Aerobiologia (2016) 32:619–634
DOI 10.1007/s10453-016-9436-4

ORIGINALPAPER

Comparisons of fungal spore distributions using air sampling at Worcester, England (2006–2010)

Magdalena Sadyś · Beverley Adams-Groom · Robert J. Herbert · Roy Kennedy

Received: 8 September 2015 / Accepted: 14 March 2016 / Published online: 30 March 2016

Abstract This study determined annual and monthly fluctuations in concentration of 20 fungal genera. The selection of taxa was made based upon their high frequency in the air as well as their well-known allergenic properties. Air samples were collected using a spore trap of Hirst design at an urban site where the trap continuously worked throughout a 5-year survey. Weather data were acquired from a meteorological station co-located with the air sampler. Influence of several meteorological parameters was then examined to reveal species–environment interactions and the potential location of fungal spore sources within the urban area. The maximum monthly sum of mean daily spore concentration varied between genera, and the earliest peaks were recorded for *Pleospora* sp. in April and *Ustilago* sp. in June. However, the majority of investigated spore types occurred in the greatest concentrations between August and September. Out of the 20 studied taxa, the most dominant genus was *Cladosporium* sp., which exceeded an allergenic threshold of 3000 s m^{-3} 40 times during very rainy years and twice as much during dry years. A Spearman's rank test showed that statistically significant ($p \leq 0.05$) relationships between spore concentration and weather parameters were mainly $r_s \leq 0.50$. Potential sources of spores at Worcester were likely to be localised outside the city area.

Keywords Aerobiology · Aeromycology · Meteorological parameters · Allergy · Bioaerosol · Urban area

1 Introduction

Since the first reported case of asthma attack caused by fungal spores in 1726 (Floyer 1745), more than 112 fungi are now recognised as allergens (Levetin et al. 2015; Twaroch et al. 2015). This list includes taxa such as *Alternaria* sp., *Aspergillus* sp., *Penicillium* sp., *Cladosporium* sp., *Botrytis* sp., *Drechslera* sp., *Epicoccum* sp., *Leptosphaeria* sp., *Pithomyces* sp., *Pleospora* sp. and *Stemphylium* sp. (Green et al. 2005; Kurup et al. 2000). A Pan-European survey, carried out by the Global Allergy and Asthma European Network (GA2LEN), determined that sensitisation rates towards *Alternaria alternata* (17.6 %) and *Cladosporium herbarum* (6.8 %) were the highest in the UK and Ireland compared to other northern and

Electronic supplementary material The online version of this article (doi:10.1007/s10453-016-9436-4) contains supplementary material, which is available to authorized users.

M. Sadyś · B. Adams-Groom · R. J. Herbert · R. Kennedy
Institute of Science and the Environment, University of Worcester, Henwick Grove, Worcester WR2 6AJ, UK

M. Sadyś (✉)
Rothamsted Research, West Common, Harpenden AL5 2JQ, UK
e-mail: magdalena.sadys@rothamsted.ac.uk

southern European countries (Heinzerling et al. 2005). In the UK, it is considered that exacerbation of allergic reactions may occur when concentrations of *Alternaria* sp. and *Cladosporium* sp. spores exceed 50 and 3000 spores per cubic metre of air, respectively (Frankland and Davies 1965). However, medical thresholds for exposure have yet to be established for the other fungal genera that are known to be allergenic (Green et al. 2005). A study by Denning et al. (2006) reported that asthma killed 1500 patients annually in the UK. Although the overall contribution of fungal sensitisation towards the death rate has not yet been established, it has been observed that mortality in young adults in the UK coincided with increased levels of fungal spores in the air between July and September (Khot and Burn 1984). Typical allergic responses include sneezing, running nose, wheezing, tightness of chest, coughing, shortness of breath, urticaria, angioedema, anaphylaxis, pruritus and nasal obstructions (Kurup et al. 2000, 2002; Simon-Nobbe et al. 2008). Such allergic symptoms cause a considerable negative impact on the quality of human health (Bousquet et al. 2001).

A pilot study (unpublished) with regard to fungal and pteridophyte spore levels was previously carried out at Worcester in 2005, where a non-standard spore counting method was initially used. The method enumerated fungal spores within a graticule (0.50 × 0.50 mm) from every third field of view at ×400 magnification, which resulted in the overall analysis of 0.81 % of the total microscope slide area. The correction factor (CF), calculated for specific microscope that was used, was equal to 31. This means that a single spore was multiplied by this CF in order to get a spore concentration per cubic metre of air. Often, it happened that a single spore, for example of *Stemphylium* sp. or *Chaetomium* sp., was found on the entire slide. Thus, the concentrations for these genera were greatly overestimated. In case of *Stemphylium* sp. such error was completely unacceptable, since the fungicide application for the brown spot, common diseases of pear, must be carried out when concentration of *Stemphylium vesicarium* conidia in the air exceeds 30 s m^{-3} (Rossi et al. 2005). Frenguelli (2003) suggested that the examined area of the microscope slide should not be smaller than 10–12 %, in relation to the studies on pollen grains. However, no previous study has reported a representative percentage of the examined area for air samples collected using the Hirst type traps in relation to fungal spores. Moreover, fungal spores were enumerated by several different operators that could possibly result in additional sources of error and inconsistency at the spore identification level. Hence, there was a necessity for an extension of data and application of a standard spore counting methods that would enable greater accuracy and comparability with other reports on fungal spore levels (Nilsson and Persson 1981; Stępalska and Wołek 2009).

Recently published studies for the Worcester area have been limited in their extent either because the analysed period of time was very short (O'Connor et al. 2014; Sadyś et al. 2015a), or it focused on a single spore type (Sadyś et al. 2014; 2015a, b) or very few fungal taxa (Sadyś et al. 2015c). Studies describing airborne concentrations of allergenic spores for other areas of the UK are also limited in their extent with the majority published between the 1950s and 1980s and nothing since 2001 (Corden and Millington 2001; Frankland and Davies 1965; Hirst 1952; Hyde and Williams 1959; Jenkins et al. 1980; Lacey 1981; Morrow Brown and Jackson 1978). A "bridge" type study that would link all previously published reports was desirable as, until now, a more detailed overview for a wider range of fungal taxa performed for a longer period of time was missing. Therefore, this study aimed to present results of a 5-year survey, where 20 clinically important fungal taxa were studied followed by comprehensive analysis of their dependence on changing weather conditions.

2 Materials and methods

2.1 Site location

The city of Worcester is located in Worcestershire, in the West Midlands, England (O'Connor et al. 2014). The city population was estimated to be 98,800 people with population density at 2969 people per km^2 (Rice 2011). The composition of green urban areas includes public parks, allotments, racecourse, cricket field, cemetery and grasslands. An important element in the landscape of the city is the River Severn that divides the city. Overall, the green urban areas occupy 1.08 %, while non-irrigated areas 11.84 % and pastures 11.12 % of the city area (Fig. 1).

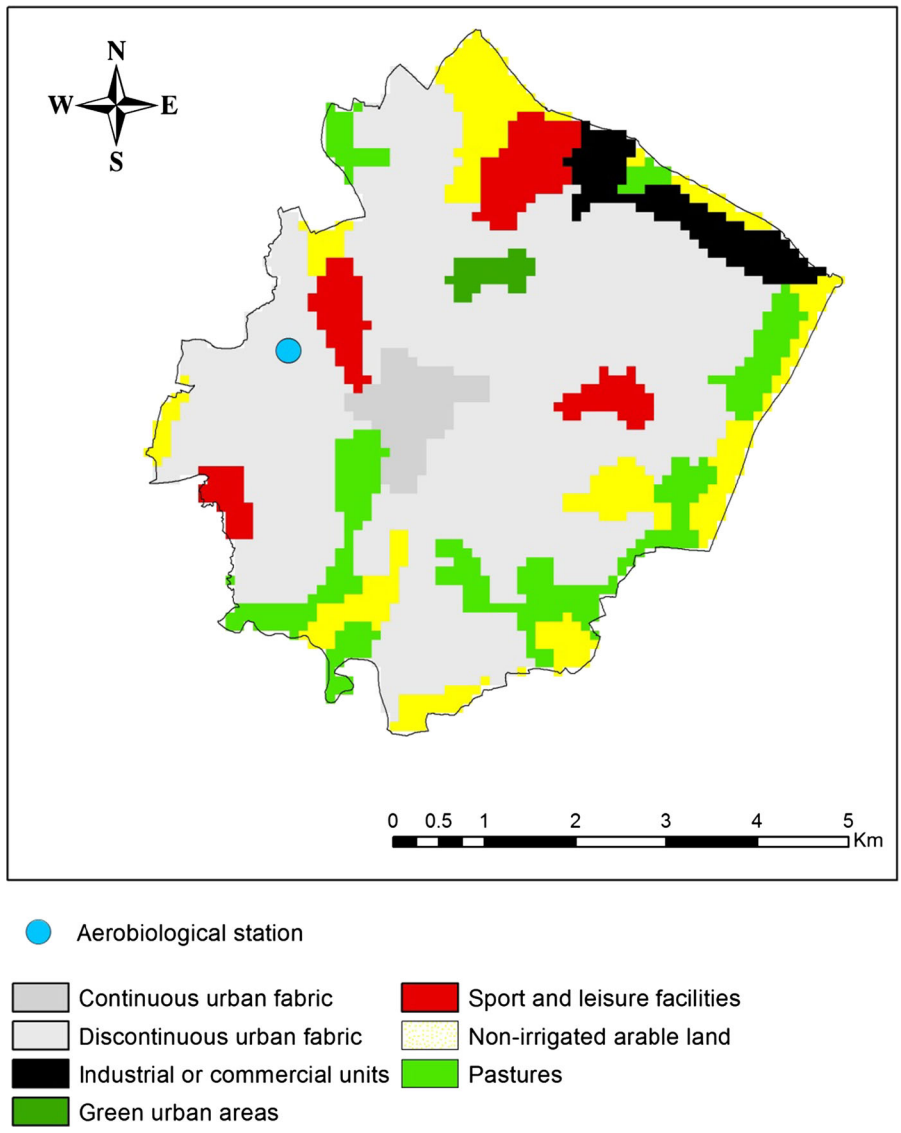


Fig. 1 Spatial plan of the city of Worcester, England, showing the location of the sampling site (Corine Land Cover 2006)

