ORIGINAL ARTICLE

Investigation of spatial and temporal variations of airborne Poaceae, Myrtaceae and Cupressaceae pollen and *Alternaria* spores in Sydney, Australia, 2017–2020

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Abstract There is a need for information on pollen exposure to assess allergy risk. Monitoring of aeroallergens in a city is usually limited to the use of a single trap for the whole area. While a single trap provides enough information on background pollen concentration for the area, varying pollen exposure across different urban environments, however, is not considered. In this study, we analysed aerobiological data of three pollen seasons (2017–2020) recorded with a volumetric pollen trap in Sydney, Australia. In order to assess spatial differences in pollen exposure across the city, we installed ten gravimetric traps recording pollen deposition for eight weeks during the summer of 2019/2020. We considered the influence of meteorological variables, land use, urbanisation and distance to the sea. Our results showed differences in pollen season characteristics across the three analysed seasons and correlations with meteorological parameters. Considering all years, we found for Poaceae and *Alternaria* the strongest positive correlation with mean temperature and for Myrtaceae and Cupressaceae with maximum temperature. Likewise, there were negative correlations with humidity (Myrtaceae, Cupressaceae, *Alternaria*) and precipitation (Myrtaceae, Cupressaceae). Days with medically relevant pollen and spore concentrations varied between years and we recorded the highest amount in 2017/2018 for Poaceae and *Alternaria* and in 2019/2020 for Myrtaceae. In addition, we found spatial and temporal variations of pollen deposition. However, we did not detect significant correlations between pollen deposition and land use, which can be attributable to drought conditions prior to the sampling campaign and the temporal setting in the pollen season. This study highlights the importance of continuous volumetric aerobiological monitoring as well as the assessment of pollen exposure at several locations across a large urban area.

1 Introduction

The analysis of pollen and spore seasons in a city or region is a necessity for assessing aeroallergen exposure to people living there. With an increasing number of urban inhabitants and with metropolitan areas expanding (OECD/European Union, 2020), the relevance of monitoring aeroallergens in cities will

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even increase in the future. Information on pollen is crucial for human health, as between 10 and 30% of the population is affected by allergic rhinitis worldwide (Pawankar et al., 2013). In addition, the impact of climate change on aeroallergens could already be observed: increasing air temperature and atmospheric carbon dioxide concentration are potential drivers that lead to modifications in regard to pollen production/concentration, pollen allergenicity, start and duration of the pollen season as well as plant and pollen distribution (Beggs, 2015; Katelaris & Beggs, 2018; Menzel & Jochner, 2016; Ziska et al., 2019). These impacts are also relevant for spores such as the allergologically relevant *Alternaria* spore (D'Amato et al., 2020; Cecchi et al., 2010).

Scientists started studying pollen in the early twentieth century and the term "aerobiology" was used from the 1930s onwards (Agashe & Caulton, 2009). The first programme including aerobiological measurements was established in 1968 in the USA and the International Association of Aerobiology (IAA) was founded in 1974 in The Hague, the Netherlands (International Biological Program, 1970). However, the density of aerobiological measuring stations differs between continents: in 2016, there were only nine stations in Africa, 151 in America, 182 in Asia, 525 in Europe and 12 in Oceania (Buters et al., 2018). Compared to the Northern Hemisphere, there is only a small number of monitoring stations in Australia. This results in a lack of research on aeroallergens in Australia (Addison-Smith et al., 2021; Beggs, 2018; Davies et al., 2021), even though about 19% of Australia's citizens reported to have allergic rhinitis in 2017/2018 (Australian Institute of Health & Welfare, 2020).

In Sydney, the biggest city in Australia, air quality has been closely monitored for several years (Paton-Walsh et al., 2019; Simmons et al., 2019; Wadlow et al., 2019), with a network of monitoring stations run by the New South Wales (NSW) Department of Planning and Environment (DPE). However, pollen and spores are not included into the broad monitoring program. Nevertheless, several studies were conducted using volumetric traps analysing airborne pollen and spores (Bass & Morgan, 1997; Beggs et al., 2015; Davies et al., 2022; Katelaris et al., 2000, 2004; Medek et al., 2016; Stennett & Beggs, 2004b).

Grass pollen are one of the major aeroallergens in Australia and New Zealand (Davies et al., 2012;

Haberle et al., 2014), which, along with Cupressaceae pollen, accounts for over 50% of total airborne pollen throughout the year. These pollen types are followed by *Betula,* Myrtaceae, *Pinus*, Oleaceae, *Casuarina*, *Plantago* and *Rumex* (Haberle et al., 2014). Therefore, it is not surprising that some studies conducted in Sydney solely focus on grass pollen (Beggs et al., 2015; Medek et al., 2016), but some also consider pollen of other species such as Cupressaceae or Eucalypt species (Katelaris et al., 2000, 2004; Stennett & Beggs, 2004b) and spores such as *Alternaria* (Bass & Morgan, 1997; Stennett & Beggs, 2004a).

Between 2008 and 2013, 90% of grass pollen in Sydney was registered between late September and early April, with peak values recorded between October and December. In some years, a second peak around February could be observed, probably caused by different grass species with different flowering times (Beggs et al., 2015; Medek et al., 2016).

Cupressaceae pollen were recorded to have their peak between August and September (Katelaris et al., 2004). Myrtaceae pollen reach peak concentrations in the summer months December and January but can be detected with small quantities almost year-round (Bass & Morgan, 1997). *Alternaria* spores can also be found in the air of Sydney throughout the year, with peaks in the summer months (Bass & Morgan, 1997).

In order to evaluate spatial differences in pollen exposure across cities as well as to detect urban–rural differences, networks of gravimetric pollen traps have been used (Jetschni & Jochner-Oette, 2021; Katz & Carey, 2014; Stas et al., 2021; Werchan et al., 2017). The use of several traps can help to evaluate different influences on the amount of airborne pollen that should be considered: local vegetation and land use (Cariñanos et al., 2002, 2019; Charalampopoulos et al., 2018), urbanisation (Katz & Batterman, 2020; Katz et al., 2019; Peel et al., 2014; Rodríguez-Rajo et al., 2010) and meteorological parameters (Oduber et al., 2019; Puc, 2012; Rojo et al., 2015; Stennett & Beggs, 2004b; Tassan-Mazzocco et al., 2015; Vara et al., 2016) including the sea-land breeze circulation (Gassmann, Pérez and Gardiol, 2002; Gassmann & Gardiol, 2007).

The aim of this study was to investigate spatial and temporal aerobiological data from Sydney. We focussed on the pollen types Poaceae, Myrtaceae

and Cupressaceae and the spore type *Alternaria*. We analysed seasonal characteristics and assessed the relationship with meteorological parameters during the period from 2017 to 2020.

2 Materials and methods

2.1 Study area

The pollen measurement campaigns were conducted in Sydney, Australia (33.85° S, 151.21° E). Sydney is located at the east coast of Australia with a mean elevation of 3 m a.s.l. The Sydney Metropolitan Area has more than 5.3 million inhabitants (Australian Bureau of Statistics, 2021). Its climate is classified as humid subtropical, with a mean annual minimum temperature of 14.7 °C, mean annual maximum temperature of 22.8 °C and an average precipitation of 1,150 mm (1991–2020) (Australian Bureau of Meteorology, 2021).

Due to the size of the Sydney Metropolitan Area (12,000 m^2) that extends over 70 km to the west, a variety of land uses can be observed: in the north and south, urban areas are adjacent to National Parks consisting of forests, while in the west, areas are covered by lower vegetation. Continuous airborne pollen and spore sampling was conducted at Richmond (October 2017 to February 2020) and we set up a network consisting of ten additional pollen traps across the study area in the summer of 2019/2020 (mid-November to mid-January) (Fig. 1).

2.2 Pollen monitoring

2.2.1 Volumetric pollen/spore trap

Airborne pollen and spores were monitored from 2017 to 2020 using a 7-day-recording volumetric pollen/spore trap (Burkard Manufacturing Co Ltd., Rickmansworth, UK) that is based on the Hirst principle (Hirst, 1952). This trap uses an integrated pump to aspirate 10 L of air per minute through an orifice (14×2 mm), behind which a rotating drum is mounted. A plastic strip (Melinex, DuPont Teijin Films, Luxembourg) attached to the drum is coated with a silicone solution (Silicone fluid mixed with Dimethylether; Lanzoni, Bologna, Italy) allowing

Fig. 1 Map of the Sydney Metropolitan Area with land cover and measurement locations. *Dark green*—woodland and forests, *yellow*—low vegetation and pastures; *red*—built-up area; *blue*–water; *grey*—mines and quarries. Land use data: Geoscience Australia (2017)
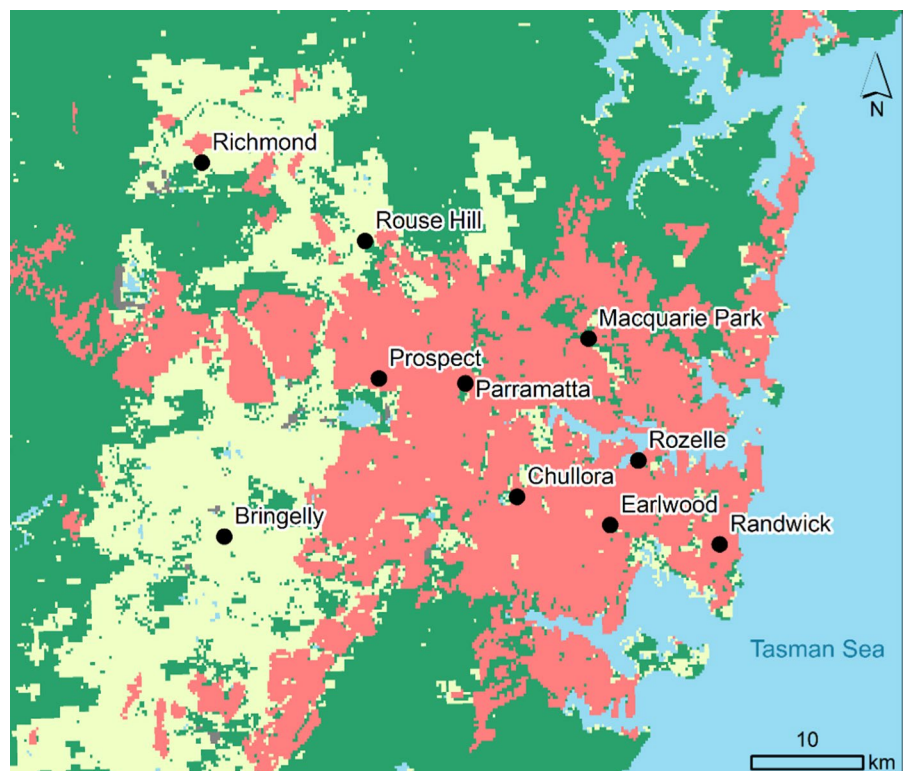
airborne particles to adhere to the tape. The drum completes one revolution in seven days (2 mm per hour) and is therefore changed once a week. Daily samples were prepared in the laboratory.

