



Spatial distribution of fungi from the analysis of aerobiological data with a gamma function

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Abstract Fungi are an important component of ecosystems. Some fungi are widely distributed, while others are limited to certain habitats. Studies based on airborne fungal spores can help to know the geographical distribution of fungi in the territory. Our aim was to show that a gamma probability density function (gpdf) based on a database of 20 airborne fungal spore taxa concentrations in eight localities of Catalonia (NE Spain) for a period of 20 years was a useful tool to map the distribution of these taxa in this region, as well as to establish a general classification on their sporulation through the alpha parameter of the validated model. This allows a more efficient study of the atmospheric dynamics of the different taxa, since the number of taxa is reduced to a representative taxon for each of the categories of the generic classification. In general, the

results obtained confirmed that the scale parameter of the gamma distribution changes from year to year, depending on the meteorological conditions, while the shape parameter remains fairly stable. At the temporal scale, airborne fungal spores of *Agrocybe* sp. showed the highest stability; at the spatial scale, *Cladosporium* sp. showed the highest stability. Regarding localities, Girona was the station with greater interannual variation, while Barcelona and Vielha showed the lowest. In addition, the results obtained allowed a non-subjective classification of these taxa in five groups, based on the gamma (shape) parameter. The taxa *Alternaria* sp., *Cladosporium* sp., *Ganoderma* sp., *Pleospora* sp., *Leptosphaeria* sp., *Aspergillus* sp.-*Penicillium* sp. were cosmopolitan and showed a similar behavior across the whole study area, with any of them possible candidates for used in predictive models; airborne fungal spores of *Agrocybe* sp.,

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Arthrimum sp., *Epicoccum* sp., *Drechslera* sp.–*Helminthosporium* sp., *Pithomyces* sp., Thelephoraceae, *Stemphylium* sp., Xylariaceae can be used as meteorological indicators and *Agaricus* sp., *Coprinaceae* sp., *Torula* sp. can be used as indicators of anthropogenic activities. The results obtained could be used to reduce the number of spore taxa analyzed and subsequently develop generic predictive models.

Keywords Fungal spores · Gamma function · Fungal taxa distribution

1 Introduction

Fungal spores are present in the atmosphere, regardless of the change in their concentration and biodiversity. This variability can be due to the complex interaction of environmental conditions such as weather, geography and anthropogenic conditions like land use, which influence the emission process (Burch and Levetin 2002; Grinn-Gofroń and Strzelczak 2008a). Fungal spore dispersion is an important biological and ecological process with a high impact on allergological and agricultural studies, which have increased in recent years (Kuparinen et al. 2007; Orlandi et al. 2010; Matyasovszky and Makra 2011). Therefore, the existence of aerobiological networks is relevant, and they allow the creation of historical records of the bioaerosol concentrations with datasets greater than 20 years as shown by Ziello et al. (2012). These historical databases have been used in a large number of studies to develop models to predict concentrations in airborne pollen (Belmonte and Canela 2002; Chuine and Belmonte 2004; Rodríguez-Rajo et al. 2006; Iglesias et al. 2007; Puc 2012; Aboulaich et al. 2013) and occasionally in airborne fungal spores (Recio et al. 2012; Sadyś et al. 2016a, b), as well as airborne pollen (Belmonte et al. 2000, 2008; Zink et al. 2012; Prank et al. 2013) and fungal spores (Sadyś et al. 2014; Fernandez-Rodriguez et al. 2015; Grewling et al. 2019) which allows an analysis of long-range transport or an identification of the emission sources (Izquierdo et al. 2011; Fernández-Rodríguez et al. 2014).

Many of these aerobiological studies performed a predictive modeling (Vélez-Pereira 2017), which used methodologies satisfying a normally distributed on the

dataset (Grinn-Gofroń and Strzelczak 2008a, b; Astray et al. 2010; Scheifinger et al. 2013; Fernández-Llamazares et al. 2014). Usually, aerobiological data do not fit with a normal distribution curve type $x \pm s$ (that covers 68% of the dataset) or $x \pm 2 s$ (equivalent to 95% of the dataset). This is mainly due to the seasonality of emissions and the high quantity of days with concentrations equal to zero (null days) or low values of concentration, which influences the average and standard deviation of the dataset (Limpert et al. 2008).