2.2 Air sample collection

The sampling of airborne fungal spores was conducted continuously from 1 Jan 2006 to 31 Dec 2010. The 7-day volumetric spore trap (Burkard Manufacturing Co. Ltd., Rickmansworth, Hertfordshire, UK) was situated on the roof of the University of Worcester (52° 11′ N, 2° 14′ W) approximately 10 m above ground level. The air sampler worked by impacting particles present in the air, directly on to collection tape, which was tightly fastened to the drum inside the sampler and covered by an adhesive medium (Hirst 1952). The pump located in the lower part of the sampler produced an air pressure with a suction power equal to 10 l of air per minute. Drum rotated with a speed of 2 mm h^{-1} due to a built-in clock mechanism and was changed weekly, on the same day at 09:00 UTC. Tape was then removed from the drum in the laboratory and cut into seven 48-mm long segments that corresponded to each of the 7 days of sampling. Each sample was mounted with glycerogelatin mountant and lactophenol Cotton Blue stain and sealed using nail varnish to prevent drying of the samples.

2.3 Spore identification and taxa selection

Fungal spores were identified at the genus level with the aid of the light microscope (Nikon Eclipse E400) and counted along one central longitudinal sweep under ×400 magnification (Nilsson and Persson 1981; Stępalska and Wołek 2009). This counting method is very popular among previously published spore work, and thus, it was chosen in order to make current study comparable with others (e.g. Skjøth et al. 2015). Then spore counts were multiplied by a correction factor resulting in an estimation of number of spores per cubic metre of air (s m^{-3}) after Lacey and West (2006). The concentration of 20 types of fungal spores were selected upon (1) their allergenic properties and (2) abundance in the air based upon the results of a pilot study conducted in 2005 and comprised: *Alternaria* sp., *Aspergillus* sp./*Penicillium* sp., *Blumeria* sp. (previously *Erysiphe* sp.), *Botrytis* sp., *Cladosporium* sp., coloured basidiospores, *Didymella* sp., *Drechslera* sp., *Entomophthora* sp., *Epicoccum* sp., *Ganoderma* sp., *Leptosphaeria* sp., *Periconia* sp., *Pithomyces* sp., *Pleospora* sp., *Polythrincium* sp., rusts, smuts, *Stemphylium* sp., *Torula* sp. Some fungal spores were counted jointly because visual distinction was not possible between genera, *i.e.*: *Aspergillus* sp. and *Penicillium* sp., or they were classified as a "group", *i.e.*: coloured basidiospores, rusts and smuts. This is established practice by many aerobiologists (e.g. Lacey and West 2006). Occasionally, when classification became problematic, several different fungal spore atlases were used to determine affinity to a certain genus or group (Ellis 1971; Grant Smith 1990; Lacey and West 2006; Ogden et al. 1974) under ×1000 magnification. The names of investigated fungal genera (groups) were abbreviated to their names only in the text. The data analysis and control was performed under the ISO/IEC 17025. Discussion on the limitations of aerobiological surveys and possible errors encountered at various stages of data sampling and analysis can be found in Comtois (1998), Galán et al. (2014), Oteros et al. (2013), Sterling et al. (1999), Stępalska and Wołek (2009).

2.4 Weather data

The weather data were collected using the WeatherLink (9.0) Vantage Pro2 station (Davis, Davis Instruments, Hayward, California, United States), which was co-located with the spore trap. The influence of the following parameters was studied: maximum temperature, minimum temperature, mean temperature, dew point temperature, wind direction, relative humidity, rain, air pressure, leaf wetness and leaf temperature. As the wind was initially recorded in 16 cardinal directions, it had to be re-calculated to the degree format to enable statistical examination (Sadyś et al. 2015c). Due to changes applied in the operation of the weather station, leaf wetness and leaf temperature were not recorded in 2010.

2.5 Statistical analyses

Fungal spore seasons were calculated using the 90 % method introduced by Nilsson and Persson (1981), which defines beginning of the season as a date when 5 % of the accumulative daily spore concentration was exceeded, and the end of the season, when 95 % of the accumulative daily spore concentration was reached. Seasonal Fungal Index (SFI), which constitutes a sum of daily mean spore concentration recorded within a spore season, was also calculated. Distribution of the spore data was analysed by application of three tests for normality, *i.e.*: Kolmogorov–Smirnov test, Kolmogorov–Smirnov test with Lilliefors correction and Shapiro–Wilk test. The nature of the species-environment dependences was tested by visual evaluation of the plotted correlation graphs. A Spearman's rank test was used to examine the relationship between concentration of investigated fungal spores and selected meteorological parameters. Since none of the investigated fungal spore seasons were normally distributed, the Kruskal–Wallis test was therefore used to examine the difference between annual sums of daily mean spore concentration, after Del Mar et al. (2000). The statistical analyses were performed with the aid of Microsoft Excel (2010), Statistica StatSoft (2012) and GenStat (17) software. The spore calendar was constructed upon a 5-year mean of monthly sums of daily spore concentration for each studied taxon. Spore counts were then presented on a logarithmic scale in order to enable comparison of extremely low or high spore counts simultaneously (Nikkels et al. 1996). Finally, a simple linear regression was used in order to detect any trend in the overall 5-year SFI.

3 Results

3.1 Overall fungal spore contribution and annual changes

The list of 20 types of fungal spores that were analysed in the air samples collected in Worcester and their 5-year mean distribution is presented on a logarithmic scale in Fig. 2. *Cladosporium* spores were the most highly occurring type out of the 20 selected taxa, with the peak recorded in August. The second largest group was coloured basidiospores, followed by *Didymella* ascospores with maximum concentrations observed in July and September, respectively (Fig. 2). The spore load of the most allergenic fungal spores (*Alternaria*) was comparable in number to *Aspergillus*/*Penicillium* and *Botrytis* spores (Fig. 2), while *Ganoderma* basidiospores were observed at twice this concentration and *Leptosphaeria* and smuts at four times as much (Fig. 2). Other taxa, such as *Periconia, Pithomyces, Pleospora, Stemphylium* and *Torula,* occurred in much lower concentrations (Fig. 2).

The Kruskal–Wallis test results (Table S1) show that, except for coloured basidiospores and *Torula,* all examined spores showed annual fluctuations in their distribution patterns. The simple linear regression analysis results (Table 1) revealed that 55 % of all examined taxa showed a reducing trend, 20 % remain unchanged and only 25 % exhibited increasing trend. However, only one trend, for *Entomophthora,* was found to be statistically significant (Table 1).

3.2 Fungal spore season characteristics

The summary statistics of main spore seasons were calculated for all examined fungal genera (Table 2). The three most frequently found types of those investigated in the air of Worcester during the study period are as follows: *Cladosporium,* coloured basidiospores and *Didymella.*

Cladosporium occurred in quite short spore seasons as their duration varied from 111 to 186 days (Table 2, Fig. 2). The daily peak values were approximately between 20,000 and 47,000, and they mainly occurred in July. In years 2006 and 2010, there were marked differences in comparison with the remaining 3 years of observations.