The trap was set up in Richmond in north-western Sydney (33.6164° S, 150.7473° E) at an air quality monitoring station run by the New South Wales Department of Planning and Environment (DPE) (NSW Department of Planning & Environment, 2021). The trap was mounted to a railing around a platform on top of the station at a height of approx. 3 m above the ground (Fig. 2a). Sampling was performed according to the Australian Airborne Pollen and Spore Monitoring Network standards (Beggs et al., 2018).

The immediate vicinity of the trap is characterised by low grassland and a few isolated trees and shrubs. In the wider surroundings, built-up structures (buildings, roads) of the Hawkesbury Campus of the Western Sydney University can be found to the north and grassland and forest areas to the east, south and west (Fig. 2b).

2.2.2 Gravimetric pollen traps–sampling network

Ten purpose-built gravimetric traps (Durham-type; Durham, 1946) (Jetschni & Jochner-Oette, 2021), based on passive sampling, were used in this study. They were composed of two horizontal circular plastic discs with a diameter of 23 cm, which were held apart at a distance of 27 cm with four threaded rods. A wooden block ($L \times W \times H = 9.5$ cm$\times 5.5$ cm$\times 4.0$ cm) was attached to the lower disc and equipped with a clip to secure a microscope slide horizontally. The microscope slides

were coated with the silicone solution described in Sect. 2.2.1, allowing airborne particles to settle and adhere to them due to gravity. The traps were attached to the railing at about 3 m above the ground (Fig. 3), similar to the volumetric trap (Fig. 2).

The traps were set up at ten locations throughout the Sydney Metropolitan Area (Fig. 1) where air quality monitoring stations (New South Wales Department of Planning and Environment) served as standardised sampling locations (e.g. same height above the ground). These stations can be found throughout the study area and provide easy accessibility and security. We selected the sampling locations based on representativeness of different environments, i.e. the distance to the sea, urbanisation and land use (Table 1).

Sampling started on 20 November 2019 and lasted for eight weeks until 14 January 2020. Microscope slides were changed weekly at the same time of the day (between 8 am and 2 pm), as the stations were
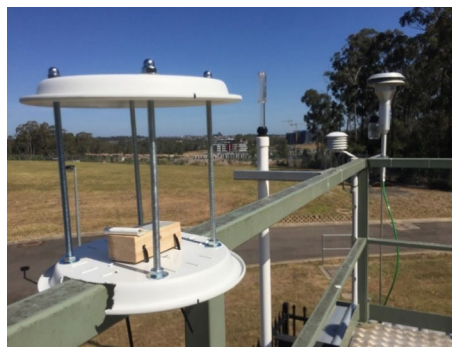

Fig. 3 Passive sampler mounted to the railing of an air quality monitoring station in Rouse Hill

Fig. 2 a Pollen/spore trap mounted to the railing in Richmond **b** Surroundings of the trap (white dot) (base map: CNES/Airbus, Maxar Technologies, Google 2022)
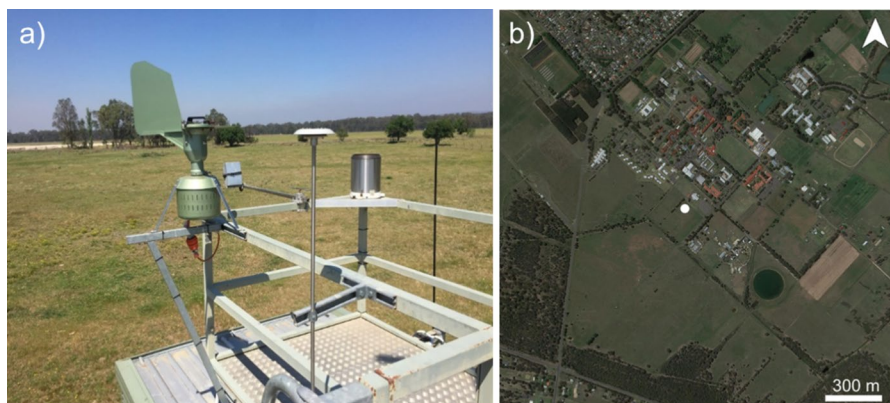
Table 1 Sampling locations and surroundings of gravimetric pollen traps

Station	Coordinates	Distance to the sea [km]	Urban index	Land cover [%] within 100 m				Characteristics of the surroundings
				Built-up area	Low vegetation and pastures	Woodland and forests	Water	
Randwick	33.9318° S, 151.2428° E	3.0	0.85	100	0	0	0	Restricted military area; low cut and maintained grass area and built-up structures
Rozelle	33.8644° S, 151.1639° E	11.9	0.66	98	0	2	0	Low cut maintained grass area, nearby shrubs and trees
Earlwood	33.9162° S 151.1358° E	13.7	0.82	87	4	9	0	Direct vicinity to residential area, playground, park land and football field; maintained and low cut grass
Macquarie Park	33.7653° S 151.1178° E	18.2	0.65	50	2	48	0	Sports area with football fields bordered by trees; nearby bushland
Chullora	33.8916° S, 151.0461° E	23.0	0.94	86	7	5	2	Green space in an industrial area; grass area with nearby shrubs and trees
Parramatta	33.7995° S 150.9978° E	29.4	0.77	89	2	9	0	Park area with single buildings and low cut grass; nearby parking lot with trees
Prospect	33.7942° S 150.9142° E	37.7	0.79	97	3	0	0	Edge of recreational area with football field and run track; low cut grass, scattered trees and bushes
Rouse Hill	33.6828° S 150.9037° E	40.8	0.39	0	65	35	0	Area of low cut grass surrounded by trees and built structures
Bringelly	33.9177° S 150.7619° E	50.7	0.50	0	100	0	0	Rural environment, large areas of grassland with shrubs and trees; few houses and streets
Richmond	33.6164° S 150.7473° E	57.3	0.80	11	79	10	0	Grassland with scattered trees

Land cover (Geoscience Australia, 2017) within 100 m of the traps (see Methods section). Stations ordered in ascending distance from the sea

visited one after the other in the same order every week. In total, we collected 80 slides, which were prepared in the laboratory.

2.2.3 Sample preparation

In the laboratory, we used glycerine jelly with fuchsine stain (Lanzoni, Bologna, Italy) to fix the daily lengths of plastic strip of the volumetric trap to microscope slides and to stain them. For the glass slides from the gravimetric trap, we used a mixture of distilled water, gelatine, glycerol, and fuchsine stain. The samples were analysed using light microscopy (AxioLab.A1 (Zeiss, Wetzlar, Germany) and Olympus CX23 (Olympus Scientific Solutions, Tokyo, Japan)) using 400× magnification.

Pollen of the taxa Poaceae, Myrtaceae and Cupressaceae as well as *Alternaria* spores were identified and counted along four longitudinal transects (resulting in approx. 10% of the whole slide). Counts were converted to pollen and spore concentration per cubic metre of air (pollen grains/m^3, spores/m^3). In the case of the gravimetric traps, Poaceae, Myrtaceae and Cupressaceae were identified and counted along four longitudinal transects and then converted to pollen grains per square centimetre of slide surface (pollen deposition in pollen grains/cm^2) (Jetschni & Jochner-Oette, 2021).

2.3 Analyses

2.3.1 Aerobiological data

To describe aerobiological data of Poaceae, Myrtaceae, Cupressaceae and *Alternaria* collected by the volumetric trap, we used the recommended terminology by Galán et al. (2017). Because of the study's location in the Southern Hemisphere, pollen data were calculated and visualised with the course of 12 months starting on 1 July and ending on 30 June of the following year (Beggs et al., 2015; Medek et al., 2016). Gaps no bigger than five consecutive days were filled using interpolation (moving mean; Picornell et al., 2021).

Due to data gaps, we calculated neither start/end dates of pollen or spore seasons nor the Seasonal Pollen/Spore Integral. We did, however, calculate the Annual Pollen Integral (APIn; the sum of the daily mean pollen concentrations, pollen*day/m^3)

during the course of a year (Galán et al., 2017) of the available data and the Annual Spore Integral (ASIn), respectively. In addition, we identified peak days with peak values, i.e. the days with the highest daily mean pollen/spore concentration of the season. In order to compare pollen and spore integrals between the years despite missing data, we calculated the mean of the daily pollen or spore concentrations by dividing the integrals by the number of observation days for each year. To account for days with medical relevance, the number of days above the threshold for "high pollen/spore days" was identified using following thresholds:

- Poaceae: > 50 grains/m^3 (Galán et al., 2007; Bannister et al., 2021; Morton et al., 2011; Ong et al., 1995)
- Myrtaceae: > 50 grains/m^3 (Galán et al., 2007)
- Cupressaceae: > 200 grains/m^3 (Galán et al., 2007)
- *Alternaria*: > 10 spores/m^3 (Aira et al., 2013)

Furthermore, we used the terminology used by Jetschni and Jochner-Oette (2021) to compare and describe data:

- Campaign Pollen Integral (CPIn)
  - The sum of all measurements for each location during the sampling campaign,
    i.e. $CPIn_{grav}$ for the gravimetric and $CPIn_{vol}$ for the volumetric trap
- Weekly Pollen Integral (WPIn)
  - The sum of all daily mean pollen concentrations of one week, i.e. $WPIn_{vol}$ for the volumetric trap at Richmond
  - The sum of the pollen deposition for all gravimetric sites for one week, i.e. $WPIn_{grav}$

We compared CPIns, WPIns and mean values to assess spatial and temporal variations and tested pollen data from all sites from the sampling campaign for significant differences using Wilcoxon rank-sum test and Kruskal–Wallis test. We analysed the relationship between daily mean pollen concentrations and meteorological variables by calculating Spearman's correlation coefficients (r_s).

2.3.2 Land use/cover

Information on land use/cover was obtained from Geoscience Australia (2017). This dataset contains information on 35 land cover classifications at a

resolution of 250 m. For this study, we aggregated the classes to "urban area", "low vegetation and pastures", "woodland and forest", "water" and "mines and quarries" (see Appendix A). We used these classes (except the latter since it was not observed) to analyse the surroundings of the sampling locations: we calculated the percentage of each class in a radius of 100 m. To quantify urbanisation, we calculated the urban index (Jochner et al., 2012) based on the same dataset. We presented Spearman's correlation coefficients (r_s) to check for relationships between pollen deposition (CPIns) and land cover as well as pollen deposition and urban index.

