (Sénéchal et al., 2015; Reinmuth-Selzle et al., 2017; Cole-Hunter et al., 2018). Moreover,  
33  
34 79 monitoring of biological particulate matter also provides relevant information for agronomic or  
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36 80 ecological purposes (Jarosz et al., 2005; Fernandez-Gonzalez et al., 2013; Charalampopoulos et  
37  
38 81 al., 2018; Romero-Morte et al., 2018).  
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40 82  
41 83 The vertical profile of the bioaerosol concentrations was analyzed in the lower atmosphere using  
42  
43 84 aircrafts or tethered balloons (Gregory, 1978; Gruber et al., 1998; Comtois et al., 2000; Damialis  
44  
45 85 et al., 2017). Although in general terms, Gregory (1978) demonstrated that the concentration of  
46  
47 86 bioaerosols decreases logarithmically with height from ground level up to the upper layers of the  
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49 87 troposphere, certain types of biological particles can show higher concentrations in higher  
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51 88 heights above ground level (Comtois et al., 2000; Damialis et al., 2017) due to the long-distance  
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53 89 transport of particulate matter below the atmospheric boundary layer (Makra et al., 2016, 2010;  
54  
55 90 Rojo et al., 2018). Different processes of the atmospheric dynamic determine changes on the  
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57 91 vertical profile of bioaerosols between tropospheric vertical profile and the near-ground vertical  
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59 92 profile (Orlanski, 1975) i.e. only reaching tens of meters above ground level (AGL).  
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4 94 Around the world, airborne pollen monitoring is mainly done by samplers located at higher  
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6 95 locations (Buters et al., 2018), such as rooftops of buildings, following the recommendations of  
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8 96 the standard methodology agreed by the international aerobiology associations (Galán et al.,  
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10 97 2014; Jäger et al., 1995). The reason of sampling at rooftops is that pollen concentrations should  
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12 98 be sampled at homogeneous conditions, enabling a single trap to cover a large area around the  
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14 99 sampling station, e.g. the area of a city. However, measured airborne pollen at rooftop levels  
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16 100 could be different from those at ground level, where patient outdoor pollen exposure occurs (Peel  
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18 101 et al., 2013; Penel et al., 2017; Fernández-Rodríguez et al., 2018). Although many stations are at  
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20 102 variable heights above ground, the effect of height on pollen sampling is not well documented,  
21  
22 103 although the subject has been addressed at a local scale in numerous papers (See Supplementary  
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24 104 Material Table S1). To estimate the near-ground level of pollen from rooftop measurements we  
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26 105 analyzed all the available data from paired traps across the world.  
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28 106  
29 107 The study of the near-ground vertical profile on pollen concentration is complex and rarely more  
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31 108 than two samplers at the same location are analyzed (Galán et al., 1995; Myszkowska et al.,  
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33 109 2012; Fernández-Rodríguez et al., 2014; Rodríguez de la Cruz et al., 2016; Borycka and  
34  
35 110 Kasprzyk, 2018) (Supplementary Material Table S1). As a consequence, up to date few  
36  
37 111 researches have considered a vertical profile using more than two sampling heights simultaneous  
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39 112 at one location (Raynor et al., 1973; Bryant et al., 1989; Fiorina et al., 1999; Alcazar and  
40  
41 113 Comtois, 2000; Jarosz et al., 2005; Chakraborty et al., 2001; Xiao et al., 2013). Representative  
42  
43 114 examples considering the near-ground vertical profile of pollen are the study of Raynor et al.  
44  
45 115 (1973) on a meteorological tower in USA up to 108 m AGL or the study by Barbosa et al.  
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47 116 (2018), at the Amazon Tall Tower Observatory (ATTO) in Brazil up to 300 m AGL, reaching the  
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49 117 maximum studied height for a static sampler. Few other heights were analyzed for the near-  
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51 118 ground vertical profile of airborne pollen and it is also difficult to find studies that were  
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53 119 maintained over a longer period of time.

54 120  
55 121 Our study estimated the near-ground vertical profile of pollen concentrations using a big data  
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57 122 approach based on a global study of paired stations located at different heights within the first  
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59 123 tens of meters above ground level. The study used data from 59 pollen stations around the world  
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4 124 (about 2,000,000 daily pollen concentrations) and yields important conclusions that can be  
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6 125 generalized to different areas across the world for most pollen types.  
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10 127 **Materials and Methods**

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13 129 *Pollen data*

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17 131 We studied the effect of height of air sampling on pollen concentrations in 25 areas around the  
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19 132 world from 99.28° west to 145.13° east and from 60.46° north to 3.83° south, mainly in Europe,  
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21 133 but also covering North America and Australia (Table 1; Supplementary Material Fig. S1).  
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23 134  
24 135 Pollen data from 2-5 monitoring stations were considered from each area and analyzed, yielding  
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26 136 a total of 59 pollen stations (Table 1). The same type of sampling device (Hirst-type volumetric  
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28 137 trap (Hirst, 1952)) was used in all studied stations. The standard methodology agreed by the  
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30 138 International Association for Aerobiology (IAA) (Jäger et al., 1995) or the European  
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32 139 Aerobiology Society (EAS) (Galán et al., 2014; Šikoparija et al., 2017) was followed.  
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34 140  
35 141 Availability of pollen data from paired station fulfilling our criteria was obtained with the help of  
36  
37 142 the Worldwide Map of Pollen Monitoring Stations (Buters et al., 2018).  
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41 144 *Calculation of the pollen ratio between paired stations*

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44 146 After pairing pollen monitoring stations, a total of 47 paired stations was obtained. For instance,  
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46 147 an area provided only one pair when two stations were combined for that area e.g. Augsburg  
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48 148 (Germany). Other areas with more concomitant stations could provide more pairs, like ten pairs  
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50 149 of stations when five stations available for that area, e.g. Munich (Germany) (Table 1). Stations  
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52 150 within 10km of each other were considered a pair (this criterium can be changed in the online  
53  
54 151 analysis program: [https://modeling-jesus-rojo.shinyapps.io/result\\_app2/](https://modeling-jesus-rojo.shinyapps.io/result_app2/), accessed March 2019).  
55  
56 152 The height of selected stations was between 1.5 and 50 m AGL (Supplementary Material, Figure  
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58 153 S2).  
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4 155 Daily ratios of pollen concentrations were used to study the effect of height, and the mean pollen  
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6 156 ratio (MPR) between two paired stations was calculated using equation 1. The standard  
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8 157 deviation was estimated from daily pollen ratios.  
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$$10 \quad 158 \quad \text{Mean Pollen Ratio (MPR)} = \frac{\sum^n PC_{\text{lower}}/PC_{\text{higher}}}{n} \quad (\text{equ. 1})$$

11  
12 159 where, MPR is the mean of the daily pollen ratio,  $PC_{\text{lower}}$  is the pollen concentration from the  
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14 160 lower pollen trap,  $PC_{\text{higher}}$  the pollen concentration from the higher pollen trap, and n is the  
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16 161 number of days with pollen concentrations  $> 10 \text{ grains/m}^3$  for both traps (this threshold has been  
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18 162 used to reduce sources of error due to very low pollen concentrations, see below).  
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20 163  
21 164 Equation 1 exemplifies that if  $MPR > 1$  then the lower pollen trap measured higher pollen  
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23 165 concentrations. Alternatively, if  $MPR < 1$ , the higher pollen trap measured more pollen than the  
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25 166 lower trap.  
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### 27 167 28 168 *Data quality assessment*