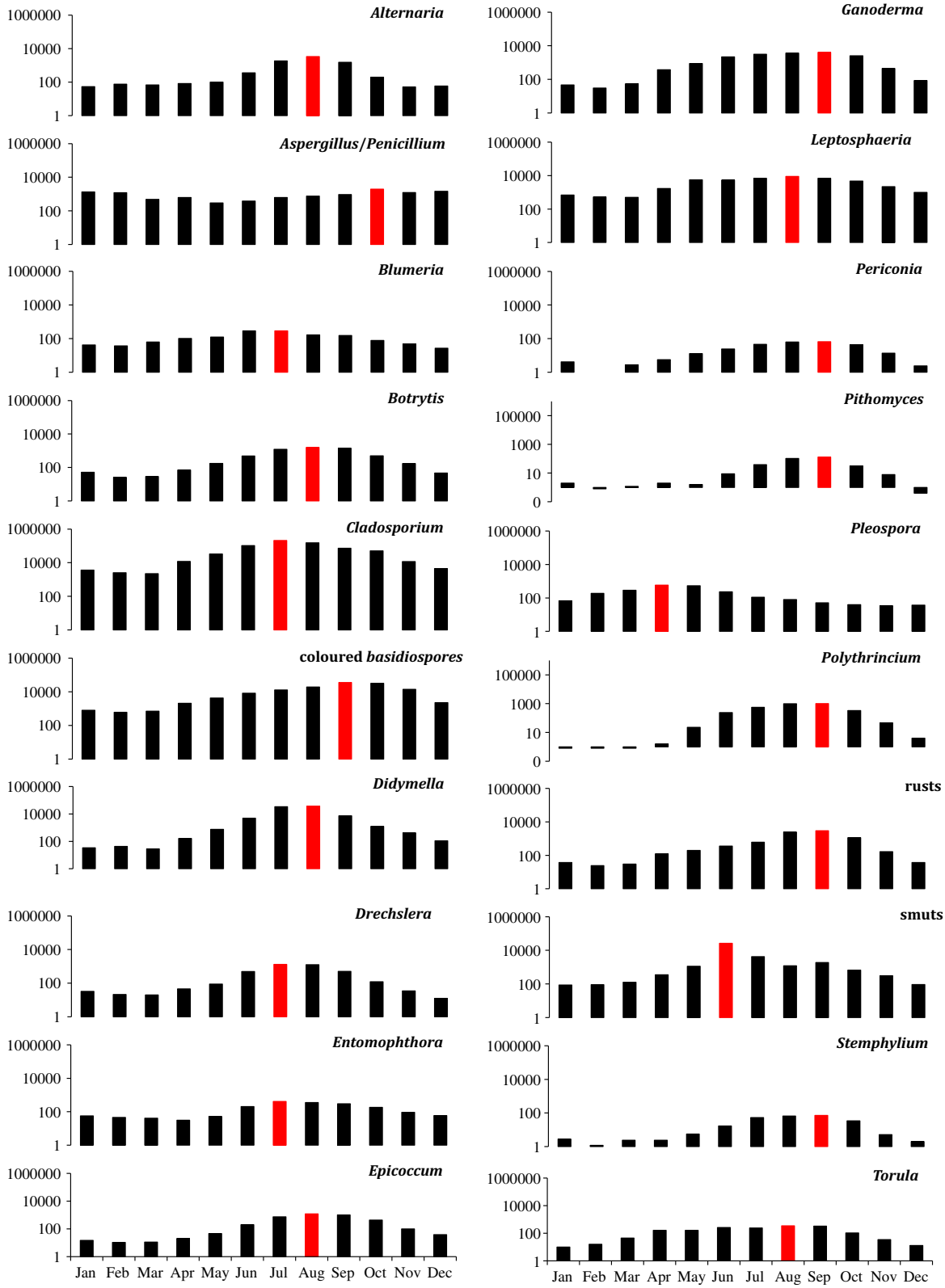
Coloured basidiospores showed stable and uniform seasons, which started in May and ended in November, with a duration lasting approximately 180 days (Table 2; Fig. 2). The only exception was found in 2010, as the length of that particular season was shorter by 40 days. Maximum spore concentrations were recorded mostly in September and October, with daily peaks oscillating between 3000 and 4600 spores per cubic metre of air. Coloured basidiospores occurred in a bi-annual pattern in their distribution, as they were found in significantly greater quantities in the years 2006, 2008 and 2010.

Didymella ascospores occurred during the shortest time periods of between 64 and 90 days (Table 2; Fig. 2). Seasons started either by the end of June or at the beginning of July, and finished mainly in September of each year. Although duration of the seasons was short, their intensity was revealed to be substantial, as the SFI scored from 26,000 to 190,186. Years 2007 and 2008 had the greatest concentration of *Didymella* ascospores during the 5-year monitoring at Worcester. The maximum spore concentration of *Didymella* ascospores recorded within a 24-h period was approximately 20,000 s m^{-3}.

3.3 Spore co-occurrence and high spore count days

The daily average concentrations were examined towards the co-occurrence between all studied taxa (Fig. 3). Two major groups of co-occurring spore types were identified: (a) *Alternaria*, *Cladosporium*, *Drechslera*, *Epicoccum*, *Polythrincium*, and (b) *Didymella* and *Leptosphaeria* (Fig. 3). The strongest associations were found between *Ganoderma* and *Polythrincium* ($r = 0.71$), as well as between *Alternaria* and *Epicoccum* ($r = 0.69$) spores. In contrast, unique distribution patterns showed *Aspergillus*/*Penicillium* group and *Pleospora* spores, which correlation coefficient values did not exceed $r = \pm 0.12$.

The number of days when established clinically allergenic thresholds were exceeded for *Alternaria* ($\geq$50 s m^{-3}), *Cladosporium* ($\geq$3000 s m^{-3}) and for both spore taxa simultaneously, are presented in Fig. 4. The overall contribution of high spore count days towards the spore seasons varied annually, and in all cases was found to be the highest in 2006 (Fig. 4c). *Alternaria* high spore count days constituted between 25 % and 45 % (Fig. 4a) and *Cladosporium* 32–74 % of the 5-year sampling period (Fig. 4b).


Alternaria
Aspergillus/Penicillium
Blumeria
Botrytis
Cladosporium
coloured basidiospores
Didymella
Drechslera
Entomophthora
Epicoccum
Ganoderma
Leptosphaeria
Periconia
Pithomyces
Pleospora
Polythrincium
rusts
smuts
Stemphylium
Torula
1000000
10000
100
1
100000
1000
10
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

◀**Fig. 2** 5-year mean distribution of examined spore types presented on a logarithmic scale. Peak months for each taxon are highlighted in *red*

3.4 Spore dependence on weather

Overall, the Spearman's rank test (Table 3) showed that statistically significant ($p \leq 0.05$) relationships between spore concentration and meteorological parameters were mainly found below $r_s = 0.50$.

The presence and high quantities of *Cladosporium* spores trapped at Worcester were shown to be correlated with all temperature parameters. The vector of these relationships was directly proportional (Table 3). Relative humidity was negatively correlated with spore counts.

Relative humidity was positively correlated with the concentration of coloured basidiospores in the air at the sampling site (Table 3). Statistically significant correlations were also observed with temperature, leaf wetness and air pressure (Table 3).

Didymella ascospores were strongly correlated with relative humidity, rainfall and leaf wetness (Table 3). The Spearman's rank coefficients varied between $r_s = 0.35$ and $r_s = 0.68$, while the influence of all temperature parameters were much lower if statistically significant at all. The direction of prevailing winds recorded in 2006 influenced to some extent the *Didymella* ascospore counts observed in Worcester ($r_s = 0.22$).

4 Discussion

This study was performed throughout a 5-year period, including two of very contrasting weather conditions in 2006 and 2007 that had a great impact on observed spore levels (Sadyś et al. 2015d). Several fungal spore types did not show any statistically significant correlation with prevailing wind directions recorded at Worcester, *i.e. Blumeria*, *Didymella*, *Leptosphaeria*, *Periconia*, *Pithomyces*, smuts and *Stemphylium* (Table 3). Based on the results, there is a possibility that some of those spores could originate from local sources. This hypothesis could also be supported by the high values of Spearman's rank coefficients, e.g. the *Blumeria* correlation with maximum temperature, *Didymella* and *Leptosphaeria* correlation with rainfall, or smuts with relative humidity (Table 3). In contrast, the origin of *Periconia*, *Pithomyces*, smuts

Table 1 Linear regression trend analysis for annual changes in Seasonal Fungal Indices

Taxon	Equation	R^2	p	Trend type
Alternaria	$y = -499.7x + 9278.3$	0.373	0.274	Descending
Aspergillus/Penicillium	$y = -1266.3x + 15110$	0.413	0.242	Descending
Blumeria	$y = -236.2x + 2107.8$	0.487	0.190	Descending
Botrytis	$y = 132x + 5364.4$	0.238	0.405	Ascending
Cladosporium	$y = 19989x + 600927$	0.022	0.812	Ascending
Coloured basidiospores	$y = 28x + 132422$	0.000	0.996	Plateau
Didymella	$y = -4360.6x + 100073$	0.010	0.873	Descending
Drechslera	$y = -1798.4x + 9356.6$	0.574	0.138	Descending
Entomophthora	$y = -490.7x + 3303.9$	0.846	**0.027***	Descending
Epicoccum	$y = -154.5x + 4302.5$	0.118	0.571	Descending
Ganoderma	$y = 135.1x + 17075$	0.008	0.884	Plateau
Leptosphaeria	$y = -180.5x + 45516$	0.001	0.969	Plateau
Periconia	$y = 7x + 263.2$	0.032	0.772	Ascending
Pithomyces	$y = -8x + 354.2$	0.016	0.838	Descending
Pleospora	$y = -695.2x + 4333$	0.738	0.062	Descending
Polythrincium	$y = 351x + 2145.4$	0.322	0.318	Ascending
Rusts	$y = 167.2x + 7590$	0.003	0.931	Ascending
Smuts	$y = 302.5x + 35240$	0.004	0.921	Plateau
Stemphylium	$y = -22.6x + 330.6$	0.187	0.468	Descending
Torula	$y = -115.2x + 2077.2$	0.360	0.284	Descending