2.3.3 Meteorological data

Hourly meteorological data for each sampling location were obtained from the monitoring network of DPE (see Fig. 1 and Table 1 for locations). For the pollen seasons from 2017 to 2020, we considered temperature (daily mean, minimum and maximum), precipitation (daily total), relative humidity (daily mean) and wind speed (daily mean) recorded at Richmond. The relationship between these variables and daily mean pollen concentrations was analysed by calculating Spearman's correlation coefficients (r_s) on a seasonal basis. For the period of the sampling campaign (November 2019 to January 2020), we analysed hourly and weekly means of temperature, daily and weekly totals of precipitation as well as the most frequent wind direction and wind speed for all ten locations.

For statistical analyses and visualisation, we used RStudio (1.3.959), packages ggplot2 (Wickham, 2016), AeRobiology (Rojo, Picornell and Oteros, 2018) and OpenAir (Carslaw & Ropkins, 2012). We used ESRI ArcMap 10.6 and QGIS 3.14 for spatial analyses and visualisation.

3 Results

3.1 Volumetric aerobiological monitoring

Volumetric aerobiological monitoring resulted in data for three pollen seasons 2017/2018, 2018/2019 and 2019/2020, in which we observed different characteristics (Fig. 4).

Figure 4 also gives information on missing data, as the pollen trap at Richmond commenced operation for the first time on 7 October 2017 and therefore the 2017/2018 year is missing the first 99 days. In the years 2018/2019 and 2019/2020, periods of missing data after interpolation were 9 January to 29 April 2019 and 4 February to 30 June 2020, resulting in 111 and 148 days of missing data from these two years, respectively.

However, for all analysed pollen and spore types, there were differences in APIn, mean of daily pollen/spore concentration, number of peak days, peak values and number of days above a threshold with medical relevance. Figure 4 and Table 2 give an overview of the course of the pollen and spore seasons as well as aerobiological characteristics. When considering these, the missing data should be kept in mind, as annual totals, peak values and other metrics could be even higher.

3.1.1 2017/2018

In 2017/2018, there were missing aerobiological data from 1 July to 8 October, resulting in available data for a total of 266 days (Table 2). For this period and among the analysed pollen types, Poaceae had the highest APIn with 3,816 pollen grains*day/m^3, which is almost twice the APIn of Myrtaceae (1,962 pollen grains*day/m^3) and almost 3.5 times the APIn of Cupressaceae (1,113 pollen grain*day/m^3). This was also reflected in the mean of the daily pollen concentration (Poaceae: 14 pollen grains/m^3, Myrtaceae: 7 pollen grains/m^3, Cupressaceae: 4 pollen grains/m^3). The peak value for Poaceae was 154 pollen grains/m^3 on 12 October, and there were 23 high pollen days in total.

The peak value for Myrtaceae was recorded on 6 November (102 pollen grains/m^3), and there were three high pollen days. The highest daily mean pollen concentration for Cupressaceae was 117 pollen grains/m^3 on 19 December.

For *Alternaria* spores, the ASIn was 10,526 spores*day/m^3, and the highest daily mean spore concentration was measured on 10 February (678 spores/m^3). There were 200 high spore days. The mean of the daily spore concentrations was 40 spores/m^3.

Considering the course of the Poaceae pollen concentration (Fig. 4a), two peaks could be identified: one peak was measured in October

Fig. 4 Daily airborne pollen concentrations of Poaceae (yellow), Myrtaceae (red) and Cupressaceae (green), spore concentrations of *Alternaria* (black line; right axis) as well as temperature (black line) and rainfall (blue bars) in the bottom parts of the figures for the seasons **a** 2017/2018, **b** 2018/2019, **c** 2019/2020 with dashed lines indicating the start and end dates of the sampling campaign with gravimetric traps
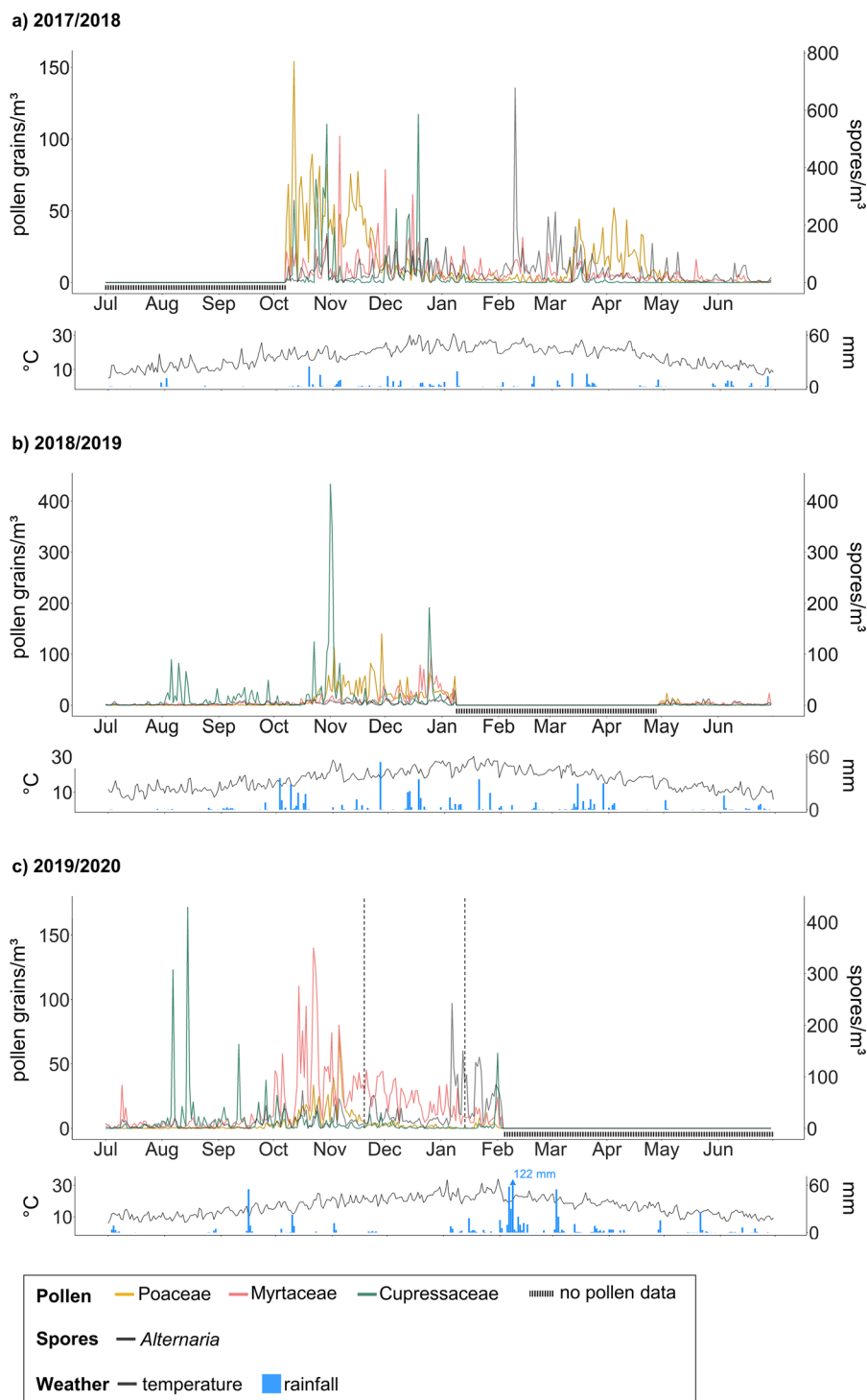
(154 pollen grains/m^3 on 12 October 2017). From the end of November onwards pollen concentrations decreased and remained on a lower level until mid-March. Then, the pollen concentrations increased again with the highest value in April (52 pollen grains/m^3 on 5 April).

Table 2 Characteristics of the pollen (spore) seasons 2017/2018, 2018/2019 and 2019/2020 for Poaceae, Myrtaceae, Cupressaceae, *Alternaria* and the Annual Pollen Integral (APIn) or Annual Spore Integral (ASIn) measured at Richmond

	Poaceae	Myrtaceae	Cupressaceae	*Alternaria*
2017/2018[a]				
APIn (pollen*day/m^3)	3,816 +	1,962 +	1,113 +	10,526 +
ASIn (spores*day/m^3)				
Mean of daily pollen/spore concentration (pollen grains/m^3; spores/m^3)	14	7	4	40
Peak day	12 Oct	6 Nov	19 Dec	10 Feb
Peak value (pollen grains/m^3; spores/m^3)	154	102	117	678
High pollen/spore days	23 +	3 +	0 +	203 +
2018/2019[b]				
APIn (pollen*day/m^3)	2,684 +	1,795 +	3,178 +	4,718 +
ASIn (spores*day/m^3)				
Mean of daily pollen/spore concentration (pollen grains/m^3; spores/m^3)	11	7	13	19
Peak day	29 Nov	26 Dec	1 Nov	8 Jan
Peak value (pollen grains/m^3; spores/m^3)	140	99	434	148
High pollen/spore days	13 +	4 +	2 +	125 +
2019/2020[c]				
APIn (pollen*day/m^3)	846 +	3,826 +	1,158 +	9,007 +
ASIn (spores*day/m^3)				
Mean of daily pollen/spore concentration (pollen grains/m^3; spores/m^3)	4	18	5	42
Peak day	6 Nov	23 Oct	15 Aug	7 Jan
Peak value (pollen grains/m^3; spores/m^3)	71	140	172	485
High pollen/spore days	1 +	11 +	0 +	144 +

Mean of daily pollen/spore concentration is calculated by dividing APIn/ASIn by the number of days with data

+ indicates the assumption of virtually higher values due to missing data

[a]266 days with data; [b]254 days with data; [c]217 days with data

The course of the Myrtaceae pollen concentration was not characterised by isolated peaks. The highest concentrations were recorded in November and December 2017. Throughout almost the entire season, airborne Myrtaceae pollen were detected.

Most of the Cupressaceae pollen concentration was recorded from October to the end of December 2017. In 2018, smaller concentrations of airborne Cupressaceae pollen were identified. *Alternaria* spores were present in the air of Sydney on almost every day, and the highest concentrations were recorded from mid-February to March 2018.