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31 170 To assess data quality, only years where the pollen data series from the paired stations were  
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33 171 significantly correlated ( $R > 0.8$ ) were included. Additionally, only days with pollen  
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35 172 concentrations  $> 10 \text{ grains/m}^3$  for both traps of a pair were considered (Buters et al., 2015). The  
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37 173 aim of these inclusion criteria was to minimize errors in the measurements of very low pollen  
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39 174 concentrations, inherent to the aerobiological methods and documented by previous studies  
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41 175 (Cotos-Yáñez et al., 2013; Šikoparija et al., 2017). This threshold of  $10 \text{ grains/m}^3$  was used for  
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43 176 all different pollen types and was a compromise value between reducing possible sources of error  
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45 177 due to inaccurate pollen measurements and the largest possible number of data and number of  
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47 178 stations for the analysis of each pollen type.  
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51 180 Pollen concentrations between sites can vary independent of the effects of height on air sampling  
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53 181 (Tormo-Molina et al., 2013). Sources of variability may be instrumental (Oteros et al., 2017),  
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55 182 environmental or human (Pedersen and Moseholm, 1993; Comtois et al., 1999; Oteros et al.,  
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57 183 2013). To assess the effect of height-independent sources of variability (e.g. variations due to  
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59 184 instrumental or human errors), pollen concentration from paired stations located at the same  
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61 185 height and at the same location were analyzed as special cases. The areas selected for this  
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4 186 comparison were: Munich (Germany), where three pollen stations were located at 8 m AGL  
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6 187 (Buters et al., 2012) and Zrenjanin (Serbia) where two pollen stations were located at 20 m AGL.  
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8 188 In these special cases, the mean pollen ratio was represented as a range of values around one,  
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10 189 since either pollen stations could be used as the numerator when calculating the pollen ratio.  
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13 191 ***Statistical analysis***  
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17 193 Although a great number of woody and herbaceous pollen types were analyzed, only the total  
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19 194 pollen sum for all pollen types and total for the woody and for the herbaceous pollen types are  
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21 195 shown in the results about the vertical profile of airborne pollen, ensuring an adequate number of  
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23 196 cases to be studied. More detailed information on individual pollen types is given in  
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25 197 Supplementary Material (Figure S3, and online at [https://modeling-jesus-  
26 198 rojo.shinyapps.io/result\\_app2/](https://modeling-jesus-rojo.shinyapps.io/result_app2/), accessed March 2019). Pollen types considered from woody  
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28 199 plants were *Alnus* (alder), *Betula* (birch), Cupressaceae/Taxaceae (cypress/yew), *Fraxinus* (ash),  
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30 200 *Olea* (olive), Pinaceae (pines and cedars), *Platanus* (plane tree) and *Quercus* (oak and holm-  
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32 201 oak). Herbaceous plants included were *Ambrosia* (ragweed), *Plantago* (plantain), Poaceae  
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34 202 (grass) and Urticaceae (nettle and pellitory). Again, the analysis can be adjusted to individual  
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36 203 preferences online (see above).  
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39 205 Differences in ratios between pollen types were analyzed using a one-way analysis of variance  
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41 206 (ANOVA) to determine whether the daily ratios of one pollen type deviated from other pollen  
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43 207 types, i.e. whether some pollen type behaved differently to other pollen types. If ANOVA  
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45 208 detected a significant difference among pollen, a Tukey test was then applied to determine  
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47 209 exactly which pollen differed significantly from the others (see Table 2). The management of the  
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49 210 pollen database and all analyses were carried out using the statistical software R (R Development  
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51 211 Core Team, 2017).  
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53 213 **Results and Discussion**  
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57 215 The results show that as the height difference increases, the pollen ratio increased (i.e. pollen  
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59 216 concentrations were lower at increased height). Above a certain height difference the ratio  
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4 217 stabilizes at around 1.5 (Figures 1A-C). Thus, the difference in pollen concentrations registered  
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6 218 by the lower station was maximally 50% higher than observed at higher height (the maximum  
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8 219 height difference considered,  $\Delta\text{height} = 33$  m). The increasing of the ratio with the height  
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10 220 difference was more evident in the first 10 m of difference between pollen traps, as observed in  
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12 221 Figure 2 showing more detailed information for this lower range (0-10 m). This general behavior  
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14 222 is shown for total pollen amounts (Figures 1A-C) and for the most pollen types studied such as  
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16 223 *Betula*, *Fraxinus*, Poaceae, *Quercus* or Urticaceae (Supplemental Material, Figure S3). Chan and  
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18 224 Kwok (2000) reported a similar pattern of vertical distribution in suspended particulate matter,  
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20 225 with a decrease in airborne particle concentrations occurring mainly within the first meters of  
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22 226 increase in height.

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25 228 Our study on the height on pollen sampling showed that most of the paired stations for most of  
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27 229 the pollen types yielded values of mean pollen ratio higher than 1. Therefore, the pollen traps at  
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29 230 lower height registered generally higher pollen concentrations. Pollen ratio higher than 1 were  
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31 231 expected according to the reviewed literature (Alcázar et al., 1999; Xiao et al., 2013), as pollen  
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33 232 concentrations decrease with height. However, this behavior was not observed for all reviewed  
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35 233 cases, possibly due to the influence of other factors than height as discussed below (Borycka and  
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37 234 Kasprzyk, 2018; Bryant et al., 1989; Khattab and Levetin, 2008).

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40 236 Not only the height difference between paired pollen stations is important. The height above  
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42 237 ground level of the lower station (minimum height) plays a crucial role on the effect of height on  
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44 238 pollen concentrations. Figure 1 (D-F) showed that the standard deviation of the pollen ratio is  
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46 239 highly variable when the lower station is located close to the ground level reaching standard  
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48 240 deviations above 3 when the height of the lower station was below 10 m AGL. Similar to pollen  
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50 241 grains, also concentrations of other particulate matter (Brady et al., 2016) and gases (that have no  
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52 242 sedimentation) at ground level showed more daily fluctuations in concentrations than those  
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54 243 registered at higher levels of the troposphere, where concentrations are more stable (Salmond et  
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56 244 al., 2013; Zhang and Rao, 1999).

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59 246 In general, a greater pollen ratio between paired stations was observed when the lower station  
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61 247 was located below 10 m AGL (Figure 1A-C). Above this level, standard deviation showed a  
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4 248 strong reduction and a marked stabilization (Figure 3). These results could be interpreted as  
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6 249 showing that airborne pollen sampled in the first few meters from ground level (emission source)  
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8 250 is dependent on the height of the trap but their concentrations are also highly fluctuating over  
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10 251 time due to local pollen emission, deposition or resuspension, or phenomena of atmospheric  
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12 252 dynamics produced at microscale . Then, pollen concentrations from a certain height tend to  
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14 253 stabilize and the height effect loses relevance (Raynor et al., 1973), as for other aerosols (Brady  
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16 254 et al., 2016). Our hypothesis that pollen concentrations would vary vertically between near-  
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18 255 ground and 50m was supported by the results. However, the effect of height on pollen  
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20 256 concentrations was limited, and was mainly determined by differences within the first ten meters  
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22 257 above ground.

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25 259 The results indicate that the pollen concentrations are much more homogenous above 10 m AGL,  
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27 260 where most pollen stations in urban areas are localized. This suggest, that if the purpose of a  
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29 261 pollen trap is to provide representative data for a relatively large geographical region in an  
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31 262 urbanized area (Velasco-Jiménez et al., 2013), then it should be placed on a building at least 10  
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33 263 m AGL, i.e. this height could be considered as the minimum optimal height to locate stations for  
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35 264 pollen sampling. A consequence of such a placement is that local effects are less likely to be  
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37 265 detected by the trap and thus pollen stations above this height analyze airborne pollen in more  
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39 266 homogeneous conditions. The optimal height for the location of a sampler also depends on the  
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41 267 urban design (Galán et al., 2014). Therefore the sampler should be located away from the edge of  
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43 268 a building and away from higher surrounding buildings avoiding the effect of turbulence due to  
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45 269 urban canyon influence (Peel et al., 2014). Thus, local building structure can demand placements  
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47 270 of a trap substantially above 10 m AGL. Supporting our results, similar considerations are  
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49 271 followed by the World Meteorological Organisation to locate anemometers for measuring wind  
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51 272 speed and direction, including an optimal height above 10 m AGL (WMO, 2017). However, our  
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53 273 results show that the influence of the height on pollen sampling is getting smaller above 10 m  
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55 274 AGL. On the other hand, traps used for other purposes could be placed near the surface where  
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57 275 airborne particles are emitted for the assessment of the spatial distribution of the allergenic flora  
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59 276 (Hjort et al., 2016; Werchan et al., 2018), the control of the levels of pathogens in agriculture  
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61 277 (Fernandez-Gonzalez et al., 2013) or the study of the fluxes of pollen emission and deposition  
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63 278 near the pollen sources (Jarosz et al., 2005).  
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6 280 The results also show that the effect of height on pollen sampling is independent of the pollen  
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8 281 type considered. Most woody and herbaceous pollen types showed a similar pattern in the  
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10 282 relationships between the mean pollen ratio or the standard deviation and the differences in  
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12 283 height on sampling (Supplementary Material, Figure S3). Only pollen types such as *Platanus*,  
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14 284 Cupressaceae or *Olea* showed a different pattern which can also be observed in Figure 4A and  
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16 285 Supplementary Material. In Figure 4A, these pollen types showed higher pollen ratio when the  
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18 286 height difference of the paired-stations decreased, contrary to other pollen types.