Based on the aforementioned analysis, some authors suggested the use of preliminary transformations on the data (Stach et al. 2008; Dara 2013; Howard and Levetin 2014), e.g. Box–Cox family transformation (Shumway and Stoffer 2001) to approximate the aerobiological dataset to a normal distribution. Frequently, the logarithm and the square root have been used (Moseholm et al. 1987; Smith and Emberlin 2005, 2006; Stach et al. 2008; Matyasovszky and Makra 2011), with the former the most commonly used, but changing the $y = \log(x)$ by $y = \log(x + 0.1)$ as a mathematical solution to the aerobiological dataset with zeros. Nonetheless, the logarithmic transformation is equivalent to applying a log normal distribution. One of the disadvantages of using the transformation function on the development of predictive models is the likelihood of introducing noise (increasing the variability) in the dataset or the complex of compressing the results (Limpert et al. 2008; Grinn-Gofroń and Strzelczak 2008a, b).

Another relevant aspect of these datasets is the sudden increase in their concentrations in a short period of time (few days), making it difficult to find a mathematical model that fits well. This last aspect, and the high annual variability of seasonal parameters such as the start, end and duration, among others, means that the statistical analysis of the dataset throughout time should be performed on a case-by-case basis. In fact, these analyses can be more complex when comparing different taxa, especially if different behaviors (e.g. concentration, duration, among others) are presented. Thus, the majority of aerobiological studies published to date only analyzed one type of taxon or fewer taxa with similar behaviors (Vélez-Pereira 2017).

Comtois (2000) proposed the use of a gamma probability density function (gpdf) as a universal model to solve these inconveniences, because this

model can describe the distribution of an annual data series of pollen and, additionally, it allows the comparison of two or more taxa from two or more places with similar behavioral differences. Belmonte and Canela (2003) applied the gamma distribution on a pollen data series, obtaining satisfactory results, whereas Kasprzyk and Walanus (2014) found that in order to define pollen curves, the Gaussian and the differential logistic functions proved to be more effective.

Taking into account the characteristics of stability, plasticity and consistency of the α parameter, this article analyzed the application of the gpdf model on 20 fungal spore types measured at the eight aerobiological stations in Catalonia during 1995–2014, aiming to:

1. Validate a gpdf, allowing the characterization of a series of annual data through the model parameters, to enable a comparison, per taxon, of the data of different years at the same station or the data for the same year at different stations.

Likewise, if the model was valid for the different taxa, it aimed to:

2. Establish, through the α parameter, a generic classification of spore types grouped by the similarity in the behavior of this parameter.

In this way, a new generic classification was established, potentially less subjective than the one carried out with other approaches based on a visual inspection of the graphics, which can facilitate the management of aerobiological databases. It also allowed us to study more efficiently the atmospheric dynamics of the different taxa, since the number of taxa can be reduced to a representative taxon for each of the categories of the generic classification. Moreover, these results helped to show the geographical distribution of airborne fungal spores in a specific region.

2 Materials and methods

2.1 Study area

The study area was Catalonia (northeast of Spain). Figure 1 shows the location of the eight aerobiological

stations, their geographical characteristics and phytoclimates. Only three stations were considered as urban environment stations: Barcelona, Girona and Tarragona; two stations were considered to be in a rural environment: Lleida and Vielha; and the remaining three were considered urban/rural stations: Bellaterra, Manresa and Roquetes-Tortosa. In general, the climate of Catalonia is Mediterranean, although one of the areas (Lleida) presented a continental influence, and another (Vielha) an Atlantic one.

According to Allue Andrade (1990) and an analysis of the temperature and precipitation of the stations under study in the period 1995–2014 (data provided by the Agencia Estatal de Meteorología, AEMET, and Servei Meteorològic de Catalunya, Meteocat), these aerobiological stations were found to correspond to four phytoclimatic regions. Vielha station, located at 42°42'00" N, 00°47'50" E and 997 m.a.s.l. at the Vall d'Aran in the Pyrenees mountain system, corresponds to the Fresh-Continental Oriental-Humid phytoclimate. This station, the highest latitude and altitude of all the stations, showed the coldest and rainiest phytoclimate with the highest annual and number of days with precipitation (Fig. 2).