3.1.2 2018/2019

In 2018/2019, there were missing aerobiological data from 9 January to 29 April 2019, resulting in data for a total of 254 days (Table 2). In this period, APIn for Cupressaceae was 3,178 pollen grains*day/

m^3 and therefore higher than Poaceae (2,684 pollen grains*day/m^3) or Myrtaceae (1,795 pollen grains*day/m^3). The highest daily mean pollen concentration of Poaceae was registered on 29 November 2018 with 140 pollen grains/m^3, of Myrtaceae on 26 December 2018 (99 pollen grains/m^3) and of Cupressaceae on 1 November 2018 with a concentration of 434 pollen grains/m^3. The mean of the daily pollen concentrations was for Poaceae 11 pollen grains/m^3, Myrtaceae 7 pollen grains/m^3, Cupressaceae 13 pollen grains/m^3. Due to missing data, the course of the pollen and spore concentrations cannot be described completely (Fig. 4b).

For all pollen types, concentrations were higher in the period up to January than in the period May to July. Similar to the previous season, *Alternaria* spores were present in the air on almost all days, reaching the highest level on 8 January with a concentration of 148 spores/m^3. The ASIn was 4,718 + spores*day/m^3,

and the mean of the daily spore concentrations was 19 spores/m^3.

3.1.3 2019/2020

In 2019/2020, there were missing aerobiological data from 4 February to 30 June 2020, resulting in data for a total of 217 days (Table 2). APIn of Poaceae was 846 pollen grains*day/m^3, which is less than 25% of the APIn in 2017/2018 and about 30% of the APIn in 2018/2019. The mean of the daily grass pollen concentrations was 4 pollen grains/m^3, which is 26% of 2017/2018 and 29% of 2018/2019. The highest value for Poaceae pollen concentration was measured on 6 November 2019 (71 pollen grains/m^3), which was the only day with a mean pollen concentration above 50 pollen grains/m^3. The course of Poaceae pollen concentrations can be described as a curve, increasing towards early November and decreasing after the peak on 6 November 2019 (Fig. 4c).

Myrtaceae APIn was 3,826 pollen grains*day/m with the peak day (140 pollen grains/m^3 on 23 October 2019) occurring much earlier than in the previous season (−64 days). The mean of daily concentrations was 18 pollen grains/m^3, which is more than twice than in the previous year. The course of Myrtaceae pollen was similar to the Poaceae course.

The APIn of Cupressaceae (1,159 pollen grain*day/m^3) and the peak value (172 pollen grains/m^3) were lower than in the previous sampling period and there was no high pollen day. The highest concentrations of Cupressaceae pollen were detected in August, with only low concentrations in the remaining season. The mean of daily Cupressaceae concentrations was 42 pollen grains/m^3.

Alternaria spores had an ASIn of 9,007 spores*day/m^3 with the peak day on 7 January 2020 (485 spores/m^3) and 144 high spore days. The mean of the daily spore concentrations was 42 spores/m^3. Highest concentrations of *Alternaria* spores were recorded in January 2020, while spores were present throughout most of the sampling period.

3.1.4 Meteorology

Daily data for temperature and rainfall are illustrated in Fig. 4. Mean, lowest and highest temperatures did not differ a lot between the years. However, rainfall

Table 3 Overview of the meteorological variables for the seasons 2017/2018, 2018/2019 and 2019/2020

	Mean temperature [°C]	Minimum temperature [°C]	Maximum temperature [°C]	Rainfall sum [mm]
2017/2018	17.6	−2.0	44.3	291.6
2018/2019	17.2	−4.5	41.9	626.6
2019/2020	16.9	−4.0	46.5	713.4

Every season starts on the 1 July and ends on 30 June of the following year

substantially varied: it was 291.6 mm in 2017/2018, 626.6 mm in 2018/2019 and 713.4 mm in 2019/2020 (Table 3). Extremely high rainfall at the start of February 2020 (Fig. 4) caused the pollen trap to break.

The correlation analyses between the three pollen types (Poaceae, Myrtaceae and Cupressaceae) as well as the spore *Alternaria* and the meteorological variables revealed significant relationships (Table 4). Correlations between temperature (mean, minimum, maximum) and each pollen type and spore were all positive for every year and significant apart from some cases paired with Cupressaceae. For this type, the pairing with minimum temperature (2017–2020) did not reveal a significant correlation, and in 2019/2020 a negative correlation with mean temperature ($r_s = -0.149$, $p < 0.05$) and maximum temperature ($r_s = -0.300$, $p < 0.01$) was observed. All significant correlations with humidity as well as precipitation were negative.

3.2 Gravimetric pollen sampling campaign

3.2.1 Pollen data

The temporal setting of the sampling campaign with gravimetric pollen traps in the 2019/2020 pollen season is shown in Fig. 4c. Sampling started after the season's peak days where the highest pollen concentrations were recorded (see Sect. 3.1.3; Table 2). We analysed the share of the Campaign Pollen Integral (CPIn$_{vol}$) as part of APIn in order to evaluate the representativeness of this campaign for the whole season. For Poaceae (CPIn$_{vol}$ = 98) it was 12%, for Myrtaceae (CPIn$_{vol}$ = 1,208) 32% and for Cupressaceae (CPIn$_{vol}$ = 80) 7% (Table 5).

These comparably low numbers were also reflected by pollen deposition, as illustrated in the

Table 4 Spearman's rank correlation coefficients between daily meteorological parameters and pollen and spore concentrations for the whole period and single seasons (July–June)

	Poaceae	Myrtaceae	Cupressaceae	*Alternaria*
2017–2020				
Mean temperature	**0.609****	**0.625****	**0.147****	**0.690****
Minimum temperature	**0.520****	**0.475****	0.010	**0.583****
Maximum temperature	**0.584****	**0.664****	**0.254****	**0.678****
Mean humidity	− 0.058	**− 0.251****	**− 0.283****	**− 0.118****
Precipitation sum	− 0.034	**− 0.160****	**− 0.102****	− 0.048
Mean wind speed	**0.083***	**0.172****	0.066	**0.179****
2017/2018				
Mean temperature	**0.364****	**0.619****	**0.365****	**0.557****
Minimum temperature	**0.242****	**0.403****	**0.261****	**0.441****
Maximum temperature	**0.410****	**0.667****	**0.373****	**0.577****
Mean humidity	**− 0.141***	**− 0.388****	**− 0.162****	**− 0.248****
Precipitation sum	− 0.067	**− 0.224****	0.036	− 0.075
Mean wind speed	0.024	**0.144***	**0.128***	**0.183****
2018/2019				
Mean temperature	**0.746****	**0.697****	**0.501****	**0.617****
Minimum temperature	**0.699****	**0.601****	**0.309****	**0.470****
Maximum temperature	**0.671****	**0.663****	**0.553****	**0.684****
Mean humidity	0.038	− 0.045	**− 0.357****	− 0.042
Precipitation sum	0.008	− 0.009	**− 0.159***	− 0.067
Mean wind speed	0.111	**0.165****	**0.180****	0.083
2019/2020				
Mean temperature	**0.545****	**0.604****	**− 0.149***	**0.751****
Minimum temperature	**0.374****	**0.438****	**− 0.300****	**0.679****
Maximum temperature	**0.579****	**0.646****	0.044	**0.665****
Mean humidity	**− 0.251****	**− 0.253****	**− 0.225****	− 0.098
Precipitation sum	− 0.122	**− 0.207****	**− 0.191****	0.025
Mean wind speed	**0.155***	**0.145***	**− 0.144***	**0.243***

Bold values indicate significant correlations ($*p < 0.05$, $**p < 0.01$)

Table 5 Characteristics of pollen/spore reference concentrations (volumetric trap at Richmond) during the gravimetric sampling campaign 20 November 2019 to 14 January 2020 for Poaceae, Myrtaceae and Cupressaceae

	Poaceae	Myrtaceae	Cupressaceae
$CPIn_{vol}$	98	1,208	80
Share of 2019/2020 APIn	12%	32%	7%
Peak day	6 Dec	21 Nov	29 Nov
Peak value (pollen grains/m^3)	6	45	12
High pollen days	0	0	0

heat maps (Fig. 5). The most abundant pollen types registered within our gravimetric sampling campaign belonged to the family Myrtaceae ($CPIn_{grav}$: 1,330). Grass (Poaceae) and Cupressaceae pollen were also detected, but in much smaller quantities ($CPIn_{grav}$ 166 and 121, respectively).

We observed a temporal and spatial variation in Poaceae pollen deposition (Fig. 5a). The first week of sampling was characterised by the highest WPIn of the campaign (62) and by the highest single value for deposition, which was recorded at Chullora (21 pollen grains/cm^2). Values for WPIn decreased after this week, showing a similar tendency compared to WPIn recorded by the volumetric trap. The highest $CPIn_{grav}$ was recorded at Chullora (36) and the lowest $CPIn_{grav}$ at Rouse Hill (8).

Regarding Myrtaceae, the highest $WPIn_{grav}$ (271) was recorded in the third week of sampling. In this week, the highest value of 126 pollen grains/cm^2 was observed at Earlwood. Values for $CPIn_{grav}$
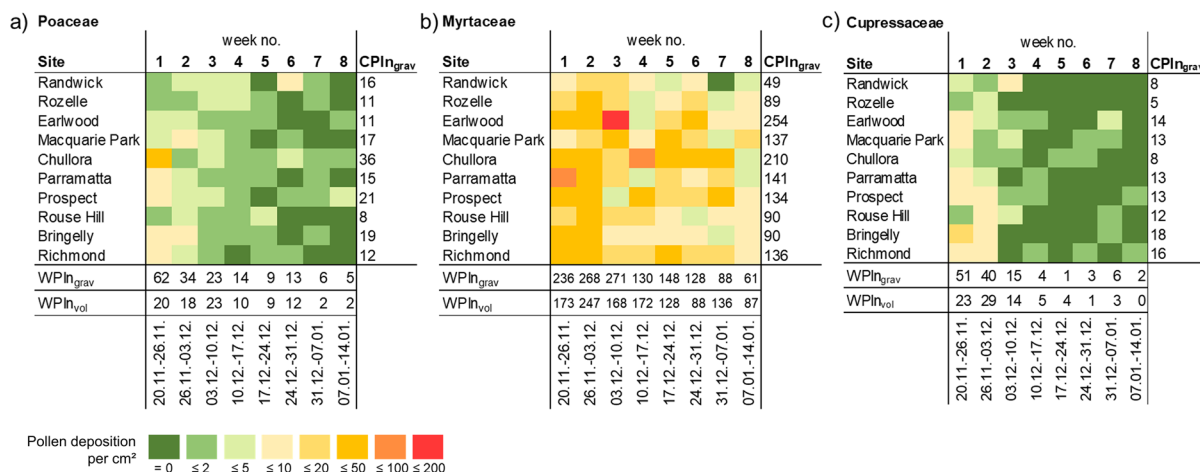
Fig. 5 Heat maps showing weekly **a** Poaceae, **b** Myrtaceae, and **c** Cupressaceae pollen deposition (pollen grains/cm^2) for the sampling campaign 20.11.2019 to 14.01.2020 and WPIn$_{vol}$ for the respective weeks. Gravimetric trap sites are ordered by distance from the sea

varied between 254 (Earlwood) and 49 (Randwick) (Fig. 5b).