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21 288 We expected relevant differences between herbaceous and woody species whose lifeform  
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23 289 determines the height from which pollen is released (Fernández-Illescas et al., 2010). However,  
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25 290 no clear differences are reported in our work with respect to the near-ground vertical profile of  
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27 291 pollen concentrations (Fig. 1A-C). Herbaceous species showed a much lower standard deviation  
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29 292 below 10 m AGL than woody pollen types (Figure 3), and these results could be related to the  
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31 293 different phenomena of pollen release, which is upward from the ground level in herbaceous  
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33 294 plants while for woody species the pollen are dropped from trees. Ranta et al. (2008) reported  
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35 295 that the percentage of the tree pollen was higher in the atmosphere than at ground level  
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37 296 deposition, and pollen coming from herbaceous plant and other low-growing plants are more  
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39 297 represented in deposition samples. Thus, the presence of tree pollen below 10 m AGL depends  
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41 298 more of dynamics that influence the deposition or dispersal (wind) of pollen.

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43 300 *Platanus* and Cupressaceae were the pollen types that showed the greatest number of differences  
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45 301 in pollen ratio, compared to the other types (Table 2). It is remarkable that pollen types showing  
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47 302 the highest differences in ratio represent the main pollen grains coming from ornamental plants  
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49 303 in many urban green zones of the cities. *Platanus* trees and Cupressaceae species are important  
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51 304 urban planted ornamental species in the western Mediterranean region (Cariñanos et al., 2017;  
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53 305 Cariñanos and Casares-Porcel, 2011; Sánchez-Reyes et al., 2009), and thus, the pollen sources in  
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55 306 this case would be near to the urban stations. Pollen types coming from species that grow  
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57 307 abundantly in urban and natural environments, and thus more widespread, could exhibit different  
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59 308 vertical distribution profiles than species planted predominantly near urban areas.

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4 310 These results also indicate the importance of the distance from the pollen source to be considered  
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6 311 on the effect of height on air sampling. Local emissions near the pollen stations will intensify the  
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8 312 effect between paired stations and probably an increased pollen concentration can be expected at  
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10 313 ground level (Šikoparija et al., 2018). Adams-Groom et al. (2017) indicated that most pollen is  
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12 314 deposited at the first few meters from the pollen sources. In a same way, air in the first few  
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14 315 meters above ground level from the pollen source would contain much greater quantities of  
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16 316 pollen than higher heights resulting in severe differences in height ratios for places close to the  
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18 317 pollen sources (Raynor et al., 1968; Jarosz et al., 2005; Katz and Carey, 2014). Otherwise, long-  
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20 318 distance transport of pollen can be important in specific situations being responsible of high  
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22 319 proportions of allergenic pollen from external sources (Izquierdo et al., 2011). We expect that the  
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24 320 amounts of pollen coming from distant pollen sources would reduce the effect of the height on  
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26 321 pollen measurements because long-range wind-transported pollen would come from high  
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28 322 elevations (Makra et al., 2016), on the contrary as could be thought from local sources. The  
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30 323 distance from the pollen source is an important factor influencing the pollen ratio, and will  
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32 324 overlap with the effect of height on pollen sampling (Spieksma et al., 2000).

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36 326 Apart from height or distance to a local source like ornamental plants, other factors can influence  
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38 327 the ratio of pollen concentrations between stations too. These factors are topography, hour of day  
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40 328 (Rantio-Lehtimäki et al. 1991; Alcazar et al. 1999; Noh et al. 2013), period of season considered  
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42 329 (Peel et al., 2014), or meteorological conditions of the atmosphere (Ríos et al., 2016; Skjøth et  
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44 330 al., 2013), especially wind direction and speed, ambient humidity or rainfall which determines  
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46 331 the pollen dispersal capacity in the air (Pérez et al., 2009; Rojo et al., 2015).

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50 333 It is remarkable that side by side stations located at the same height ( $\Delta\text{height} = 0$  m), such as in  
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52 334 Munich, Germany or Zrenjanin, Serbia (Table 1) showed pollen ratios different to 1 (Figure 1A-  
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54 335 C). Although pollen concentrations between pollen traps located at the same height were not  
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56 336 significantly different (Giorato et al., 2003; Irdi et al., 2002; Velasco-Jiménez et al., 2013),  
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58 337 certain level of variability for daily pollen data was observed in our results (Fig. 5). Therefore,  
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60 338 the standard deviation of Hirst-type traps in the analysis of Munich (Germany) and Zrenjanin  
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62 339 (Serbia) was 0.34 (34%) on average, being the maximum uncertainty estimated by Pedersen and  
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64 340 Moseholm (1993) in a similar approach. The value of the standard deviation from daily pollen  
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4 341 ratio showed an important daily variation despite that the mean pollen ratio was near to 1 (0.83-  
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6 342 1.17) i.e. the mean pollen concentrations were similar for both paired stations. This fact explains  
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8 343 why no significant differences were found in previous works (Tormo-Molina et al., 2013). The  
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10 344 daily variability observed could be explained by random variations caused by instrumental error  
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12 345 but could also be influenced again by meteorological conditions (Pedersen and Moseholm,  
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14 346 1993). All samples between paired stations were processes and counted at the same laboratory  
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16 347 and the error is independent of the interlaboratory variability.  
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19 349 In conclusion, the effect of height of air sampling between stations is only one of the factors  
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21 350 which influences the pollen ratio between paired stations, together with other factors such as the  
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23 351 height of the lower station or the distance between the stations. The data shows that the effect of  
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25 352 sampling pollen at different heights is clear but limited, and that pollen concentrations are much  
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27 353 more homogenous above 10 m AGL. Thus, depending on the purpose of the trap, the optimal  
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29 354 height of a pollen monitor could be >10 m AGL. These findings reveal the importance of the  
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31 355 vertical distribution of bioaerosols and further contribute to the study of the general pattern of  
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33 356 pollen exposure at ground level and, hence, are highly relevant to clinical practice. Until now,  
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35 357 the results of our study constitute the most complete estimation of the variability of the near-  
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37 358 ground vertical profile of airborne pollen.  
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58 370 The authors declare they have no actual or potential competing financial interests.  
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4 372 **References**  
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**Supplementary Material**

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- 658 - Supplementary Material Figure S1
- 659 - Supplementary Material Figure S2
- 660 - Supplementary Material Figure S3
- 661 - Supplementary Material Table S1
- 662 - Supporting data evaluation: all parameters leading to our conclusions can be individually
- 663 adjusted to the user needs with a supplemental data evaluation tool available at [https://modeling-](https://modeling-jesus-rojo.shinyapps.io/result_app2/)
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4 **668 Figure legends**

5 **669**  
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8 **670** Figure 1. Relationship between the mean pollen ratio and the height difference between paired-  
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10 **671** stations (A-C). Relationship between the standard deviation of the mean pollen ratio and the  
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12 **672** height of the lower station (D-F). A logarithmic function was fitted and the 99% confidence  
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14 **673** intervals are shown. The vertical dashed line in D-F is the minimum height proposed for the  
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16 **674** lower station. The plots for the individual pollen types are given in Supplemental Material.

17 **675**  
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19 **676** Figure 2. Relationship between the mean pollen ratio and the height difference between paired-  
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21 **677** stations, only for the lower range of height difference (0-10 m).