Statistically significant correlations at the p level below 0.05 were distinguished by an asterisk (*)

Table 2 Characteristics of investigated fungal spore types

Taxon	Year	Period of occurrence	Duration	Daily peak value (s m^{-3})	Date of daily peak	SFI
Alternaria	2006	27.05–20.09	117	607	25.07	9297
	2007	19.05–06.10	141	275	05.08	6966
	2008	21.05–26.09	129	605	22.08	8092
	2009	24.06–08.10	107	644	08.08	8519
	2010	03.06–22.09	112	412	02.09	6022
Aspergillus/Penicillium	2006	05.01–01.12	331	311	02.01	10841
	2007	24.01–22.12	333	882	24.01	15844
	2008	18.01–16.12	334	536	26.01	12500
	2009	21.01–23.12	337	356	18.07	9877
	2010	07.01–11.12	339	410	10.10	7493
Blumeria	2006	27.02–01.12	278	58	06.06	2051
	2007	17.01–10.09	237	70	17.03	1690
	2008	04.03–30.09	211	29	10.06, 15.07	765
	2009	19.04–27.10	192	108	29.06	1550
	2010	20.05–11.10	145	29	06.08	940
Botrytis	2006	15.05–15.11	185	148	30.09	5039
	2007	13.06–27.10	137	1102	16.07	6187
	2008	30.05–16.10	140	203	09.09	5867
	2009	08.05–25.10	171	254	07.08	5833
	2010	03.06–06.10	126	313	11.09	5876
Cladosporium	2006	14.06–02.10	111	36783	25.07	863607
	2007	27.04–29.10	186	19813	16.07	489363
	2008	20.05–12.10	146	22316	06.08	437171
	2009	23.05–28.10	159	23040	29.06	612198
	2010	26.05–29.09	127	46831	14.07	902136
Coloured basidiospores	2006	22.05–24.11	187	4034	25.09	140349
	2007	17.05–13.11	181	3161	03.11	121892
	2008	09.05–04.11	180	3298	19.09	144061
	2009	24.05–23.11	184	3019	30.10	109588
	2010	13.06–31.10	141	4604	08.10	146641
Didymella	2006	27.06–24.09	90	2981	09.08	26976
	2007	17.06–22.08	67	9961	21.07	115817
	2008	08.07–09.09	64	19966	07.08	190186
	2009	11.07–20.09	72	11623	07.08	77793
	2010	13.07–17.09	67	2862	22.08	24185
Drechslera	2006	28.06–22.09	87	461	25.07	9465
	2007	01.05–30.09	153	290	19.06	5919
	2008	08.03–10.10	217	32	24.07	591
	2009	14.04–24.10	194	67	29.06	799
	2010	24.05–29.09	129	99	28.07	3033
Entomophthora	2006	13.02–02.12	293	47	18.09	2418
	2007	09.02–17.11	282	63	14.06	2684
	2008	04.04–14.11	225	70	08.08	1988
	2009	07.04–12.11	220	43	25.08	1525
	2010	23.03–06.11	229	18	24.07, 10.09	544

Table 2 continued

Taxon	Year	Period of occurrence	Duration	Daily peak value (s m^{-3})	Date of daily peak	SFI
Epicoccum	2006	07.07–15.10	101	216	21.09	4982
	2007	10.06–05.11	149	97	22.08	3075
	2008	09.06–23.10	137	113	21.09	3481
	2009	24.06–30.10	129	108	19.08	3820
	2010	13.06–15.10	125	148	19.07	3837
Ganoderma	2006	02.06–29.10	150	376	11.09	19103
	2007	23.04–29.10	190	225	14.10	14947
	2008	10.05–17.10	161	281	18.09	15793
	2009	22.05–29.10	161	310	14.08	20612
	2010	25.05–14.10	143	254	22.09	16946
Leptosphaeria	2006	23.04–17.11	209	983	17.08	36662
	2007	23.04–20.11	212	796	14.06	43240
	2008	24.04–02.11	193	1350	06.08	62836
	2009	16.04–17.11	216	1193	01.08	49505
	2010	29.03–01.11	218	821	13.07	32627
Periconia	2006	06.03–09.11	249	13	28.08, 15.10	270
	2007	08.05–06.11	183	9	17.07	229
	2008	31.05–26.10	149	13	07.09	315
	2009	23.05–30.10	161	54	28.07	375
	2010	12.04–11.11	214	14	22.08	232
Pithomyces	2006	27.07–12.10	78	27	21.09	371
	2007	20.06–20.10	123	27	11.09	343
	2008	16.04–07.10	175	13	03.09	203
	2009	13.08–28.10	77	64	20.08	463
	2010	14.06–25.10	134	23	19.07	271
Pleospora	2006	07.03–19.09	197	405	14.05	3493
	2007	10.02–18.08	190	234	23.04	3782
	2008	27.01–18.10	266	27	20.04, 05.05	1300
	2009	09.02–12.11	277	68	15.04	1508
	2010	18.02–28.09	223	59	29.04	1154
Polythrincium	2006	25.06–25.10	123	121	17.09	2060
	2007	19.06–24.10	128	92	05.08	3115
	2008	24.06–12.10	111	117	16.09	3061
	2009	27.06–03.10	99	115	07.09	4767
	2010	26.06–15.10	112	92	10.10	2989
Rusts	2006	25.04–31.10	190	297	21.09	4934
	2007	08.05–19.10	165	522	10.09	10144
	2008	25.05–20.10	149	423	29.09	6797
	2009	07.07–09.10	95	760	20.08	15482
	2010	05.05–01.11	181	158	29.09	3101
Smuts	2006	09.06–12.10	126	2950	10.06	44066
	2007	28.04–07.09	133	4903	19.06	28047
	2008	24.05–21.09	121	2509	10.06	27923
	2009	05.06–05.09	93	4019	24.06	42194
	2010	04.06–23.07	50	2646	26.06	38505

Table 2 continued

Taxon	Year	Period of occurrence	Duration	Daily peak value (s m^{-3})	Date of daily peak	SFI
Stemphylium	2006	08.05–24.10	170	18	25.07	333
	2007	27.04–03.11	191	14	19.08	199
	2008	17.06–13.10	119	22	22.08	369
	2009	25.06–05.11	134	7	07.08, 10.10	187
	2010	13.06–27.10	137	23	15.08	226
Torula	2006	12.04–15.10	187	61	10.09	1667
	2007	01.04–16.10	199	119	05.08	2176
	2008	24.03–21.10	212	50	21.10	1882
	2009	02.04–19.10	201	41	14.08	1508
	2010	12.04–10.10	182	32	27.04, 24.05	1425

SFI seasonal fungal index

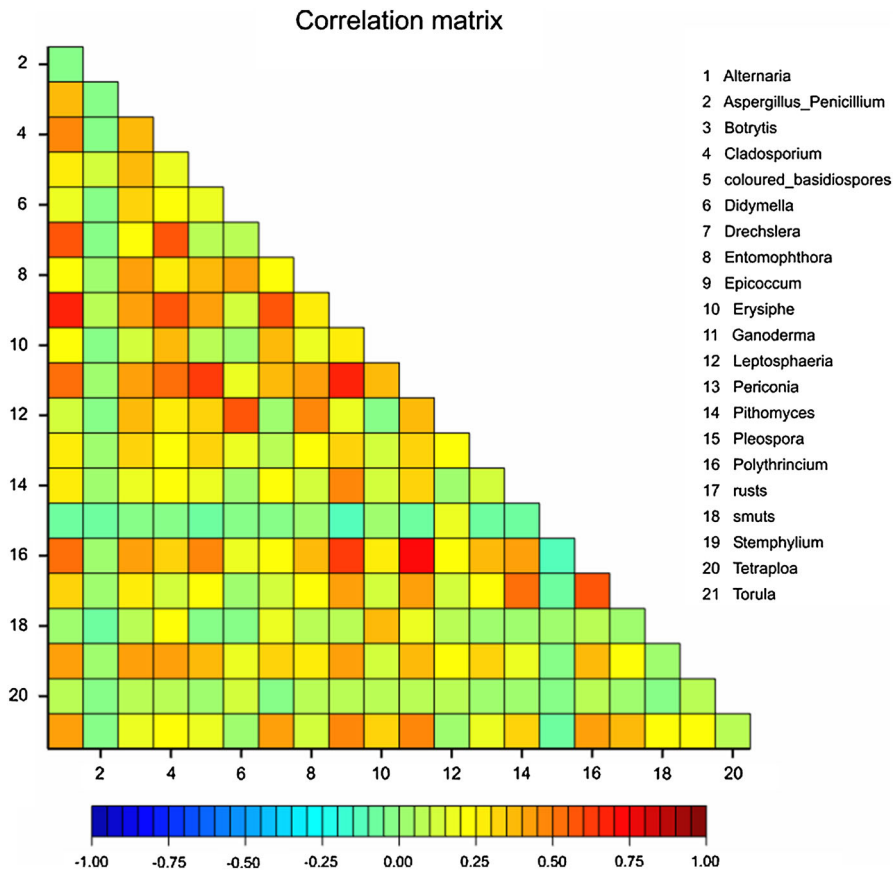


Fig. 3 Co-occurrence of all examined fungal spore types; average daily spore concentrations were tested. *Colour* indicates level of correlation between fungal taxa, where *brown* colours stand for $r_s = 1$, and *navy blue* for $r_s = 0$