Highest WPIn of Cupressaceae pollen and highest single value for pollen deposition were recorded in the first week of sampling. WPIn was 51 and the highest value for pollen deposition was recorded at Bringelly with 10 pollen grains/cm^2. CPIn$_{grav}$ values did not vary substantially (range 5 (Rozelle) to 18 (Bringelly)) (Fig. 5c). Kruskal–Wallis test revealed no significant differences in pollen deposition among sites (Poaceae: Kruskal–Wallis chi-squared = 6.810, p value = 0.657; Myrtaceae: Kruskal–Wallis chi-squared = 16.793, p value = 0.052; Cupressaceae: Kruskal–Wallis chi-squared = 3.648, p value = 0.933).

3.2.2 Land use

The land use surrounding the traps varied between the locations (Table 1 and Fig. 1). Areas classified as "built-up" were within 100 m of all but two of the locations (Rouse Hill, Bringelly). For Randwick, this was the only land cover class within 100 m of the trap. "Low vegetation and pastures" were surrounding eight traps.

We investigated the relationship of each CPIn and each land cover class and urban index. We only detected one correlation of significance ($p \leq 0.05$), which was the relationship between CPIn of Cupressaceae and the land use class "low vegetation and pastures" ($r_s = 0.663$, p value = 0.037).

3.2.3 Meteorology

Table 6 gives an overview of mean, minimum and maximum temperature and rainfall measured at the sampling locations. Mean temperature during sampling ranged between 21.2 °C (Randwick) and 22.6 °C (Rouse Hill). The lowest and highest temperature was both measured at Richmond (7.4 °C and 46.5 °C). During the sampling campaign, rainfall totals were 21.8 mm at Richmond, 18.6 mm at Rouse Hill and 20.8 mm at Rozelle. Most rain fell in the first and in the last two sampling weeks. The prevailing wind directions varied between locations (Table 6). Highest mean wind speed was registered at Randwick (3.0 m/s), which is the site closest to the sea.

4 Discussion

This study provides new data and insights into pollen in the ambient air of Sydney. Hereby, we add to previous studies, that published findings on pollen and spores from several years between 1993 and 2012 (i.e. Bass & Morgan, 1997; Beggs et al., 2015; Katelaris et al., 2004; Medek et al., 2016; Stennett & Beggs, 2004b). The novelty of our study was the assessment of spatial differences of airborne pollen in Sydney, which had not been done before to this extent. Until now, only Katelaris et al. (2000) and Katelaris et al. (2004) analysed spatial differences in airborne pollen

Table 6 Overview of daily meteorological data measured at the sampling locations for the period of the sampling campaign (20 January 2019 to 14 January 2020)

Location	Temperature [°C]			Rain [mm]	Main wind direction	Mean wind speed [m/s]
	Mean	Minimum	Maximum			
Randwick	21.2	12.2	38.8	*NA*	NE	3.0
Rozelle	21.6	12.4	40.3	20.8	S	2.3
Earlwood	22.1	10.5	44.5	*NA*	S	1.3
Macquarie Park	21.6	9.3	44.7	*NA*	E	1.5
Chullora	22.2	11.9	45.9	*NA*	NE	1.9
Paramatta	22.3	11.0	46.4	*NA*	SW	1.5
Prospect	22.5	12.0	45.9	*NA*	SW	2.0
Rouse Hill	22.6	11.6	45.7	18.6	SW	1.9
Bringelly	21.8	7.6	46.1	*NA*	E	1.7
Richmond	22.5	7.4	46.5	21.8	E	1.7

Precipitation data only available for three locations. See Table 1 for location characteristics

in Sydney using three volumetric pollen traps more than 20 years ago between 1997 and 1999.

We used a 7-day volumetric trap for volumetric aerobiological monitoring for three pollen seasons. Even though we had to deal with gaps in data, our data allowed us to examine the course and characteristics of pollen and spore seasons as well as the relationship with meteorological parameters. We found differences in the Annual Pollen Integral (APIn), Annual Spore Integral (ASIn) and number of high pollen/spore days as well as peak values of daily mean pollen and spore concentrations and the mean of the daily concentrations. While the volumetric Hirst trap (Hirst, 1952) is used as a standard for continuous volumetric pollen monitoring (Beggs et al., 2018; Galán et al., 2014) as it is suitable to provide data over a longer period, sampling campaigns using gravimetric traps provide other advantages. These include cost-effectiveness and therefore the opportunity to set up numerous traps for one study. Furthermore, these traps are easy to operate, not very prone to breaking because of the absence of moving parts, and they do not require power. While pollen counts recorded by volumetric traps can be converted to pollen concentrations, gravimetric sampling is based on the sedimentation of pollen and can therefore only be expressed as pollen deposition, which does not allow precise comparison to pollen concentration (Agashe & Caulton, 2009; Jetschni & Jochner-Oette, 2021). In this study, we used ten gravimetric pollen traps to gather data on spatial variations of pollen deposition for eight weeks from late spring 2019 to mid-summer 2020. These traps have proven to be useful for comparing pollen deposition at a smaller spatial scale.

We used the category "high pollen days" and "high spore days" to describe the medical relevance of pollen and spore concentrations above specific thresholds. Such thresholds should ideally be specific to the region or country of the study, as they can vary across regions and are influenced by environmental conditions (Galán et al., 2007; Şimşek et al., 2019; Weger et al., 2013). We used thresholds that have been published in other studies (Aira et al., 2013; Bannister et al., 2021; Galán et al., 2007), which are, however, only in the case of Poaceae specific to Australia (Morton et al., 2011; Ong Singh and Knox, 1995). Future studies should additionally examine pollen and spore thresholds that exert allergic reactions and symptoms related to other species. A useful tool for this might be crowd-sourced symptom data. Recently, citizen science gained in popularity and crowed-sourced symptom data were increasingly used for analysing the relationship between pollen concentrations, pollen seasons and symptom severity in Europe (Bastl et al., 2021; Karatzas et al., 2018) as well as in Australia (Jones et al., 2020, 2021).

4.1 Poaceae

In the season 2017/2018, we observed two peaks of grass pollen concentration. A similar pattern was documented by Beggs et al. (2015) and Medek et al. (2016). The authors observed the peak date for grass pollen at the end of October/start of November in three out of five observed years (2008–2009, 2012–2013). There was a second peak around March, which could be explained by different flowering times of different grass species (Frenguelli et al., 2010), or

multiple flowering events of the same species (Medek et al., 2016). Grass can only be determined at the family level using light microscopy (Jaeger, 2008; Driessen, Willemse and Luyn, 1989); thus, phenological observation of different grass species might improve the interpretation of aerobiological data.

The peak values in our study were recorded on 12 October 2017 and 6 November 2019. In 2018, the highest value was recorded on 29 November. Despite of data gaps, we observed a varying intensity of the grass pollen seasons (APIns vary between $846 + $ pollen*day/m^3 and $3,816 + $ pollen*day/m^3, Table 2). Large variations in grass pollen concentrations might be attributable to different factors such as land use change or meteorology. In the case of the grass pollen season 2019/2020, the lower intensity might be caused by the prevailing drought until January 2020. In the period from 1 June to 1 January, 151.6 mm of rain was recorded, which is less than in previous years (2017: 653.8 mm, 2018: 344.4 mm).

Precipitation and temperature strongly influence pollen release and season duration in the air (Dahl & Standhede, 1996; Jato et al., 2002; Bonofiglio et al., 2008; García-Mozo et al., 2010; Oduber et al., 2019;). The effect of drought on the characteristics of grass pollen seasons has been observed in several studies: Gehrig (2006) observed an earlier onset of grass flowering during a heatwave in 2003 in Switzerland. Here, grass pollen production and dispersion were increased by warm conditions, but eventually led to a decrease as soon as water was not sufficiently available. García-Mozo et al. (2010) reported a relationship between pollen production and rainfall before flowering, pointing to the influence of water availability during the development of grasses. Correlation analyses conducted in our study revealed positive correlations between grass pollen concentration and mean, maximum and minimum temperature in all years. In each case, the correlation with mean temperature was the strongest. The correlations with the daily precipitation sum were negative in all seasons but 2018/2019, they were, however, not significant.

Grass pollen deposition during the sampling campaign 2019/2020 was strongly influenced by the drought in the second half of 2019 (Nolan et al., 2020) preceding this campaign. We observed small values of pollen deposition, which can be attributed to the drought and temporal setting of the campaign, which started in the post-peak period of a comparably weak pollen season associated with a smaller number of days with medical relevance (> 50 pollen grains/m^3). Our data showed spatial variations between the ten locations, but no relationship with land use (low vegetation/pastures and woodlands/forests) and meteorology could be found. This suggests the influence of other factors such as long-range pollen transport or resuspension of pollen. Other studies showed correlations between pollen deposition/concentration and land cover and land use in the surroundings of the traps. In Germany, Jetschni and Jochner-Oette (2021) detected correlations between pollen deposition and agricultural area, grass cover and urban index. Werchan et al. (2017) also observed highest grass pollen sedimentation in traps closest to agricultural land. The lack of correlation in this study might be due to the comparably small amount of pollen in the air. However, it can be also concluded that people affected by grass pollen allergies can plan their outdoor activities regardless of the surrounding land use, as pollen loads remain comparably low at this point in the season.

4.2 Myrtaceae

Myrtaceae pollen were present in the air almost year round. The trees belonging to the Myrtaceae family (Eucalypt trees) are native in Australia and pollinate throughout the year (Bass & Morgan, 1997). The presence of their pollen in the air was documented by Bass and Morgan (1997), who reported annual totals between 3,048 and 3,257 between 1993 and 1995, with lowest daily concentrations between June and August. In this study, we reported APIns between $1,795 + $ pollen*day/m^3 and $3,826 + $ pollen*day/m^3. Similar to the other pollen types investigated in our study, we detected positive correlations between daily mean Myrtaceae pollen concentration and temperature (mean, minimum, maximum), which was also observed in a study in China (Bishan et al., 2020). Considering precipitation, we found negative correlations, pointing towards the negative effect of rain on airborne pollen amounts (Oduber et al., 2019).

In the sampling campaign, Myrtaceae pollen were the most abundant pollen type registered. We did not detect correlations between Myrtaceae pollen deposition and land use. Overall, our weekly data reflect the seasonal course shown in the background pollen data, with decreasing amounts over the sampling time.