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24 **679** Figure 3. Relationship between the standard deviation of the standard deviation (SD) of the mean  
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26 **680** pollen ratio and the height of the lower station for (A) woody, (B) herbaceous and (C) all pollen  
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28 **681** types. This figure shows the SD of the figure 1 (D-F) and supports the minimum height for the  
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30 **682** lower station of >10 m AGL as this reduces the variability of the measurements.

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34 **684** Figure 4. Boxplots comparing the mean pollen ratio depending on: (A)  $\Delta$ height or (B) height of  
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36 **685** the lower station.

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39 **687** Figure 5. Mean pollen ratio and standard deviation calculated for the pollen concentrations  
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41 **688** registered by pollen traps located at the same height and location. This special case was studied  
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43 **689** for three stations in Munich (Germany) (A, B) and two stations in Zrenjanin (Serbia) (C). The  
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45 **690** standard deviation of Hirst-type traps in this analysis was 34% on average. Values of <10  
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47 **691** pollen/m<sup>3</sup> were not considered.

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**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
Krakov (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 Kingdom)	(United 4, 10	52.20 – 52.25	-2.25 – -2.24
Zrenjanin (Serbia)	20, 20	45.38	20.40

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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.

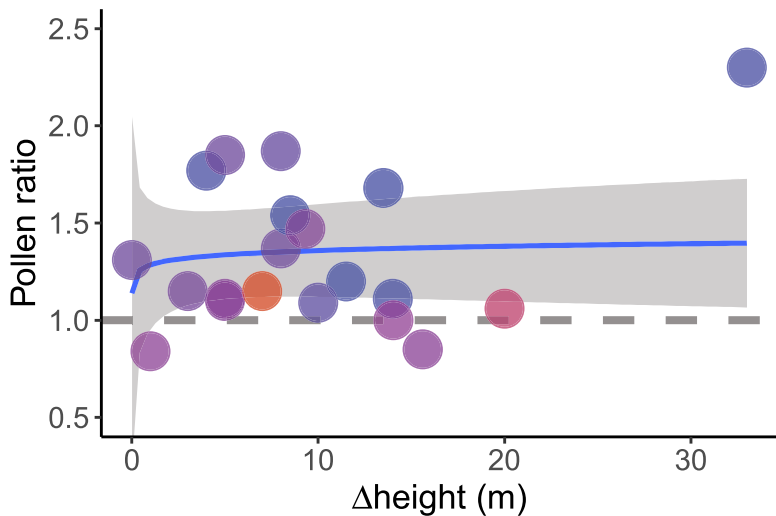
	*Paired-station	Alnu	Ambr	Betu	Cupr	Frax	Olea	Pina	Plan	Plat	Poac	Popu	Urti
1	Badajoz (2/16)						2	2	1	1			
2	Badajoz (2/6)						1		2		1		
3	Badajoz (6/16)						2		2		2		
4	Copenhagen (15/20)			1		3		2			1		1
5	Cordoba (1.5/15)				1		2				1		
6	Madrid (10/18)				1	1	1	1	1	7	1	1	
7	Madrid (8/16)				4	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

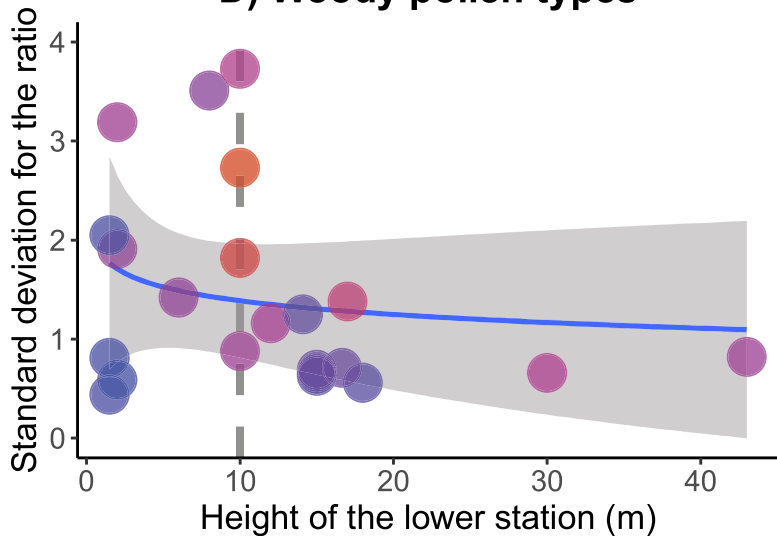
Pollen types: Alnu Alnus, Ambr Ambrosia, Betu Betula, Cupr Cupressaceae/Taxaceae, Frax Fraxinus, Olea Olea, Pina Pinaceae, Plan Plantago, Plat Platanus, Poac Poaceae, Popu Populus, Urti Urticaceae