and *Stemphylium* cannot be fully explained in a similar manner, as further analysis showed that most of the associations were not strong or even statistically significant. However, this could be caused by low spore counts recorded in the air samples (Fig. 2); hence, outcomes of the association test were likewise poor. Perhaps, due to certain features, like size, shape or surface structures some spores may not become easily airborne. For instance, the size of *Stemphylium* spores may be between 50–200 and 3–10 μm, and

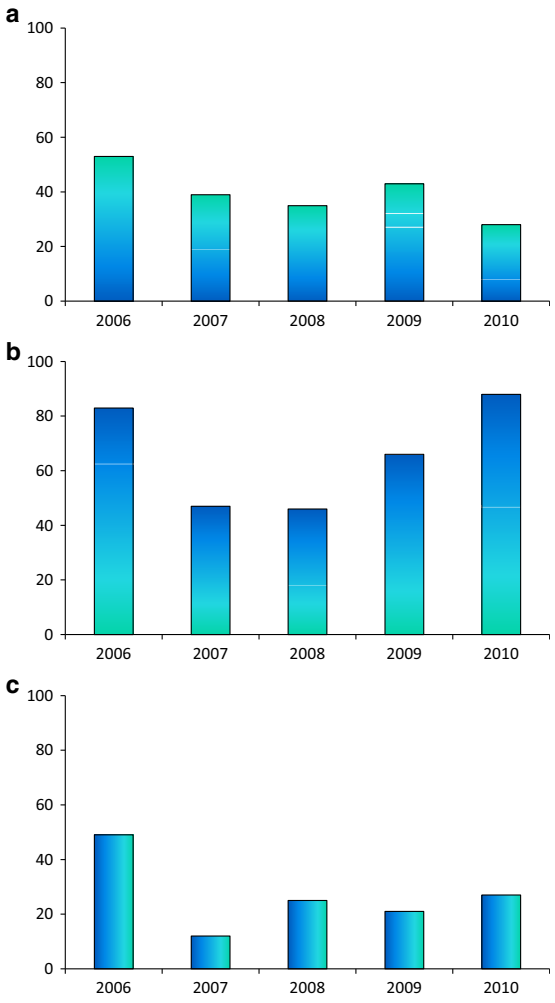


Fig. 4 Number of days within each year when allergenic thresholds were exceeded during the spore survey for: (**a**) *Alternaria* $\geq$50 s m^{-3}, (**b**) *Cladosporium* $\geq$3000 s m^{-3} and (**c**) both taxa

their shape varies from oblong to ellipsoidal and often the wall surface is rough, as it contains verruca or prickles (Ellis 1971). Another explanation may be the fact that an elongated shape accelerates the deposition, as they fall horizontally with the long axis, which has been reported for *Alternaria* spores (Lacey 1991).

The only long-term spore data set collected in the UK based upon volumetric sampling is available for Derby, located in the East Midlands of England (MAARA 2004). Results of spore surveys carried out both in Derby and Worcester showed the dominance of *Cladosporium* spores in the air, with maximum concentrations recorded between July and August (Fig. 2; MAARA 2004). Similar trends in spore distributions were found for *Alternaria* and *Leptosphaeria* with peaks observed in August. Smuts (*Ustilago*) peaks occurred in June and *Blumeria* maximum concentrations were recorded between June and August. Simultaneously, other taxa showed 1–2 month differences in their occurrence between sites. In Worcester, taxa such as *Aspergillus/Penicillium* type, *Didymella* and *Polythrincium* were sporulating later compared to Derby, while at the same time *Epicoccum* was sporulating earlier. Some of these differences could be caused by the distance between spore source and location of the aerobiological station, where these spores were trapped. An application of atmospheric models, such as Hybrid Single-Particle Lagrangian Trajectory (HYSPLIT), has already demonstrated and explained potential transport of bioaerosols at the regional and long-distance scale along with moving air masses (Sadyś et al. 2014; 2015b; Skjøth et al. 2012), although the differences in local and regional climate and land use should not be neglected (e.g. Kasprzyk et al. 2015).

The prevalence of *Cladosporium* spores above other taxa was also found in other European sites, for example in Rzeszów (Poland), Timişoara (Romania) and Leiden (Netherlands) with a contribution varying between 41 and 93 % (Ianovici and Tudorica 2009; Kasprzyk 2008; Nikkels et al. 1996). This is a characteristic feature for the temperate climate (D'Amato and Spieksma 1995) in contrast to tropical climates, where the key role is played by *Aspergillus/Penicillium* taxa (Desbois et al. 2006).

Results of the trend analysis showed that although only 25 % of investigated taxa had an increase in their spore count throughout a 5-year survey (Table 1, Fig. 4), the *Cladosporium* genus was found among this group. Taking into account that *Cladosporium* along with *Alternaria* are the most allergenic fungal genera (D'Amato and Spieksma 1995), this is a trend that should be carefully monitored. The result of *Ganoderma* distribution fits well with previous findings reported by Sadyś et al. (2014), who examined changes in *Ganoderma* spore distribution in combination with air mass and land cover analysis. They found that 78 % of the air masses reached Worcester from a 180° arc direction from the East to the West, where large complexes of broadleaf and mixed forests (*Ganoderma* hosts) were located. Assuming that forest areas did not experience any significant damage in the form of a fire, pest, etc. during the period under

Table 3 Spearman's rank correlation coefficients between fungal spore concentrations and meteorological parameters