However, a comparably high amount of pollen deposition (126 pollen grains/cm^2) was recorded in the third week at Earlwood. This indicates that even at a later time in the season, local conditions might lead to a temporary increase in pollen amount in the air or might point to long-distance transport of Eucalyptus pollen from other regions in Australia.

4.3 Cupressaceae

Cupressaceae pollen are, along with Poaceae, the most prevalent in urban areas in Australia (Haberle et al., 2014). There are multiple Cupressaceae genera and species (e.g. *Cupressus*, *Taxus*, *Juniperus*) and since the morphology of their pollen grains is very similar, they are only analysed at family level using light microscopy (Charpin et al., 2017). The predominant species of cypress pine in the studied region are *Cupressus sempervirens* and *Cupressus macrocarpa* with highest concentrations previously detected from August to November (Bass & Morgan, 1997). In this study, annual totals ranged between 1,307 and 11,788 pollen grains*day/m^3, which is generally higher than the APIns that we recorded. These differences could be explained by changes of land cover, which was observed for some species and regions worldwide (García-Mozo et al., 2016; Ziello et al., 2012), as well as by the use of Cupressaceae species as ornamental plants in cities (Ziello et al., 2012). We found positive correlations between daily mean Cupressaceae concentration and temperature in the seasons 2017/2018 and 2018/2019, as it has also been found in other studies (Rojo et al., 2015). In 2019/2020, there was a negative correlation with temperature, which could be explained by the fact that peak concentrations were already reached in August, a month associated with lower temperatures compared to November and December, where peak values were recorded in the previous seasons. Similar to Myrtaceae, there was a negative correlation of daily precipitation and daily mean Cupressaceae pollen concentration in two seasons.

In our sampling campaign, we detected spatial differences in Cupressaceae pollen deposition, but overall low values, which is also reflected by the low intensity during the time of the gravimetric sampling campaign. Spatial variability across three different locations in Sydney was analysed by Katelaris et al. (2004), where differences in Cupressaceae pollen concentration could be attributed to the vegetation species composition in the surroundings of the pollen traps. This was also documented by a study in Spain, where the abundance of cypress pines was reflected in the pollen spectrum (Rojo et al., 2015).

4.4 *Alternaria*

Alternaria is an important airborne allergen, regarded as the most prevalent (Burch & Levetin, 2002; Kasprzyk et al., 2021; Mitakakis et al., 2001a, 2001b), and is, like pollen, also influenced by climate change (D'Amato et al., 2020). These spores can be found on vegetation and the ground and cause high spore concentrations in the air, especially after crop harvesting (Mitakakis et al., 2001a, 2001b; Skjøth et al., 2012). *Alternaria* spores in the air of southwestern Sydney recorded in the years 1993 to 1995 were analysed by Bass and Morgan (1997). The authors found *Alternaria* to be present in the air year round, but with higher numbers in late spring and summer; annual totals ranged between 10,748 and 40,104 spores/m^3. These numbers are higher than the ASIns that we presented in this study, ranging between 4,718+ and 10,526+ spores/m^3. These differences might be due to missing data, but also changes in land cover, i.e. crop land, that could have influenced the amount of airborne *Alternaria* spores (Olsen et al., 2020. Comparably high *Alternaria* spore concentrations in 2019/2020 with high numbers from January until end of the sampling in early February might be due to the drought in previous months. Eucalypt trees in Australia tend to drop leaves in response to drought, increasing litter on the ground, which promotes the growth of *Alternaria* spores (Bass & Morgan, 1997). In addition to leave fall, the dieback of annual grasses favours *Alternaria* growth (Mitakakis et al., 1997).

The influence of meteorological variables such as temperature on spore concentration was observed in several studies. Rodríguez-Rajo et al. (2005) identified a strong positive relationship between spore concentration and temperature, which was also reported by a study in Sydney analysing *Alternaria* spore concentration of the years 1992 to 1995 (Stennett & Beggs, 2004a). Similarly, we found significant strong positive relationships of daily spore concentration and mean temperature of the same day.

Temperature seems to increase spore concentration and prolong the spore season; however, only until a certain point, as it was observed that *Alternaria* concentrations decline after extreme heat (Picornell et al., 2022). Based on our data, we could not observe such a decline in 2019/2020.

5 Conclusion

Monitoring airborne pollen and spores is important as it generates knowledge on the seasonality and intensity of aeroallergens and therefore on people's exposure. Based on our data, it seems that land use has a limited impact on the amount of pollen in the air when the season's intensity decreases. In case of grass pollen, we observed two peaks in some seasons, which points to the importance of phenological observations, that are needed to evaluate the different timing of pollen released from different grass species. Compared to countries in the Northern Hemisphere, there is a lack of continuous monitoring in Australia, and therefore, data series are incomplete. In regards to climate change, longer data series would be needed to estimate its impact in the future in detail. We propose the implementation of continuous volumetric aerobiological monitoring at least at one location in the Sydney Metropolitan area. The installation of more than one trap would provide additional data on spatial variations. To facilitate monitoring, the use of automatic pollen monitors could be tested. Further studies should establish pollen and spore thresholds, which are medically relevant for allergic people specifically in Sydney/Australia. Therefore, we encourage the additional implementation of symptom data, skin prick test or molecular methods.

Declarations

Appendix A

See Table 7

Table 7 Aggregated land cover classes (Geoscience Australia, 2017)

Class	Aggregated class
Extraction sites	Mines and quarries
Inland waterbodies	Water
Salt lakes	Water
Irrigated cropping	Low vegetation and pastures
Irrigated pasture	Low vegetation and pastures
Irrigated sugar	Low vegetation and pastures
Rainfed cropping	Low vegetation and pastures
Rainfed pasture	Low vegetation and pastures
Rainfed sugar	Low vegetation and pastures
Wetlands	Low vegetation and pastures
Tussock grasses—Closed	Low vegetation and pastures
Alpine grasses—Open	Low vegetation and pastures
Hummock grasses—Closed	Low vegetation and pastures
Tussock grasses—Open	Low vegetation and pastures
Shrubs and grasses—Sparse-scattered	Low vegetation and pastures
Hummock grasses—Open	Low vegetation and pastures
Shrubs—Closed	Low vegetation and pastures
Shrubs—Open	Low vegetation and pastures
Trees—Closed	Woodland and forests
Trees—Open	Woodland and forests
Trees—Scattered	Woodland and forests
Trees—Sparse	Woodland and forests
Built-up surface	Built-up area

References

Addison-Smith, B., Milic, A., Dwarakanath, D., Simunovic, M., van Haeften, S., Timbrell, V., et al. (2021). Medium-term increases in ambient grass pollen between 1994–1999 and 2016–2020 in a subtropical climate zone. *Frontiers in Allergy*. https://doi.org/10.3389/falgy.2021.705313

Agashe, S. N., & Caulton, E. (2009). *Pollen and spores: Applications with special emphasis on aerobiology and allergy*. Science Publishers.

Aira, M.-J., Rodríguez-Rajo, F.-J., Fernández-González, M., Seijo, C., Elvira-Rendueles, B., Abreu, I., et al. (2013). Spatial and temporal distribution of *Alternaria* spores in the Iberian Peninsula atmosphere, and meteorological relationships: 1993–2009. *International Journal of Biometeorology, 57*(2), 265–274. https://doi.org/10.1007/s00484-012-0550-x

Geoscience Australia (2017). Dynamic land cover dataset. V2.1 7 June 2017. Retrieved November 29, 2021, from https://www.ga.gov.au/scientific-topics/earth-obs/accessing-satellite-imagery/landcover

Australian Institute of Health and Welfare (2020). Allergic rhinitis ('hay fever'). Canberra. Retrieved April 16, 2022, from https://www.aihw.gov.au/reports/chronic-respiratory-conditions/allergic-rhinitis-hay-fever/contents/allergic-rhinitis

Australian Bureau of Meteorology (2021). Climate statistics for Australian locations. Summary statistics Sydney (Observatory Hill). Retrieved November 24, 2021, from http://www.bom.gov.au/climate/averages/tables/cw_066062.shtml

Australian Bureau of Statistics (2021). Regional populations. Statistics about the population and components of change (births, deaths, migration) for Australia's capital cities and regions. Retrieved May 5, 2022, from https://www.abs.gov.au/statistics/people/population/regional-population/latest-release

Bannister, T., Ebert, E. E., Williams, T., Douglas, P., Wain, A., Carroll, M., et al. (2021). A pilot forecasting system for epidemic thunderstorm asthma in southeastern Australia. *Bulletin of the American Meteorological Society, 102*(2), E399–E420. https://doi.org/10.1175/BAMS-D-19-0140.1

Bass, D., & Morgan, G. (1997). A three year (1993–1995) calendar of pollen and *Alternaria* mould in the atmosphere of south western Sydney. *Grana, 36*(5), 293–300. https://doi.org/10.1080/00173139709362620

Bastl, M., Bastl, K., Dirr, L., Berger, M., & Berger, U. (2021). Variability of grass pollen allergy symptoms throughout the season: Comparing symptom data profiles from the patient's Hayfever diary from 2014 to 2016 in Vienna (Austria). *The World Allergy Organization Journal, 14*(3), 100518. https://doi.org/10.1016/j.waojou.2021.100518

Beggs, P. J., Davies, J. M., Milic, A., Haberle, S. G., Johnston, F. H., Jones, P. J., et al. (2018). Australian airborne pollen and spore monitoring network interim standard and protocols: Version 2.