The Fresh-Transitional-Semiarid type station, Lleida, located at 41°37'41" N, 00°35'44" E and 192 m.a.s.l., in the El Segrià region, had the lowest annual precipitation and average temperature ranges from 12.0 to 15.5°C (Fig. 2). A great deal of crops are found in this area of Catalunya, especially cereal.

Likewise and in the central part of Catalonia, the Fresh-Continental Oriental-Semihumid phytoclimate was reported, such as the Bellaterra station (41°30'02" N, 02°06'28" E and 245 m.a.s.l.) located in Vallès Occidental region, Girona station (41°59'03" N, 02°49'23" E and 80 m.a.s.l.) in Gironès region and Manresa station (41°43'12" N, 01°50'23" E and 291 m.a.s.l.) in Bages region. In these stations the range of mean temperatures was similar to Lleida (from 12.0 to 15.5°C) but the rainfall was higher. Between them, Girona was the station with highest precipitation, thermal oscillation and relative humidity throughout the year (Fig. 2).

Finally, at the coastal zone, the Fresh-Thetyc-Semiarid phytoclimate was reported, corresponding to the Barcelona station (41°23'37" N, 02°09'53" E and 67 m.a.s.l.) in the Barcelonès region, the Roquetes-Tortosa station (40°49'13" N, 00°29'35" E y 50 m.a.s.l.) in El Baix Ebre region and Tarragona