Taxon	Year	T_{MAX}	T_{MIN}	T_{MEAN}	DPT	WD	RH	R	AP	LW	LT
Alternaria	2006	**0.49***	**0.49***	**0.49***	0.06	0.04	**−0.43***	**−0.24***	0.02	−0.08	**0.49***
	2007	**0.57***	**0.56***	**0.57***	0.13	**0.25***	**−0.42***	**−0.43***	0.14	**−0.36***	**0.58***
	2008	**0.37***	**0.37***	**0.37***	**0.28***	**−0.19***	−0.06	**−0.19***	**0.22***	−0.02	**0.33***
	2009	**0.48***	**0.48***	**0.48***	**0.23***	−0.13	**−0.32***	**−0.19***	**0.19***	−0.19	**0.41***
	2010	0.08	0.08	0.08	0.02	0.15	−0.05	−0.18	0.10	–	–
	Total	**0.43***	**0.43***	**0.43***	0.15	**0.02***	**−0.26***	**−0.28***	**0.16***	**−0.19***	**0.44***
Aspergillus/Penicillium	2006	**−0.28***	**−0.28***	**−0.28***	**−0.26***	−0.04	**0.12***	**−0.11***	**0.11***	0.05	**−0.29***
	2007	**−0.35***	**−0.35***	**−0.35***	**−0.25***	**−0.13***	**0.29***	−0.09	**0.25***	**0.14***	**−0.31***
	2008	**−0.19***	**−0.19***	**−0.19***	**−0.12***	**−0.12***	**0.22***	−0.09	**0.25***	**0.13***	**−0.21***
	2009	0.10	0.10	0.10	**0.17***	0.00	**0.13**	−0.05	0.05	0.08	0.01
	2010	−0.01	−0.01	−0.01	0.02	0.00	0.07	0.06	0.05	–	–
	Total	**−0.16***	**−0.15***	**−0.16***	**−0.11***	−0.05	**0.14***	−0.05	0.15	**0.12***	**−0.21***
Blumeria	2006	**0.48***	**0.48***	**0.48***	**0.35***	0.00	**−0.27***	**−0.26***	**0.20***	**−0.28***	**0.48***
	2007	**0.26***	**0.26***	**0.26***	**0.14***	0.01	**−0.22***	**−0.24***	**0.15***	**−0.24***	0.08
	2008	**0.43***	**0.43***	**0.43***	**0.27***	−0.02	**−0.28***	**−0.32***	**0.31***	**−0.34***	**0.48***
	2009	**0.36***	**0.36***	**0.36***	0.12	−0.11	**−0.40***	**−0.27***	**0.21***	**−0.31***	**0.44***
	2010	**0.55***	**0.55***	**0.55***	**0.19***	0.11	**−0.41***	**−0.34***	**0.30***	–	–
	Total	**0.41***	**0.40***	**0.40***	**0.24***	0.01	**−0.28***	**−0.29***	**0.24***	**−0.28***	**0.34***
Botrytis	2006	**0.18***	**0.19***	**0.19***	**0.18***	−0.04	−0.02	0.06	**−0.31***	**0.16***	**0.18***
	2007	**0.46***	**0.46***	**0.46***	**0.36***	**0.20***	**−0.20***	0.01	**−0.23***	−0.14	**0.46***
	2008	−0.04	−0.04	−0.04	**0.20***	**−0.24***	**0.31***	0.07	−0.01	**0.25***	−0.10
	2009	**0.49***	**0.49***	**0.49***	**0.51***	0.04	0.01	0.01	**−0.16***	−0.06	**0.31***
	2010	−0.12	−0.12	−0.12	−0.02	**0.29***	0.16	0.07	−0.14	–	–
	Total	**0.23***	**0.22***	**0.22***	**0.28***	0.05	**0.08***	0.05	**−0.19***	0.07	**0.22***
Cladosporium	2006	**0.44***	**0.44***	**0.44***	0.01	0.06	**−0.40***	−0.08	0.17	−0.14	**0.45***
	2007	**0.29***	**0.29***	**0.29***	**0.31***	**−0.16***	0.00	−0.01	−0.05	0.06	**0.28***
	2008	**0.49***	**0.49***	**0.49***	**0.34***	**−0.24***	−0.16	−0.11	0.13	0.04	**0.51***
	2009	**0.41***	**0.40***	**0.41***	**0.40***	−0.16	−0.02	0.06	−0.11	0.13	**0.37***
	2010	**0.53***	**0.53***	**0.53***	**0.26***	−0.05	**−0.24***	**−0.21***	0.15	–	–
	Total	**0.52***	**0.51***	**0.51***	**0.37***	**−0.11***	**−0.15***	**−0.09***	0.02	−0.01	**0.46***
Coloured basidiospores	2006	**−0.45***	**−0.44***	**−0.44***	−0.07	**−0.30***	**0.56***	0.12	**−0.28***	**0.36***	**−0.46***
	2007	**−0.16***	**−0.15***	**−0.15***	−0.07	**−0.20***	**0.21***	−0.05	0.09	−0.02	**−0.15***
	2008	0.02	0.02	0.02	**0.25***	0.06	**0.32***	−0.10	0.21	0.14	−0.09
	2009	**0.41***	**0.41***	**0.41***	**0.49***	−0.08	0.09	0.12	**−0.22***	0.03	**0.23***
	2010	−0.01	−0.01	−0.01	**0.19***	0.00	**0.16***	0.04	0.08	–	–
	Total	**−0.11***	**−0.11***	**−0.11***	**0.13***	**−0.09***	**0.33***	0.02	−0.04	**0.17***	**−0.15***
Didymella	2006	**−0.23***	**−0.23***	**−0.23***	**0.22***	**0.22***	**0.44***	**0.58***	**−0.33***	**0.50***	**−0.24***
	2007	**−0.27***	**−0.26***	**−0.26***	**0.39**	−0.05	**0.63***	**0.55***	**−0.39***	**0.64***	**−0.33***
	2008	**−0.34***	**−0.35***	**−0.35***	−0.14	−0.04	**0.45***	**0.68***	**−0.65***	**0.63***	**−0.35***
	2009	0.18	0.18	0.18	**0.43***	−0.06	**0.34***	**0.63***	**−0.43***	**0.67***	**0.34***
	2010	0.02	0.02	0.01	0.20	0.09	**0.35***	**0.48***	−0.15	–	–
	Total	**−0.23***	**−0.22***	**−0.23***	**0.13***	0.02	**0.40***	**0.57***	**−0.49***	**0.56***	**−0.20***

Table 3 continued

Taxon	Year	T_{MAX}	T_{MIN}	T_{MEAN}	DPT	WD	RH	*R*	AP	LW	LT
Drechslera	2006	**0.43***	**0.44***	**0.44***	**−0.29***	0.00	**−0.74***	**−0.39***	**0.34***	**−0.61***	**0.48***
	2007	**0.57***	**0.57***	**0.57***	**0.21***	**0.20***	**−0.35***	**−0.33***	0.15	**−0.31***	**0.57***
	2008	**0.50***	**0.51***	**0.51***	**0.43***	**−0.22***	−0.06	**−0.19***	**0.30***	−0.08	**0.47***
	2009	**0.48***	**0.48***	**0.48***	**0.39***	−0.10	**−0.15***	**−0.18***	**0.19***	**−0.19***	**0.38***
	2010	**0.46***	**0.46***	**0.46***	**0.18***	0.05	**−0.27***	**−0.30***	**0.31***	–	–
	Total	**0.56***	**0.56***	**0.56***	**0.40***	**0.07***	**−0.17***	**−0.19***	**0.19***	**−0.10***	**0.38***
Entomophthora	2006	**0.42***	**0.42***	**0.42***	**0.55***	−0.10	**0.24***	0.01	−0.10	**0.15***	**0.40***
	2007	**0.49***	**0.49***	**0.49***	**0.59***	0.12	**0.20***	0.08	**−0.22***	**0.12***	**0.41***
	2008	**0.51***	**0.51***	**0.51***	**0.63***	0.12	**0.16***	0.08	−0.05	0.07	**0.36***
	2009	**0.50***	**0.50***	**0.50***	**0.64***	0.01	**0.24***	**0.27***	**−0.31***	**0.19***	**0.40***
	2010	**0.27***	**0.27***	**0.27***	**0.39***	**0.24***	**0.27***	**0.16***	**−0.16***	–	–
	Total	**0.40***	**0.41***	**0.40***	**0.50***	**0.07***	**0.18***	**0.11***	**−0.15***	**0.14***	**0.37***
Epicoccum	2006	**0.51***	**0.51***	**0.51***	−0.08	0.08	**−0.60***	**−0.46***	**0.25***	**−0.41***	**0.53***
	2007	0.04	0.04	0.04	−0.17	**0.18***	**−0.23***	**−0.48***	**0.57***	**−0.24***	0.03
	2008	**0.33***	**0.33***	**0.33***	**0.30***	**−0.33***	−0.06	**−0.19***	**0.23***	0.00	**0.33***
	2009	**0.40***	**0.40***	**0.40***	0.14	−0.10	**−0.36***	**−0.38***	**0.20***	**−0.38***	**0.31***
	2010	**0.20***	**0.19***	**0.20***	0.12	0.14	−0.12	−0.11	0.03	–	–
	Total	**0.34***	**0.34***	**0.34***	**0.11***	−0.03	**−0.26***	**−0.32***	**0.26***	**−0.23***	**0.33***
Ganoderma	2006	**0.17***	**0.17***	**0.17***	**0.35***	**−0.32***	0.14	0.01	−0.04	**0.21***	**0.17***
	2007	**0.41***	**0.41***	**0.41***	**0.38***	**0.21***	0.01	**−0.31***	**0.24***	−0.04	**0.35***
	2008	**0.34***	**0.35***	**0.35***	**0.40***	−0.08	0.10	**−0.21***	**0.37***	0.07	**0.28***
	2009	**0.48***	**0.49***	**0.49***	**0.55***	**−0.19***	0.10	−0.12	0.03	0.03	**0.19***
	2010	**0.53***	**0.53***	**0.53***	**0.55***	−0.12	0.10	−0.05	0.05	–	–
	Total	**0.42***	**0.42***	**0.42***	**0.46***	**−0.10***	0.07	**−0.16***	**0.14***	0.02	**0.30***
Leptosphaeria	2006	−0.12	−0.11	−0.11	**0.25***	−0.04	**0.49***	**0.54***	**−0.53***	**0.51***	**−0.16***
	2007	**0.15***	**0.16***	**0.16***	**0.41***	−0.04	**0.32***	**0.45***	**−0.40***	**0.38***	0.11
	2008	0.08	0.08	0.08	**0.41***	−0.11	**0.49***	**0.55***	**−0.40***	**0.58***	−0.09
	2009	0.09	0.09	0.09	**0.33***	−0.08	**0.43***	**0.68***	**−0.55***	**0.58***	0.08
	2010	**0.16***	**0.17***	**0.16***	**0.44***	−0.07	**0.55***	**0.63***	**−0.52***	–	–
	Total	**0.07***	**0.07***	**0.07***	**0.35***	**−0.07***	**0.44***	**0.56***	**−0.46***	**0.50***	0.00
Periconia	2006	**0.21***	**0.21***	**0.21***	**0.21***	0.12	0.02	−0.06	−0.07	0.04	**0.20***
	2007	−0.05	−0.05	−0.05	0.00	−0.03	0.05	0.13	**−0.17***	0.10	−0.05
	2008	**−0.25***	**−0.25***	**−0.25***	−0.14	−0.08	0.12	−0.14	**0.20***	0.02	**−0.21***
	2009	**0.32***	**0.32***	**0.32***	**0.27***	−0.04	−0.06	0.00	−0.09	−0.03	**0.21***
	2010	0.07	0.07	0.07	**0.14***	0.06	0.13	0.09	**−0.19***	–	–
	Total	**0.10***	**0.10***	**0.10***	**0.12***	0.02	0.05	0.01	**−0.08***	0.03	**0.10***
Pithomyces	2006	**0.34***	**0.34***	**0.34***	−0.06	−0.05	−0.42*	−0.34*	0.27*	−0.31*	0.34*
	2007	−0.03	−0.04	−0.04	−0.17	0.00	−0.15	−0.30*	0.39*	−0.14	−0.04
	2008	0.09	0.09	0.09	0.11	0.08	0.03	0.04	−0.07	0.13	0.05
	2009	0.33*	0.33*	0.33*	0.21	−0.19	−0.20	−0.16	0.05	−0.32*	0.33*
	2010	0.25*	0.25*	0.25*	0.14	0.07	−0.25*	−0.18*	0.09	–	–
	Total	0.18*	0.18*	0.18*	0.07	0.05	−0.16*	−0.20*	0.16*	−0.10*	0.03