Figure 1

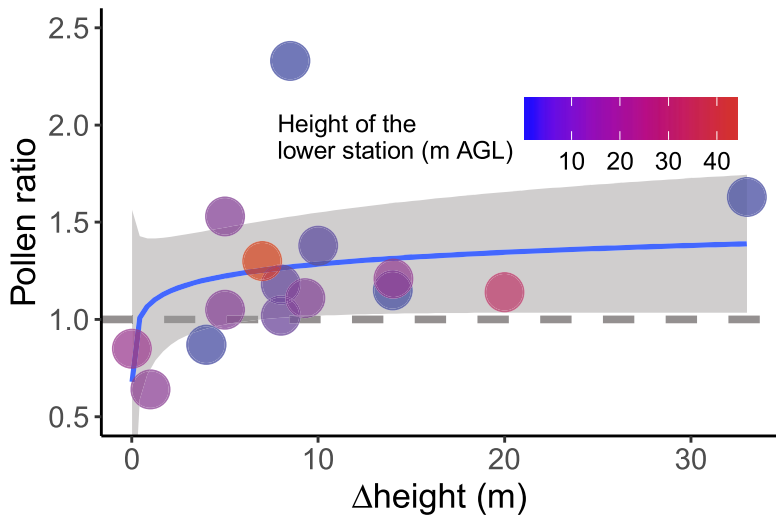
### A) Woody pollen types



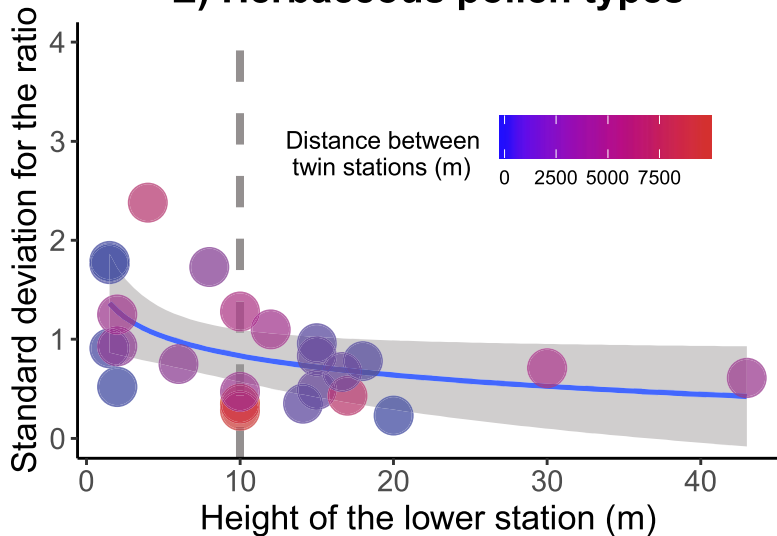
### D) Woody pollen types



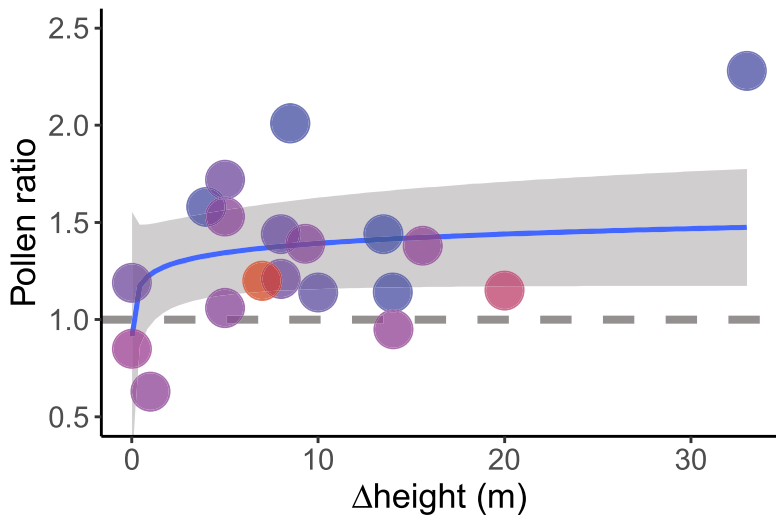
### B) Herbaceous pollen types



### E) Herbaceous pollen types



### C) All pollen types



### F) All pollen types

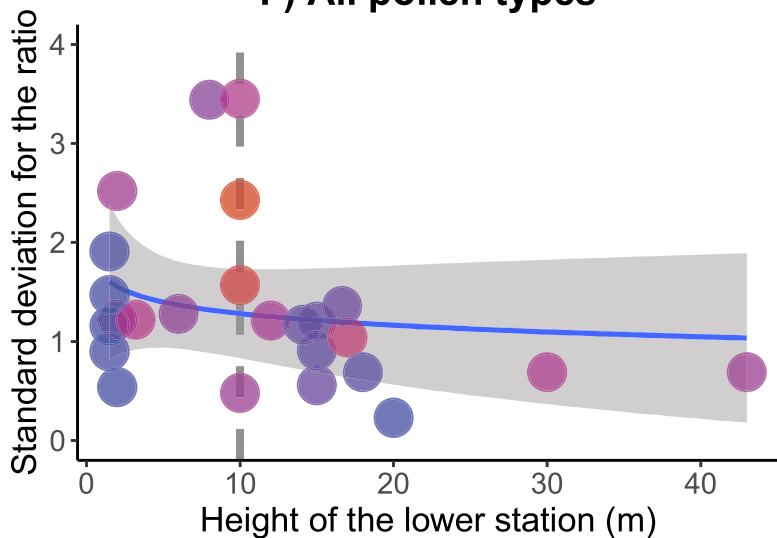
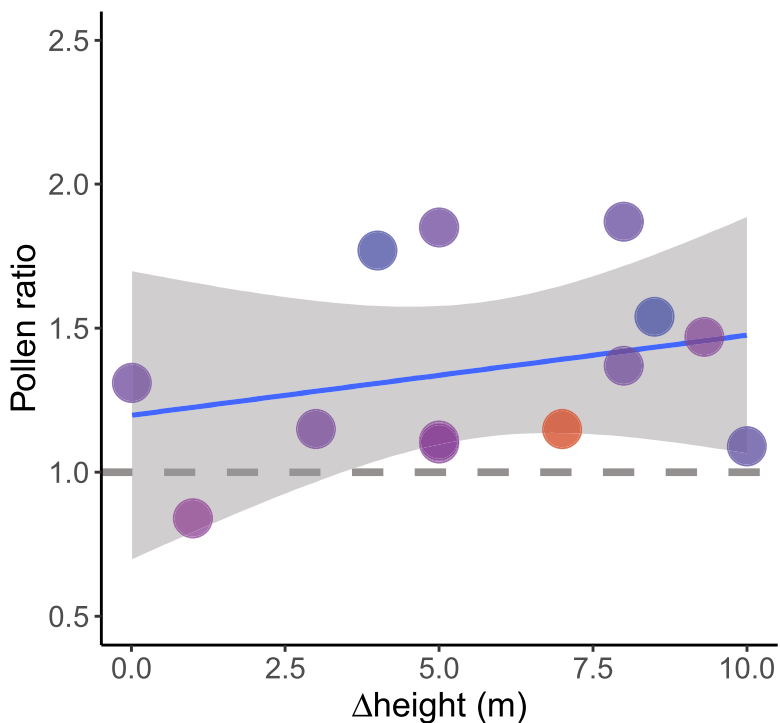
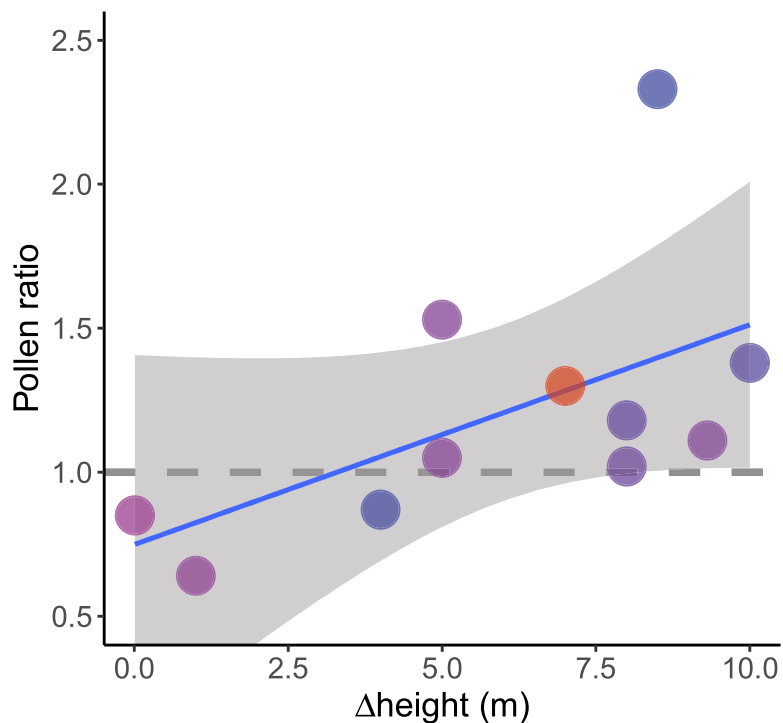