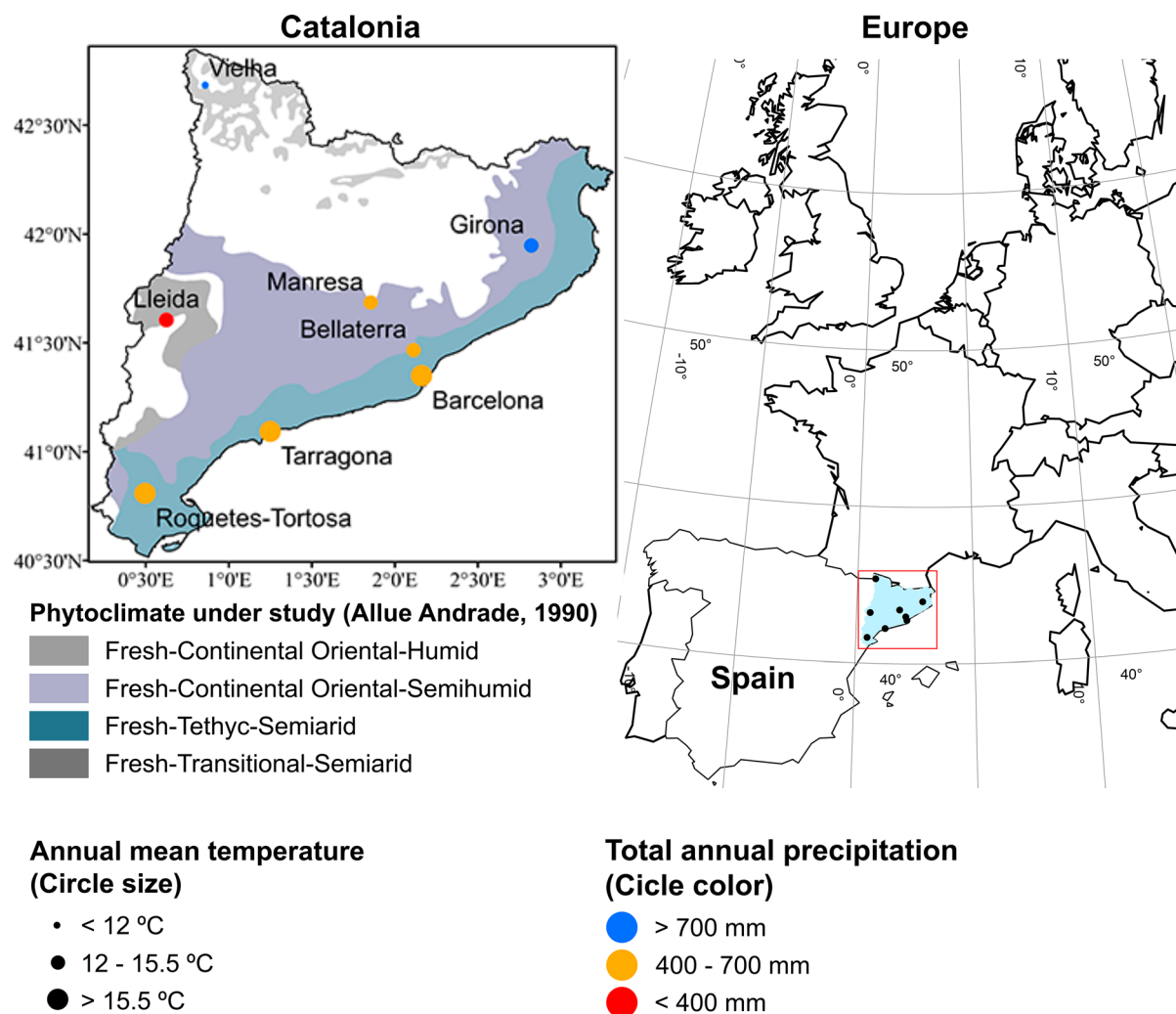


Fig. 1 Geographical situation, phytoclimates and meteorological characteristics of the study stations (Vélez-Pereira 2017)

(41°07'12" N, 01°14'37" E y 44 m.a.s.l.) in the Tarragonès region. Temperatures ranging from 12.0 to 15.5°C were found in all of these stations, like the two prior phytoclimates, but in this case, the rainfall was intermediate compared to the rest (Fig. 2).

2.2 Aerobiological data

Data were extracted from the database of the Catalan Aerobiological Network (Xarxa Aerobiològica de Catalunya, XAC). The samples were obtained with Hirst traps (Hirst 1952) and analyzed following the standard methodology proposed by the Spanish Aerobiology Network, Red Española de Aerobiología, REA (Galán et al. 2007). Terminology used in this

paper followed the International Association for the Aerobiology (IAA) recommendations (Galán et al. 2017). Data were expressed as the mean daily number of spores per cubic meter of air (spore/m³) and converted to annual spore integral (ASIn) by summing up the mean daily spore concentrations for the whole year. The stations provided different numbers of yearly periods comprised between 1995 and 2014: the whole series of 20 years in the case of Barcelona and Bellaterra, 19 years (1996–2014) in Girona, Lleida, Manresa and Tarragona, 11 years (2004–2014) in Vielha and 9 years (2006–2014) in Roquetes-Tortosa. A minimum of 276 mean daily concentration records were required in each yearly data series..