Table 3 continued

Taxon	Year	T_{MAX}	T_{MIN}	T_{MEAN}	DPT	WD	RH	*R*	AP	LW	LT
Pleospora	2006	−0.29*	−0.29*	−0.29*	−0.06	−0.03	0.48*	0.55*	−0.39*	0.38*	−0.31*
	2007	−0.42*	−0.42*	−0.42*	−0.22*	−0.26*	0.34*	0.20*	−0.03	0.33*	−0.18*
	2008	−0.03	−0.03	−0.03	0.06	−0.23*	0.27*	0.42*	−0.30*	0.35*	−0.08
	2009	−0.18*	−0.18*	−0.18*	−0.07	−0.26*	0.24*	0.46*	−0.29*	0.34*	−0.13*
	2010	−0.14*	−0.13*	−0.14*	0.04	−0.19*	0.38*	0.55*	−0.38*	–	–
	Total	−0.17*	−0.17*	−0.17*	−0.04	−0.18*	0.29*	0.43*	−0.28*	0.35*	−0.15*
Polythrincium	2006	−0.04	−0.03	−0.03	0.01	−0.15	0.01	−0.28*	0.00	−0.13	−0.02
	2007	0.56*	0.56*	0.56*	0.28*	0.25*	−0.37*	−0.38*	0.11	−0.36*	0.56*
	2008	0.25*	0.26*	0.26*	0.11	−0.07	−0.35*	−0.46*	0.43*	−0.33*	0.39*
	2009	0.48*	0.48*	0.48*	0.15	−0.09	−0.40*	−0.42*	0.28*	−0.32*	0.32*
	2010	0.17	0.18	0.17	0.01	0.24*	−0.28*	−0.34*	0.09	–	–
	Total	0.23*	0.23*	0.23*	0.09*	0.06	−0.23*	−0.37*	0.19*	−0.30*	0.28*
Rusts	2006	0.18*	0.18*	0.18*	0.27*	−0.09	0.10	−0.10	−0.22*	0.07	0.13
	2007	0.33*	0.33*	0.33*	0.02	0.38*	−0.38*	−0.45*	0.24*	−0.37*	0.30*
	2008	−0.11	−0.11	−0.11	0.08	−0.19*	0.20*	−0.06	0.09	0.02	−0.21*
	2009	0.16	0.17	0.16	−0.02	0.02	−0.24*	−0.48*	0.25*	−0.45*	−0.13
	2010	0.05	0.06	0.05	0.17*	0.11	0.28*	0.12	−0.05	–	–
	Total	0.11*	0.12*	0.12*	0.09*	0.07*	−0.01	−0.15*	0.05	−0.12*	0.00
Smuts	2006	0.31*	0.31*	0.31*	0.06	−0.30*	−0.31*	−0.29*	0.41*	−0.39*	0.33*
	2007	0.38*	0.38*	0.38*	0.11	−0.02	−0.34*	−0.03	−0.28*	−0.13	0.43*
	2008	−0.11	−0.11	−0.11	−0.52*	0.10	−0.60*	−0.32*	0.40*	−0.30*	0.19*
	2009	0.06	0.05	0.06	−0.21*	0.02	−0.38*	−0.17	0.23*	−0.22*	0.29*
	2010	−0.12	−0.14	−0.13	−0.46*	0.08	−0.43*	−0.37*	0.35*	–	–
	Total	0.20*	0.19*	0.20*	−0.11*	−0.08	−0.42*	−0.22*	0.18*	−0.25*	0.32*
Stemphylium	2006	0.19*	0.19*	0.19*	0.07	−0.07	−0.13	−0.17*	−0.03	−0.03	0.19*
	2007	0.19*	0.19*	0.19*	0.07	0.16*	−0.14	−0.03	0.02	−0.06	0.20*
	2008	−0.03	−0.02	−0.03	0.04	−0.01	−0.02	−0.18	0.24*	−0.13	−0.01
	2009	0.29*	0.29*	0.29*	0.18	−0.01	−0.17	0.01	0.03	0.01	0.28*
	2010	0.04	0.03	0.03	0.03	−0.03	−0.06	0.05	−0.04	–	–
	Total	0.17*	0.16*	0.16*	0.11*	−0.01	−0.10*	−0.05	0.00	−0.06	0.22*
Torula	2006	0.32*	0.32*	0.33*	0.09	0.01	−0.36*	−0.28*	0.28*	−0.27*	0.34*
	2007	0.26*	0.25*	0.26*	0.01	0.27*	−0.26*	−0.31*	0.28*	−0.19*	0.24*
	2008	0.40*	0.40*	0.40*	0.18*	−0.17*	−0.38*	−0.36*	0.41*	−0.34*	0.49*
	2009	0.39*	0.39*	0.39*	0.19*	−0.15*	−0.30*	−0.28*	0.27*	−0.28*	0.32*
	2010	0.20*	0.19*	0.20*	−0.11	0.04	−0.46*	−0.38*	0.38*	–	–
	Total	0.31*	0.31*	0.31*	0.08*	0.01	−0.34*	−0.32*	0.32*	−0.27*	0.34*

T_{MAX} maximum temperature, T_{MIN} minimum temperature, T_{MEAN} mean temperature, *DPT* dew point temperature, *WD* wind direction

RH relative humidity, *R* rain, *AP* air pressure, *LW* leaf wetness, *LT* leaf temperature

Statistically significant correlations at the *p* level below 0.05 were distinguished by an asterisk (*)

investigation and the overall wind direction remained constant due to the terrain orography, it would be expected that there would be no significant change in the overall *Ganoderma* SFI (Table 1).

A limited number of studies have focused on an analysis of the co-occurrence between pollen and spore taxa in the air (Damialis et al. 2015; Kasprzyk 2008). However, an internal cross-examination for

spores has often being overlooked, although all spore season characteristics are reported (e.g. Kasprzyk et al. 2004). This study has, for the first time, included this type of analysis (Fig. 3). A continuation of this study would be beneficial as differing results were found for *Alternaria* spores compared with previous findings, which suggested a potential increase in spore production (Sadyś et al. 2015d). In addition, some caution would be advisable as these results are based on 5-year data and an extension of the observation period would be recommended (Nikkels et al. 1996).

5 Conclusion

Allergenic fungal spores can be found throughout the year in the atmosphere of the studied area. The analysis depicted time periods when allergenic spore types occurred in the air with a maximum concentration. This information hopefully will be used by local allergists while setting up a treatment for patients sensitised to fungal spores and will help sufferers to avoid exposure to fungal spores during the most dangerous hours and days by planning their activities and holidays accordingly. The maximum monthly sum of mean daily spore concentration varied between taxa, and the earliest peaks were recorded for *Pleospora* in April and *Ustilago* fungi in June. However, the majority of investigated spore types occurred in the greatest concentrations between August and September. The most dominant genus was *Cladosporium*, which exceeded an allergenic threshold of 3000 s m^{-3} 40 times during very rainy years and twice as much during dry years.

Acknowledgments This study was jointly funded by the National Pollen and Aerobiology Research Unit and Graduate Research School at the University of Worcester and conducted within a framework of the doctoral studies of the first author.

References

Bousquet, J., van Cauwenberge, P., & Khaltaev, N. (2001). Allergic rhinitis and its impact on asthma. *Journal of Allergy and Clinical Immunology, 108*, S147–S334.

Comtois, P. (1998). Statistical analysis of aerobiological data. In P. Mandrioli, P. Comtois, & V. Levizzani (Eds.), *Methods in aerobiology* (pp. 217–251). Bologna: Pitagora Editrice.

Corden, J. M., & Millington, W. M. (2001). Long-term trends and seasonal variation in the aeroallergen *Alternaria* in Derby, UK. *Aerobiologia, 17*, 127–136.

D'Amato, G., & Spieksma, F. T. M. (1995). Aerobiologic and clinical aspects of mould allergy in Europe. *Allergy, 50*, 870–877.