Figure 2

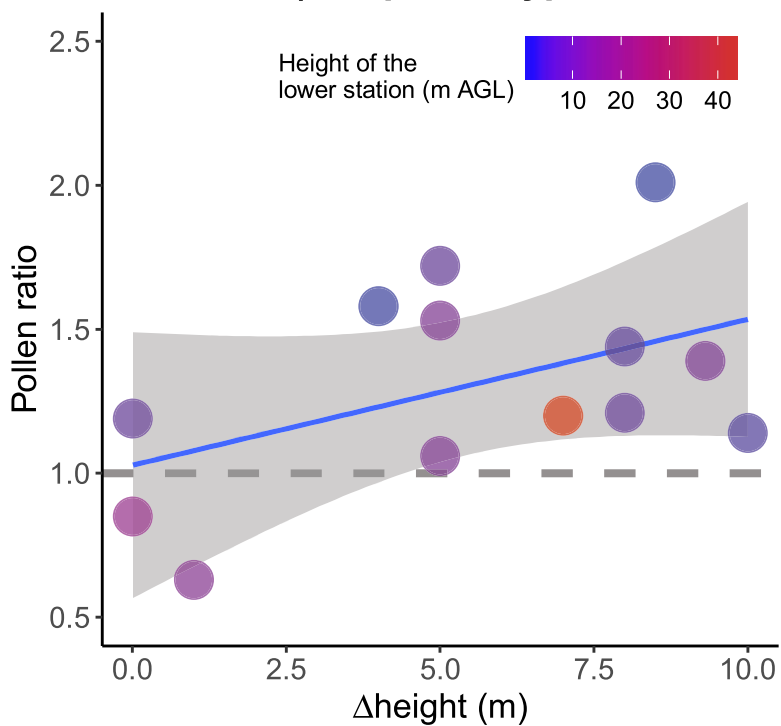
### A) Woody pollen types



### B) Herbaceous pollen types



### C) All pollen types



**Figure 3**

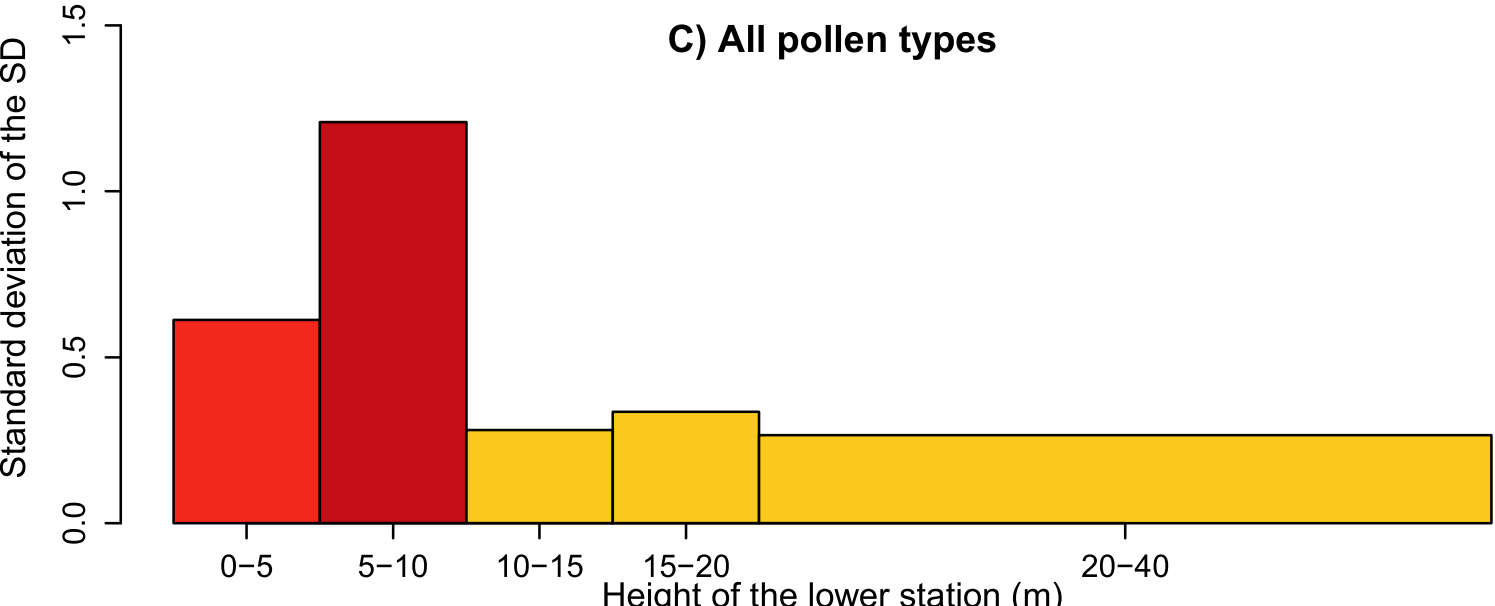
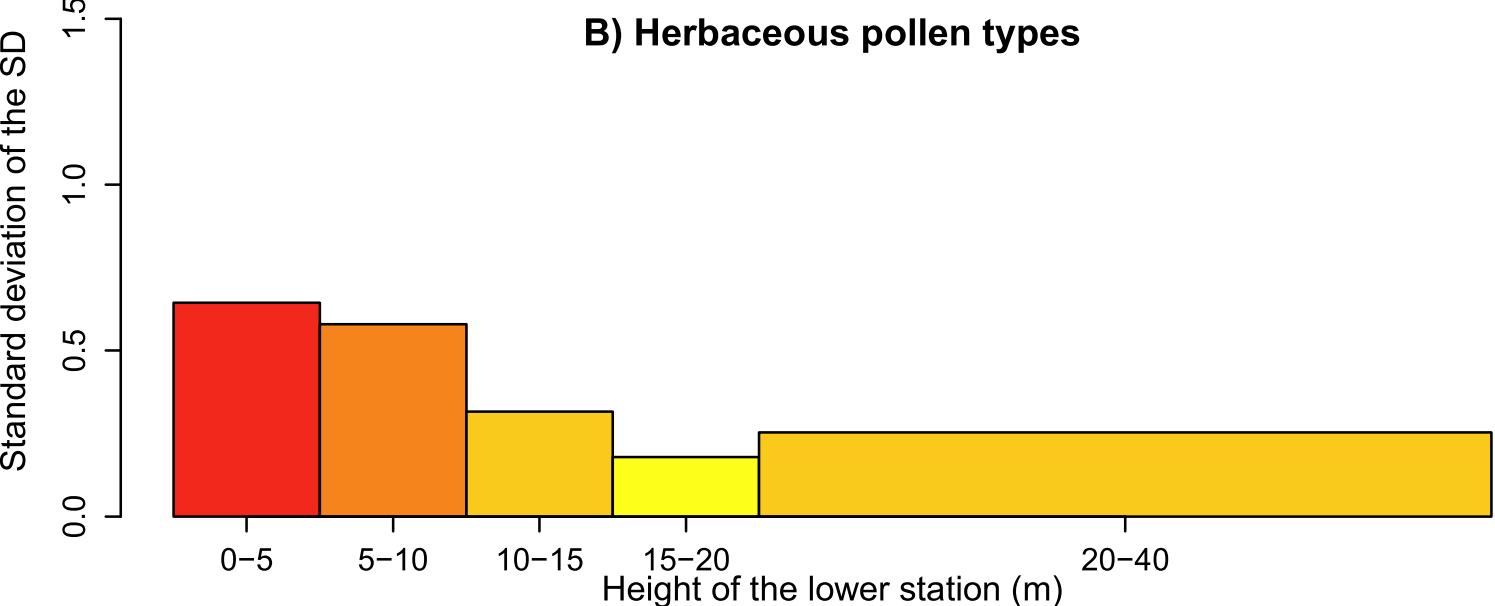
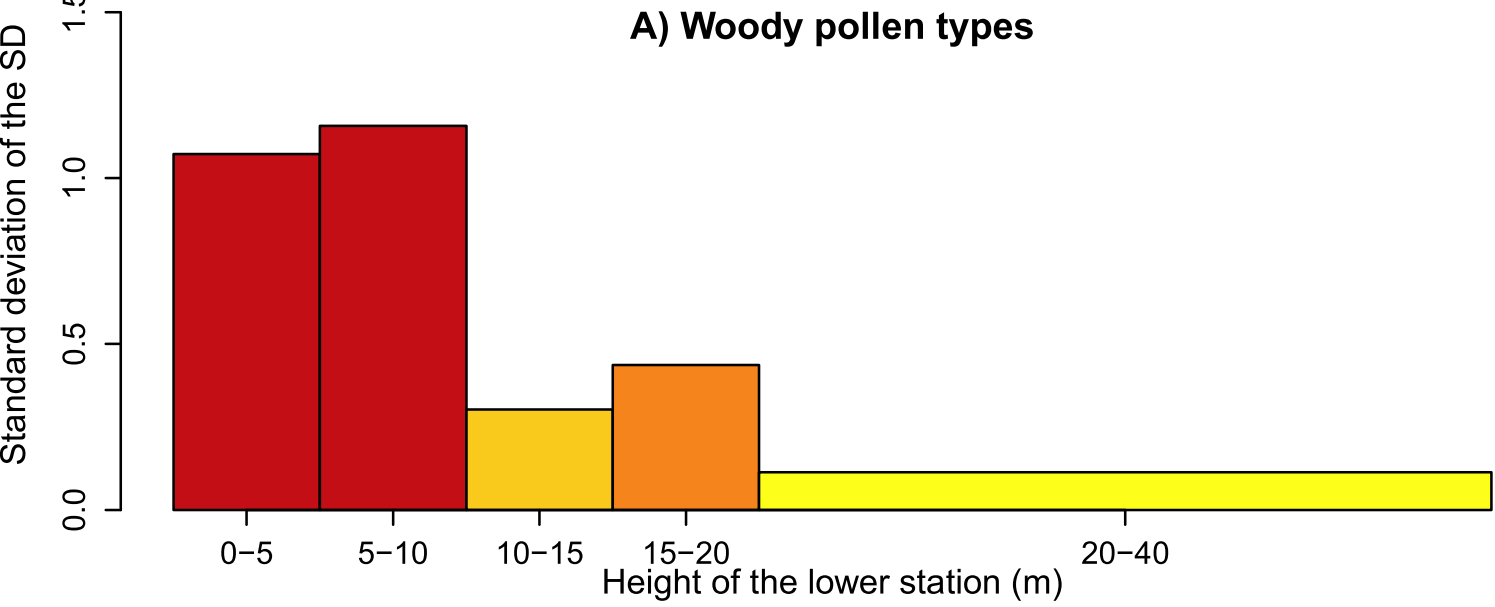