Beggs, P. J. (2015). Environmental allergens: From asthma to hay fever and beyond. *Current Climate Change Reports, 1*(3), 176–184. https://doi.org/10.1007/s40641-015-0018-2

Beggs, P. J. (2018). Climate change and allergy in Australia: An innovative, high-income country, at potential risk. *Public Health Research & Practice, 28*(4), e2841828. https://doi.org/10.17061/phrp2841828

Beggs, P. J., Katelaris, C. H., Medek, D., Johnston, F. H., Burton, P. K., Campbell, B., et al. (2015). Differences in grass pollen allergen exposure across Australia. *Australian and New Zealand Journal of Public Health, 39*(1), 51–55. https://doi.org/10.1111/1753-6405.12325

Bishan, C., Bing, L., Chixin, C., Junxia, S., Shulin, Z., Cailang, L., et al. (2020). Relationship between airborne pollen assemblages and major meteorological parameters in Zhanjiang. *South China PLOS ONE, 15*(10), e0240160. https://doi.org/10.1371/journal.pone.0240160

Bonofiglio, T., Orlandi, F., Sgromo, C., Romano, B., & Fornaciari, M. (2008). Influence of temperature and rainfall on timing of olive (*Olea europaea*) flowering in southern Italy. *New Zealand Journal of Crop and Horticultural Science, 36*(1), 59–69. https://doi.org/10.1080/01140670809510221

Burch, M., & Levetin, E. (2002). Effects of meteorological conditions on spore plumes. *International Journal of Biometeorology, 46*(3), 107–117. https://doi.org/10.1007/s00484-002-0127-1

Buters, J. T. M., Antunes, C., Galveias, A., Bergmann, K.-C., Thibaudon, M., Galán, C., et al. (2018). Pollen and spore monitoring in the world. *Clinical and Translational Allergy, 8*, 9. https://doi.org/10.1186/s13601-018-0197-8

Cariñanos, P., Grilo, F., Pinho, P., Casares-Porcel, M., Branquinho, C., Acil, N., et al. (2019). Estimation of the allergenic potential of urban trees and urban parks: Towards the healthy design of urban green spaces of the future. *International Journal of Environmental Research and Public Health, 16*(8), 1357. https://doi.org/10.3390/ijerph16081357

Cariñanos, P., Sánchez-Mesa, J. A., Prieto-Baena, J. C., Lopez, A., Guerra, F., Moreno, C., et al. (2002). Pollen allergy related to the area of residence in the city of Córdoba, south-west Spain. *Journal of Environmental Monitoring*. https://doi.org/10.1039/b205595c

Carslaw, D. C., & Ropkins, K. (2012). Openair—An R package for air quality data analysis. *Environmental Modelling & Software, 27–28*, 52–61. https://doi.org/10.1016/j.envsoft.2011.09.008

Cecchi, L., D'Amato, G., Ayres, J. G., Galán, C., Forastiere, F., Forsberg, B., et al. (2010). Projections of the effects of climate change on allergic asthma: The contribution of aerobiology. *Allergy, 65*(9), 1073–1081. https://doi.org/10.1111/j.1398-9995.2010.02423.x

Charalampopoulos, A., Lazarina, M., Tsiripidis, I., & Vokou, D. (2018). Quantifying the relationship between airborne pollen and vegetation in the urban environment. *Aerobiologia, 34*(3), 285–300. https://doi.org/10.1007/s10453-018-9513-y

Charpin, D., Pichot, C., Belmonte, J., Sutra, J.-P., Zidkova, J., Chanez, P., et al. (2017). Cypress pollinosis: From tree to clinic. *Clinical Reviews in Allergy & Immunology, 56*(2), 174–195. https://doi.org/10.1007/s12016-017-8602-yDahl

D'Amato, G., Chong-Neto, H. J., Monge Ortega, O. P., Vitale, C., Ansotegui, I., Rosario, N., et al. (2020). The effects of climate change on respiratory allergy and asthma induced by pollen and mold allergens. *Allergy, 75*(9), 2219–2228. https://doi.org/10.1111/all.14476

Dahl, Å., & Strandhede, S.-O. (1996). Predicting the intensity of the birch pollen season. *Aerobiologia, 12*(1), 97–106. https://doi.org/10.1007/BF02248133

Davies, J. M., Berman, D., Beggs, P. J., Ramón, G. D., Peter, J., Katelaris, C. H., et al. (2021). Global climate change and pollen aeroallergens: A Southern Hemisphere perspective. *Immunology and Allergy Clinics of North America, 41*(1), 1–16. https://doi.org/10.1016/j.iac.2020.09.002

Davies, J. M., Li, H., Green, M., Towers, M., & Upham, J. W. (2012). Subtropical grass pollen allergens are important for allergic respiratory diseases in subtropical regions. *Clinical and Translational Allergy, 2*(1), 4. https://doi.org/10.1186/2045-7022-2-4

Davies, J. M., Smith, B. A., Milic, A., Campbell, B., Van Haeften, S., Burton, P., et al. (2022). The AusPollen partnership project: Allergenic airborne grass pollen seasonality and magnitude across temperate and subtropical eastern Australia, 2016–2020. *Environmental Research, 214*, 113762. https://doi.org/10.1016/j.envres.2022.113762

de Morton, J., Bye, J., Pezza, A., & Newbigin, E. (2011). On the causes of variability in amounts of airborne grass pollen in Melbourne Australia. *International Journal of Biometeorology, 55*(4), 613–622. https://doi.org/10.1007/s00484-010-0361-x

de Weger, L. A., Bergmann, K. C., Rantio-Lehtimäki, A., Dahl, Å., Buters, J., Déchamp, C., et al. (2013). Impact of pollen. In M. Sofiev & K.-C. Bergmann (Eds.), *Allergenic Pollen* (pp. 161–215). Springer, Netherlands.

Driessen, M. N. B. M., Willemse, M. T. M., & van Luijn, J. A. G. (1989). Grass pollen grain determination by light and UV microscopy. *Grana, 28*(2), 115–122. https://doi.org/10.1007/BF02248133

Durham, O. C. (1946). The volumetric incidence of atmospheric allergens: IV. A proposed standard method of gravity sampling, counting, and volumetric interpolation of results. *Journal of Allergy, 17*(2), 79–86. https://doi.org/10.1016/0021-8707(46)90025-1

Frenguelli, G., Passalacqua, G., Bonini, S., Fiocchi, A., Incorvaia, C., Marcucci, F., et al. (2010). Bridging allergologic and botanical knowledge in seasonal allergy: A role for phenology. *Annals of Allergy, Asthma & Immunology, 105*(3), 223–227. https://doi.org/10.1016/j.anai.2010.06.016

Galán, C., Cariñanos, P., Alcázar, P., & Domínguez-Vilches, E. (2007). Spanish aerobiology network (REA): Management and quality manual. Accessed 21 November 2020.

Galán, C., Ariatti, A., Bonini, M., Clot, B., Crouzy, B., Dahl, A., et al. (2017). Recommended terminology for aerobiological studies. *Aerobiologia, 33*(3), 293–295. https://doi.org/10.1007/s10453-017-9496-0

Galán, C., Smith, M., Thibaudon, M., Frenguelli, G., Oteros, J., Gehrig, R., et al. (2014). Pollen monitoring: Minimum requirements and reproducibility of analysis. *Aerobiologia, 30*(4), 385–395. https://doi.org/10.1007/s10453-014-9335-5

García-Mozo, H., Galán, C., Alcázar, P., de La Guardia, D., Nieto-Lugilde, D., Recio, M., et al. (2019). Trends in grass pollen season in southern Spain. *Aerobiologia, 26*, 157–169. https://doi.org/10.1007/s10453-009-9153-3

García-Mozo, H., Oteros, J. A., & Galán, C. (2016). Impact of land cover changes and climate on the main airborne pollen types in Southern Spain. *Science of the Total Environment, 58–549*, 221–228. https://doi.org/10.1016/j.scitotenv.2016.01.005

Gassmann, M. I., & Gardiol, J. M. (2007). Weather conditions associated with the potential for pollen recirculation in a coastal area. *Meteorological Applications, 14*(1), 39–48. https://doi.org/10.1002/met.4

Gassmann, M. I., Pérez, C. F., & Gardiol, J. M. (2002). Sealand breeze in a coastal city and its effect on pollen transport. *International Journal of Biometeorology*. https://doi.org/10.1007/s00484-002-0135-1

Gehrig, R. (2006). The influence of the hot and dry summer 2003 on the pollen season in Switzerland. *Aerobiologia, 22*(1), 27–34. https://doi.org/10.1007/s10453-005-9013-8

Haberle, S. G., Bowman, D. M. J. S., Newnham, R. M., Johnston, F. H., Beggs, P. J., Buters, J. T. M., et al. (2014). The

macroecology of airborne pollen in Australian and New Zealand urban areas. *PLOS ONE, 9*(5), e97925. https://doi.org/10.1371/journal.pone.0097925

Hirst, J. M. (1952). An automatic volumetric spore trap. *Annals of Applied Biology, 39*(2), 257–265. https://doi.org/10.1111/j.1744-7348.1952.tb00904.x

International Biological Program (1970). *Aerobiology Newsletter* (01).

Jaeger, S. (2008). Exposure to grass pollen in Europe. *Clinical & Experimental Allergy Reviews, 8*(1), 2–6. https://doi.org/10.1111/j.1472-9733.2008.00125.x

Jato, V., Dopazo, A., & Aira, M. J. (2002). Influence of precipitation and temperature on airborne pollen concentration in Santiago de Compostela (Spain). *Grana, 41*(4), 232–241. https://doi.org/10.1080/001731302321012022

Jetschni, J., & Jochner-Oette, S. (2021). Spatial and temporal variations of airborne Poaceae pollen along an urbanization gradient assessed by different types of pollen traps. *Atmosphere, 12*(8), 974. https://doi.org/10.3390/atmos12080974

Jochner, S., Sparks, T. H., Estrella, N., & Menzel, A. (2012). The influence of altitude and urbanisation on trends and mean dates in phenology (1980–2009). *International Journal of Biometeorology, 56*(2), 387–394. https://doi.org/10.1007/s00484-011-0444-3

Jones, P. J., Koolhof, I. S., Wheeler, A. J., Williamson, G. J., Lucani, C., Campbell, S. L., et al. (2020). Can smartphone data identify the local environmental drivers of respiratory disease? *Environmental Research, 182*, 109118. https://doi.org/10.1016/j.envres.2020.109118

Jones, P. J., Koolhof, I. S., Wheeler, A. J., Williamson, G. J., Lucani, C., Campbell, S. L., et al. (2021). Characterising non-linear associations between airborne pollen counts and respiratory symptoms from the AirRater smartphone app in Tasmania, Australia: A case time series approach. *Environmental Research, 200*, 111484. https://doi.org/10.1016/j.envres.2021.111484

Karatzas, K., Papamanolis, L., Katsifarakis, N., Riga, M., Werchan, B., Werchan, M., et al. (2018). Google trends reflect allergic rhinitis symptoms related to birch and grass pollen seasons. *Aerobiologia, 30*(3), 269. https://doi.org/10.1007/s10453-018-9536-4

Kasprzyk, I., Grinn-Gofroń, A., Ćwik, A., Kluska, K., Cariñanos, P., & Wójcik, T. (2021). Allergenic fungal spores in the air of urban parks. *Aerobiologia, 37*(1), 39–51. https://doi.org/10.1007/s10453-020-09671-7

Katelaris, C. H., & Beggs, P. J. (2018). Climate change: Allergens and allergic diseases. *Internal Medicine Journal, 48*(2), 129–134. https://doi.org/10.1111/imj.13699

Katelaris, C. H., Burke, T. V., & Byth, K. (2004). Spatial variability in the pollen count in Sydney, Australia: Can one sampling site accurately reflect the pollen count for a region? *Annals of Allergy, Asthma and Immunology, 93*(2), 131–136. https://doi.org/10.1016/S1081-1206(10)61464-0