Damialis, A., Vokou, D., Gioulekas, D., & Halley, J. M. (2015). Long-term trends in airborne fungal-spore concentrations: a comparison with pollen. *Fungal Ecology, 13*, 150–156.

Del Mar, Trigo M., Toro, F. J., Recio, M., & Cabezudo, B. (2000). A statistical approach to comparing the results from different aerobiological stations. *Grana, 39*(5), 252–258.

Denning, D. W., O'Driscoll, B. R., Hogaboam, C. M., Bowyer, P., & Niwen, R. M. (2006). The link between fungi and severe asthma: a summary of the evidence. *European Respiratory Journal, 27*, 615–626.

Desbois, N., Beguin, H., Ruck, G., Nere, J., & Nolard, N. (2006). Calendrier des spores fongiques de la Martinique. *Journal of Medical Mycology, 16*, 189–196.

Ellis, M. B. (1971). *Dematiaceous hyphomycetes*. London: The Eastern Press Ltd.

Floyer, J. (1745). *Violent asthma after visiting a wine cellar*. London: Innys and Parker.

Frankland, A. W., & Davies, R. R. (1965). Allergy to mold spores in England. *Le Poumon et le coeur, 21*, 11–31.

Frenguelli, G. (2003). Basic microscopy, calculating the field of view, scanning of slides, sources of error. *Post Dermatol Alergol, 20*, 227–229.

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*, 385–395.

Grant Smith, E. (1990). *Sampling and identifying allergenic pollens and molds. An illustrated identification manual for air samplers*. San Antonio: Blewstone Press.

Green, B. J., Sercombe, J. K., & Tovey, E. R. (2005). Fungal fragments and undocumented conidia function as new aeroallergen sources. *Journal of Allergy and Clinical Immunology, 115*, 1043–1048.

Heinzerling, L., Frew, A. J., Bindslev-Jensen, C., Bonini, S., Bousquet, J., Bresciani, M., et al. (2005). Standard skin prick testing and sensitization to inhalant allergen across Europe: a survey from the GA2LEN network. *Allergy, 60*, 1287–1300.

Hirst, J. (1952). An automatic volumetric spore trap. *Annals of Applied Biology, 39*, 257–265.

Hyde, H. A., & Williams, D. A. (1959). Air-borne allergens. *Postgraduate Medical Journal, 35*, 458–462.

Ianovici, N., & Tudorica, D. (2009). Aeromycoflora in outdoor environment of Timisoara city (Romania). *Notulae Scientia Biologicae, 1*(1), 21–28.

Jenkins, P. F., Mullins, J., Davies, B. H., & Williams, D. A. (1980). The possible role of aero-allergens in the epidemic of asthma deaths. *Clinical and Experimental Allergy, 11*, 611–620.

Kasprzyk, I. (2008). Co-occurrence of airborne allergenic pollen grains and fungal spores in Rzeszów, Poland (2000–2002). *Acta Agrobotanica, 61*(2), 65–73.

Kasprzyk, I., Rodinkova, V., Šaulienė, I., Ritenberga, O., et al. (2015). Air pollution by allergenic spores of the genus *Alternaria* in the air of central and eastern Europe. *Environmental Science and Pollution Research International, 22*(12), 9260–9274.

Kasprzyk, I., Rzepowska, B., & Wasylów, M. (2004). Fungal spores in the atmosphere of Rzeszów (South-East Poland). *Annals of Agricultural and Environmental Medicine, 11*, 285–289.

Khot, A., & Burn, R. (1984). Seasonal variation and time trends of deaths from asthma in England and Wales 1960–1982. *BMJ, 289*, 233–234.

Kurup, V. P., Shen, H.-D., & Banerjee, B. (2000). Respiratory fungal allergy. *Microbes and Infection, 2*, 1101–1110.

Kurup, V. P., Shen, H.-D., & Vijay, H. (2002). Immunobiology of fungal allergens. *International Archives of Allergy and Immunology, 129*, 181–188.

Lacey, J. (1981). The aerobiology of conidial fungi. In G. T. Cole & B. Kendrick (Eds.), *Biology of conidial fungi* (pp. 373–416). New York: Academic Press.

Lacey, J. (1991). Aggregation of spores and its effect on aerodynamic behaviour. *Grana, 30*, 437–445.

Lacey, M. E., & West, J. (2006). *The air spora. A manual for catching and identifying airborne biological particles*. Dordrecht: Springer.

Levetin, E., Horner, W. E., & Scott, J. A. (2015). Taxonomy of allergenic fungi. *The Journal of Allergy and Clinical Immunology: In Practice,*. doi:10.1016/j.jaip.2015.10.012.

MAARA (2004) Spore calendar. Available from: http://www.maara.org/2013-08-19-06-21-06/spore-calendar. Accessed on 3 Aug 2015.

Morrow Brown, H., & Jackson, F. A. (1978). Aerobiological studies based in Derby. II. Simultaneous pollen and spore sampling at eight sites within a 60 km radius. *Clinical Allergy, 8*, 599–609.

Nikkels, A. H., Terstegge, P., & Spieksma, F. T. M. (1996). Ten types of microscopically identifiable airborne fungal spores at Leiden, the Netherlands. *Aerobiologia, 12*, 107–112.

Nilsson, S., & Persson, S. (1981). Tree pollen spectra in the Stockholm region (Sweden), 1973–1980. *Grana, 20*(3), 179–182.

O'Connor, D. J., Sadyś, M., Skjøth, C. A., Healy, D. A., Kennedy, R., & Sodeau, J. R. (2014). Atmospheric concentrations of *Alternaria*, *Cladosporium*, *Ganoderma* and *Didymella* spores monitored in Cork (Ireland) and Worcester (England) during the summer of 2010. *Aerobiologia, 30*, 397–411.

Ogden, E. C., Raynor, G. S., Hayes, J. V., Lewis, D. M., et al. (1974). *Manual for sampling airborne pollen*. New York: Hafner Press.

Oteros, J., Galán, C., Alcazár, P., & Dominguez Vilches, E. (2013). Quality control in bio-monitoring networks, Spanish Aerobiology Network. *Science of the Total Environment, 443*, 559–565.

Rice, M. (2011). *Worcestershire demographic report 2011 with South Worcestershire Appendix* (pp. 1–21). Worcester: Worcestershire County Council.

Rossi, V., Bugiani, R., Giosué, S., & Natali, P. (2005). Patterns of airborne conidia of *Stemphylium vesicarium*, the causal agent of brown spot disease of pears, in relation to weather conditions. *Aerobiologia, 21*, 203–216.

Sadyś, M., Kennedy, R., & West, J. S. (2015a). Possible scenarios of climate change impact on fungi: Analysis of 2 years of contrasting weather in the UK. *Aerobiologia,*. doi:10.1007/s10453-015-9402-6.

Sadyś, M., Skjøth, C. A., & Kennedy, R. (2014). Back-trajectories show export of airborne fungal spores (*Ganoderma* sp.) from forests to agricultural and urban areas in England. *Atmospheric Environment, 84*, 88–99.

Sadyś, M., Skjøth, C. A., & Kennedy, R. (2015b). Forecasting methodologies for *Ganoderma* spore concentration using combined statistical approaches and model evaluations. *International Journal of Biometeorology,*. doi:10.1007/s00484-015-1045-3.

Sadyś, M., Skjøth, C. A., & Kennedy, R. (2015c). Determination of *Alternaria* spp. habitats using 7-day volumetric spore trap, Hybrid Single Particle Lagrangian Integrated Trajectory model and geographic information system. *Urban Climate, 14*, 429–440.

Sadyś, M., Strzelczak, A., Grinn-Gofroń, A., & Kennedy, R. (2015d). Application of redundancy analysis for aerobiological data. *International Journal of Biometeorology, 59*, 25–36.

Simon-Nobbe, B., Denk, U., Pöll, V., & Rid, R. (2008). The spectrum of fungal allergy. *International Archives of Allergy and Immunology, 145*, 58–86.

Skjøth, C. A., Damialis, A., Belmonte, J., De Linares, C., Fernández Rodríguez, S., Grinn-Gofroń, A., et al. (2015). *Alternaria* spores in the air across Europe: Abundance, seasonality and relationships with climate, meteorology and local environment. *Aerobiologia,*. doi:10.1007/s10453-016-9426-6.

Skjøth, C. A., Sommer, J., Frederiksen, L., & Karlson, U. G. (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*, 11107–11123.

Stępalska, D., & Wołek, J. (2009). The estimation of fungal spore concentrations using two counting methods. *Acta Agrobotanica, 62*, 117–123.

Sterling, M., Rogers, C., & Levetin, E. (1999). An evaluation of two methods used for microscopic analysis of airborne fungal spore concentrations from the Burkard Spore Trap. *Aerobiologia, 15*(1), 9–18.

Twaroch, T. E., Curin, M., Valenta, R., & Swoboda, I. (2015). Mold allergens in respiratory allergy: from structure to therapy. *Allergy, Asthma & Immunology Research, 7*(3), 205–220.