Figure 4

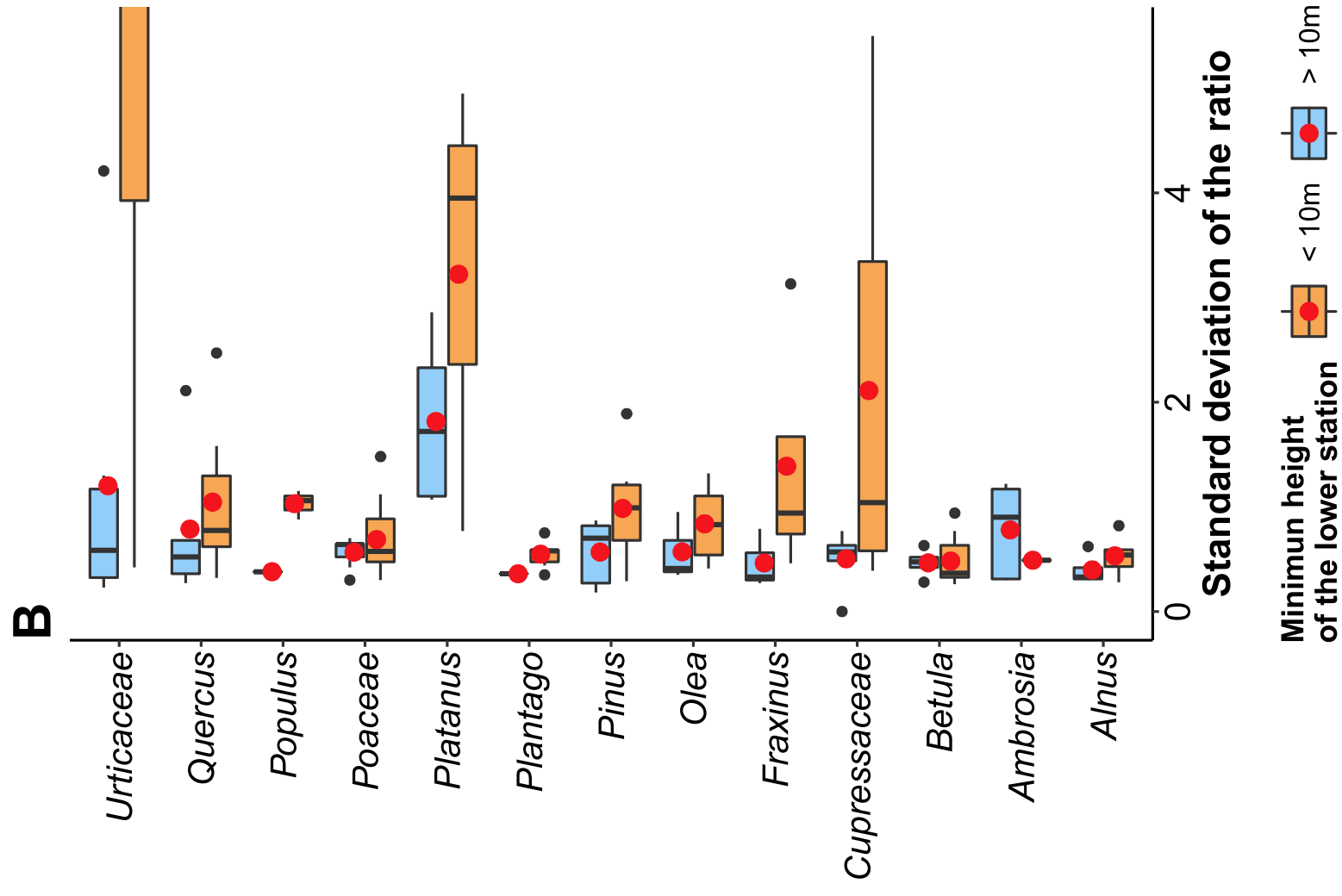
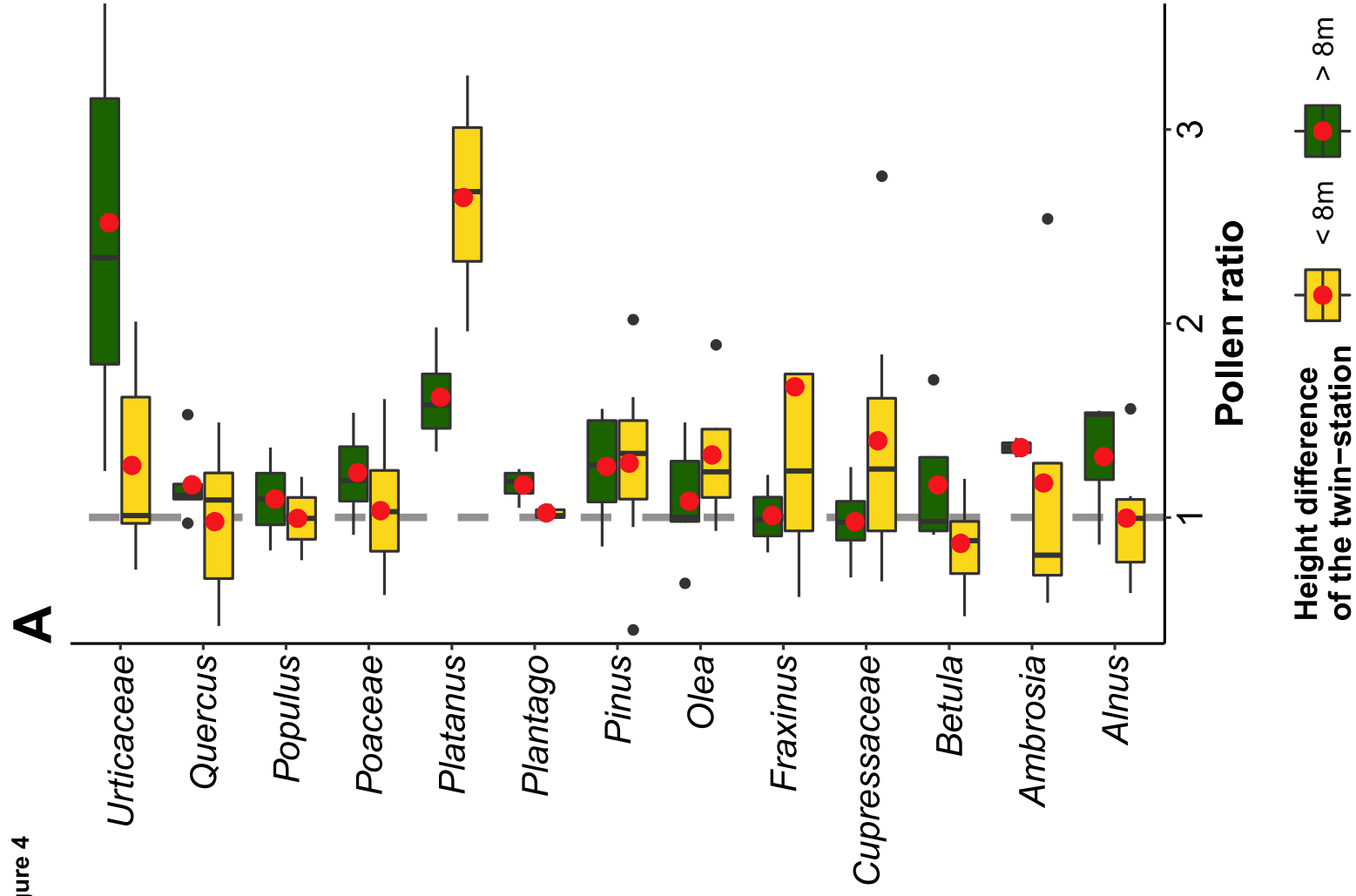
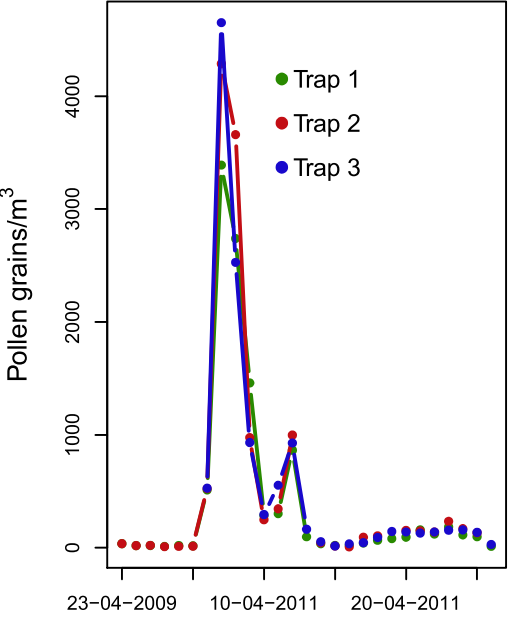
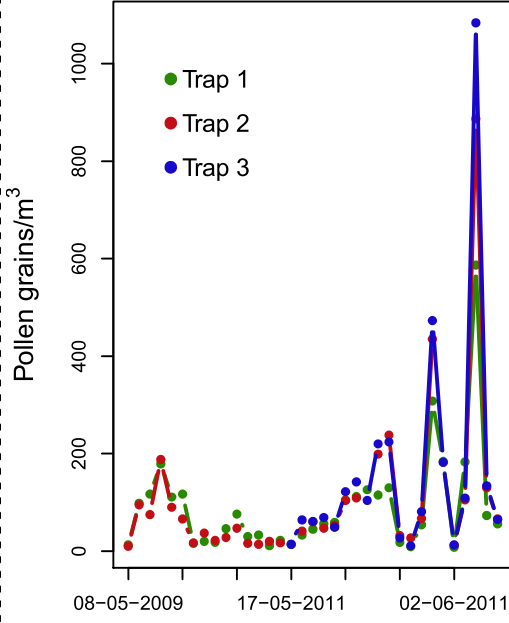