Katelaris, C. H., Carrozzi, F. M., Burke, T. V., & Byth, K. (2000). A springtime olympics demands special consideration for allergic athletes. *The Journal of Allergy and Clinical Immunology, 106*(2), 260–266. https://doi.org/10.1067/mai.2000.108603

Katz, D. S. W., & Batterman, S. A. (2020). Urban-scale variation in pollen concentrations: A single station is insufficient to characterize daily exposure. *Aerobiologia, 36*(3), 417–431. https://doi.org/10.1007/s10453-020-09641-z

Katz, D. S. W., & Carey, T. S. (2014). Heterogeneity in ragweed pollen exposure is determined by plant composition at small spatial scales. *Science of the Total Environment, 485–486*, 435–440. https://doi.org/10.1016/j.scitotenv.2014.03.099

Katz, D. S. W., Dzul, A., Kendel, A., & Batterman, S. A. (2019). Effect of intra-urban temperature variation on tree flowering phenology, airborne pollen, and measurement error in epidemiological studies of allergenic pollen. *Science of the Total Environment, 653*, 1213–1222. https://doi.org/10.1016/j.scitotenv.2018.11.020

Medek, D. E., Beggs, P. J., Erbas, B., Jaggard, A. K., Campbell, B. C., Vicendese, D., et al. (2016). Regional and seasonal variation in airborne grass pollen levels between cities of Australia and New Zealand. *Aerobiologia, 32*(2), 289–302. https://doi.org/10.1007/s10453-015-9399-x

Menzel, A., & Jochner, S. (2016). Impacts of climate change on aeroallergen production and atmospheric concentration. In P. J. Beggs (Ed.), *Impacts of climate change on allergens and allergic diseases* (pp. 10–28). Cambridge University Press.

Mitakakis, T. Z., Barnes, C., & Tovey, E. R. (2001a). Spore germination increases allergen release from *Alternaria*. *Journal of Allergy and Clinical Immunology, 107*(2), 388–390. https://doi.org/10.1067/mai.2001.112602

Mitakakis, T. Z., Clift, A., & McGee, P. A. (2001b). The effect of local cropping activities and weather on the airborne concentration of allergenic *Alternaria* spores in rural Australia. *Grana, 4–5*, 230–239. https://doi.org/10.1080/001731301317223268

Mitakakis, T., Ong, E. K., Stevens, A., Guest, D., & Knox, R. B. (1997). Incidence of Cladosporium, *Alternaria* and total fungal spores in the atmosphere of Melbourne (Australia) over three years. *Aerobiologia, 13*(2), 83–90. https://doi.org/10.1007/BF02694423

Nolan, R. H., Boer, M. M., Collins, L., Resco de Dios, V., Clarke, H., Jenkins, M., et al. (2020). Causes and consequences of eastern Australia's 2019–20 season of megafires. *Global Change Biology, 26*(3), 1039–1041. https://doi.org/10.1111/gcb.14987

NSW department of planning and environment (2021). Air quality monitoring in Sydney. NSW department of planning and environment. Retrieved May 20, 2022, from https://www.environment.nsw.gov.au/topics/air/monitoring-air-quality/sydney.

Oduber, F., Calvo, A. I., Blanco-Alegre, C., Castro, A., Vega-Maray, A. M., Valencia-Barrera, R. M., et al. (2019). Links between recent trends in airborne pollen concentration, meteorological parameters and air pollutants. *Agricultural and Forest Meteorology, 264*, 16–26. https://doi.org/10.1016/j.agrformet.2018.09.023

OECD, European Union. (2020). *Cities in the world: A new perspective on urbanisation (OECD urban studies)*. OECD Publishing.

Olsen, Y., Skjøth, C. A., Hertel, O., Rasmussen, K., Sigsgaard, T., & Gosewinkel, U. (2020). Airborne *Cladosporium*

and *Alternaria* spore concentrations through 26 years in Copenhagen. *Denmark Aerobiologia, 36*(2), 141–157. https://doi.org/10.1007/s10453-019-09618-7

Ong, E. K., Singh, M. B., & Knox, R. B. (1995). Grass pollen in the atmosphere of Melbourne: Seasonal distribution over nine years. *Grana, 34*(1), 58–63. https://doi.org/10.1080/00173139509429034

Paton-Walsh, C., Rayner, P., Simmons, J., Fiddes, S. L., Schofield, R., Bridgman, H., et al. (2019). A clean air plan for Sydney: An overview of the special issue on air quality in New South Wales. *Atmosphere, 10*(12), 774. https://doi.org/10.3390/atmos10120774

Pawankar, R., Canonica, G. W., Holgate, S. T., Lockey, R. F., & Blaiss, M. S. (2013). World allergy organization (WAO) White book on allergy: Update 2013. Resource document. World allergy organization. Retrieved September 9, 2020, from https://www.worldallergy.org/UserFiles/file/WhiteBook2-2013-v8.pdf

Peel, R. G., Kennedy, R., Smith, M., & Hertel, O. (2014). Do urban canyons influence street level grass pollen concentrations? *International Journal of Biometeorology, 58*(6), 1317–1325. https://doi.org/10.1007/s00484-013-0728-x

Picornell, A., Oteros, J., Ruiz-Mata, R., Recio, M., Trigo, M. M., Martínez-Bracero, M., et al. (2021). Methods for interpolating missing data in aerobiological databases. *Environmental Research, 200*, 111391. https://doi.org/10.1016/j.envres.2021.111391

Picornell, A., Rojo, J., Trigo, M. M., Ruiz-Mata, R., Lara, B., Romero-Morte, J., et al. (2022). Environmental drivers of the seasonal exposure to airborne *Alternaria* spores in Spain. *Science of the Total Environment, 823*, 153596. https://doi.org/10.1016/j.scitotenv.2022.153596

Puc, M. (2012). Artificial neural network model of the relationship between *Betula* pollen and meteorological factors in Szczecin (Poland). *International Journal of Biometeorology, 56*(2), 395–401. https://doi.org/10.1007/s00484-011-0446-1

Rodríguez-Rajo, F. J., Fdez-Sevilla, D., Stach, A., & Jato, V. (2010). Assessment between pollen seasons in areas with different urbanization level related to local vegetation sources and differences in allergen exposure. *Aerobiologia, 109*(Pt 4), 497–507. https://doi.org/10.1007/s10453-009-9138-2

Rodríguez-Rajo, F. J., Iglesias, I., & Jato, V. (2005). Variation assessment of airborne *Alternaria* and Cladosporium spores at different bioclimatical conditions. *Mycological Research*. https://doi.org/10.1017/S0953756204001777

Rojo, J., Picornell, A., & Oteros, J. (2018). AeRobiology: A computational tool for aerobiological data in the air. *Methods Ecol Evol, 10*(8), 1371–1376.

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. *Science of the Total Environment, 538*, 672–682. https://doi.org/10.1016/j.scitotenv.2015.08.074

Simmons, J., Paton-Walsh, C., Phillips, F., Naylor, T., Guérette, É. -A., Burden, S., et al. (2019). Understanding spatial variability of air quality in Sydney: Part 1—A suburban balcony case study. *Atmosphere, 10*(4), 181. https://doi.org/10.3390/atmos10040181

Şimşek, F., Mengi, E., & Topuz, B. (2019). Juniper-pollen monosensitivity; correlation between airborne pollen concentrations and clinical symptoms in Denizli, Turkey. *European Journal of Rhinology and Allergy, 1*(3), 63–66. https://doi.org/10.5152/ejra.2019.57

Skjøth, C. A., Sommer, J., Frederiksen, L., & Gosewinkel Karlson, U. (2012). Crop harvest in Denmark and central Europe contributes to the local load of airborne *Alternaria* spore concentrations in Copenhagen. *Atmospheric Chemistry and Physics, 12*(22), 11107–11123. https://doi.org/10.5194/acp-12-11107-2012

Stas, M., Aerts, R., Hendrickx, M., Bruffaerts, N., Dendoncker, N., Hoebeke, L., et al. (2021). Association between local airborne tree pollen composition and surrounding land cover across different spatial scales in Northern Belgium. *Urban Forestry & Urban Greening, 61*, 127082. https://doi.org/10.1016/j.ufug.2021.127082

Stennett, P. J., & Beggs, P. J. (2004a). *Alternaria* spores in the atmosphere of Sydney, Australia, and relationships with meteorological factors. *International Journal of Biometeorology, 49*(2), 98–105. https://doi.org/10.1007/s00484-004-0217-3

Stennett, P. J., & Beggs, P. J. (2004b). Pollen in the atmosphere of Sydney, Australia, and relationships with meteorological parameters. *Grana, 43*(4), 209–216. https://doi.org/10.1080/00173130410000758

Tassan-Mazzocco, F., Felluga, A., & Verardo, P. (2015). Prediction of wind-carried Gramineae and Urticaceae pollen occurrence in the Friuli Venezia Giulia region (Italy). *Aerobiologia, 31*(4), 559–574. https://doi.org/10.1007/s10453-015-9386-2

Vara, A., Fernández-González, M., Aira, M. J., & Rodríguez-Rajo, F. J. (2016). *Fraxinus* pollen and allergen concentrations in Ourense (south-western Europe). *Environmental Research, 147*, 241–248. https://doi.org/10.1016/j.envres.2016.02.014

Wadlow, I., Paton-Walsh, C., Forehead, H., Perez, P., Amirghasemi, M., Guérette, É. -A., et al. (2019). Understanding spatial variability of air quality in Sydney: Part 2—A roadside case study. *Atmosphere, 10*(4), 216. https://doi.org/10.3390/atmos10040217

Werchan, B., Werchan, M., Mücke, H.-G., Gauger, U., Simoleit, A., Zuberbier, T., et al. (2017). Spatial distribution of allergenic pollen through a large metropolitan area. *Environmental Monitoring and Assessment, 189*(4), 169. https://doi.org/10.1007/s10661-017-5876-8

Wickham, H. (2016). *ggplot2: Elegant graphics for data analysis (Use R!)*. Springer.

Ziello, C., Sparks, T. H., Estrella, N., Belmonte, J., Bergmann, K. C., Bucher, E., et al. (2012). Changes to airborne pollen counts across Europe. *PLoS ONE, 7*(4), e34076. https://doi.org/10.1371/journal.pone.0034076

Ziska, L. H., Makra, L., Harry, S. K., Bruffaerts, N., Hendrickx, M., Coates, F., et al. (2019). Temperature-related changes in airborne allergenic pollen abundance and seasonality across the northern hemisphere: a retrospective data analysis. *The Lancet Planetary Health, 3*(3), e124–e131. https://doi.org/10.1016/S2542-5196(19)30015-4