Figure 5

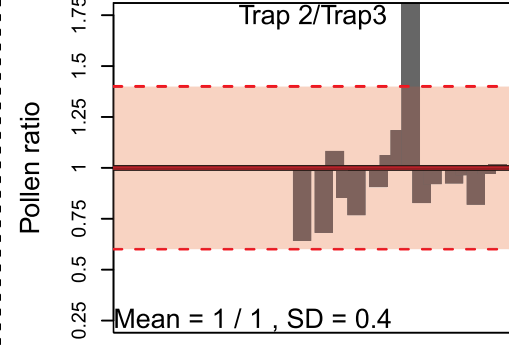
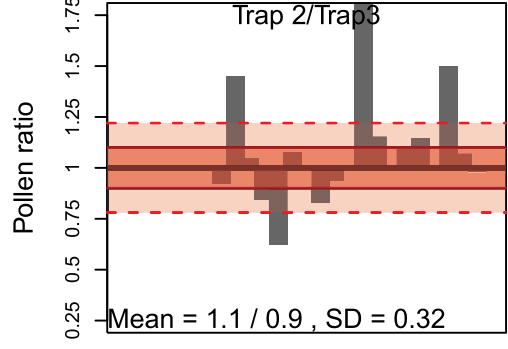
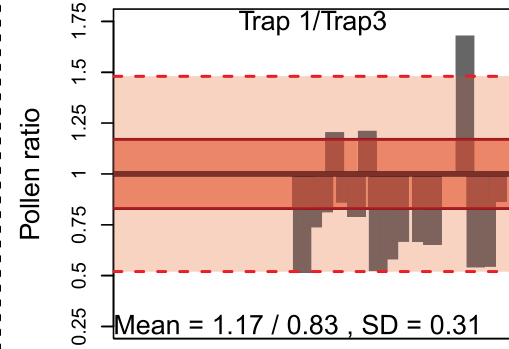
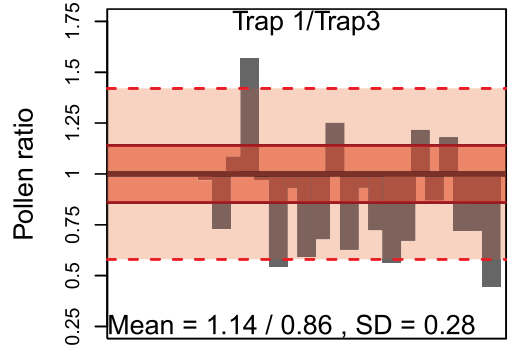
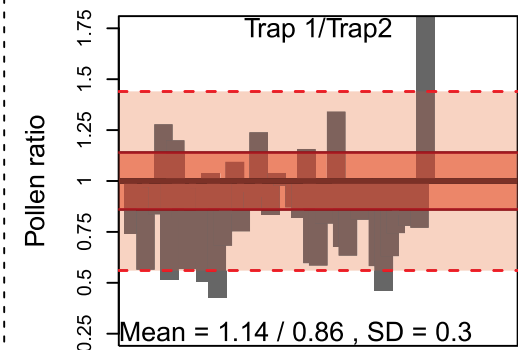
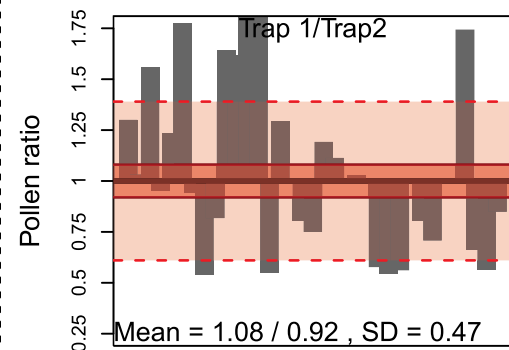
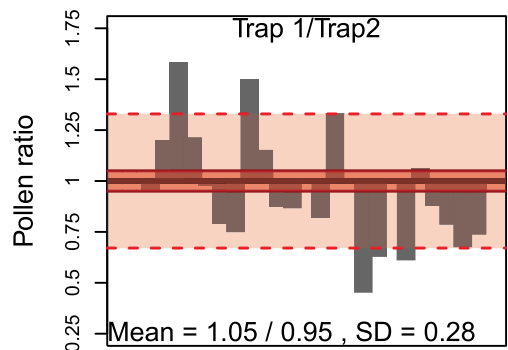
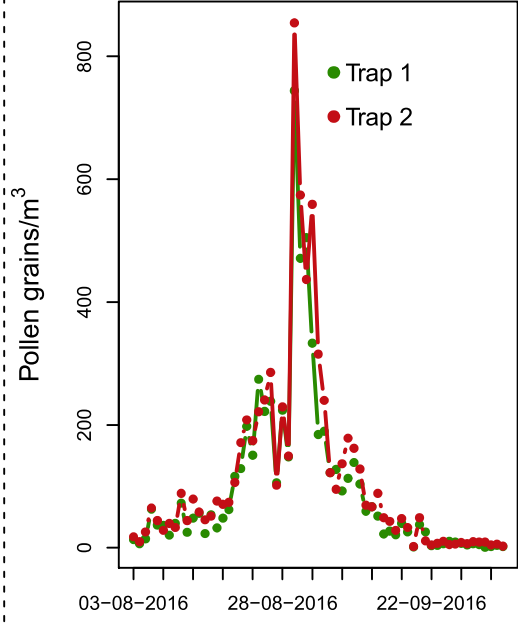
**A) Betula pollen from Munich (Germany)**



**B) Poaceae pollen from Munich (Germany)**



**C) Ambrosia pollen from Zrenjanin (Serbia)**



— Mean  
- - - SD