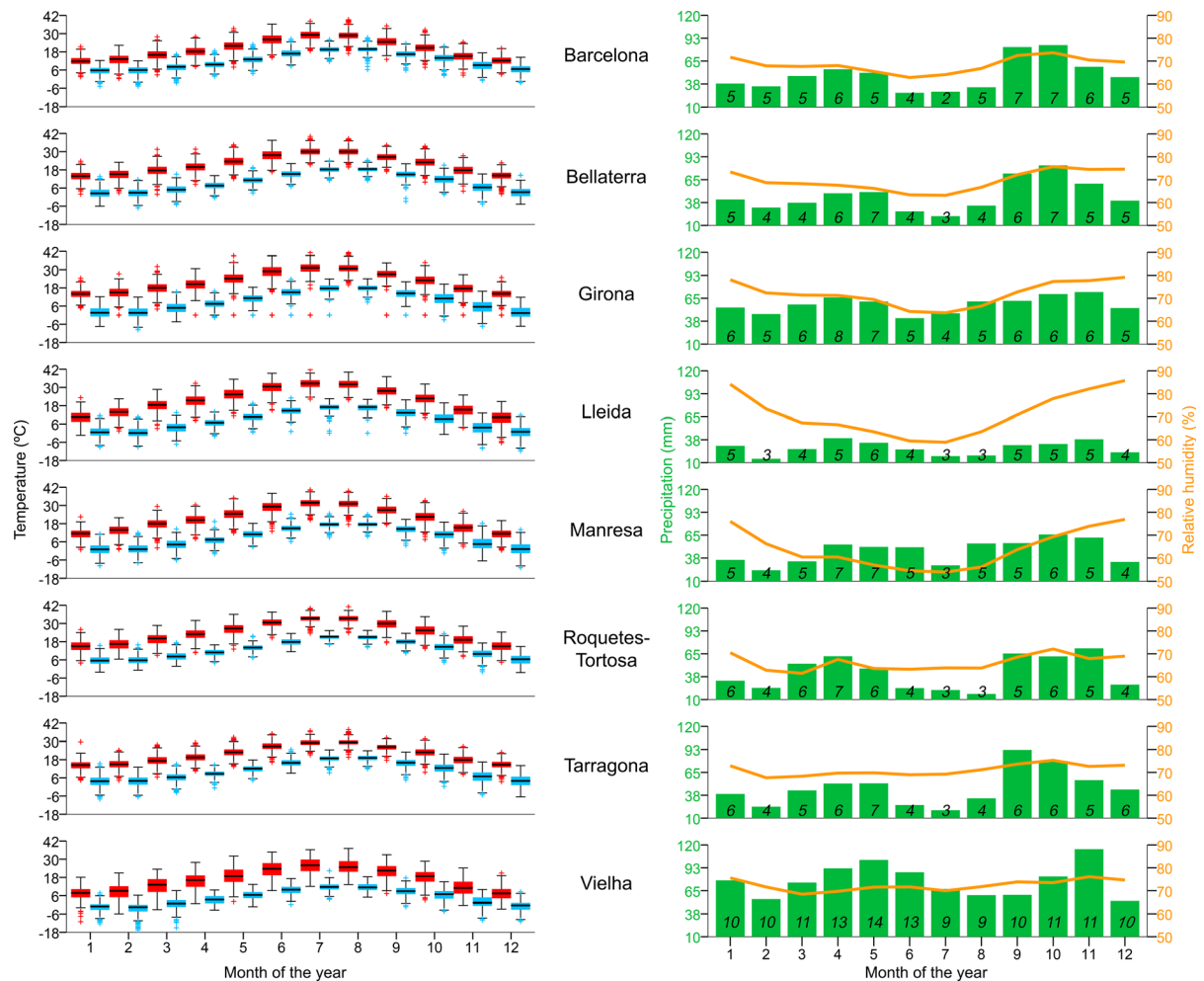


Fig. 2 Monthly averages of the maximum temperature (red boxplot) and minimum (blue boxplot), total precipitation (green bar), number of days with precipitation (italic number inside de

bar) and relative humidity (orange line) of the station under study in the period 1995–2014 (Vélez-Pereira 2017)

In this paper, we considered 20 fungal spore taxa: 5 ascospore types (*Chaetomium* sp., *Leptosphaeria* sp., *Pleospora* sp., Venturiaceae and Xylariaceae), 5 basidiospore types (*Agaricus* sp., *Agrocybe* sp., Coprinaceae, *Ganoderma* sp. and Thelephoraceae) and 10 conidiospore or anamorphic fungal types (*Alternaria* sp., *Arthrinium* sp., *Aspergillus* sp.–*Penicillium* sp., *Cladosporium* sp., *Curvularia* sp., *Drechslera* sp.–*Helminthosporium* sp., *Epicoccum* sp., *Pithomyces* sp., *Stemphylium* sp. and *Torula* sp.).

In the generic classification the exclusion criterion of not taking into account taxa and stations that presented more than two annual series with less than 10 non-null days (NND) was established. This was due to the fact that any alfa parameter estimated with less

than 10 NND was not reliable and could provoke noise on the analyses of the station-taxa series.

2.3 Statistical methods

The gamma probability density function (gpdf) statistical method was applied. The data series were analyzed by year, station and taxon studied and only when the number of non-null days (NND), or days with concentration records over a threshold was greater than or equal to 10 days/year. Null threshold was zero in all taxa except in *Cladosporium* sp. where it was from 0 to 200 spores/m³, because the average value of *Cladosporium* sp. in Catalonia during the year was over 200 spores/m³, and this value has been

considered as background level (Vélez-Pereira et al. 2019).

From the multiple possible options of gamma equation distribution, the gamma (α , β) was the one used.

$$f(x) = C(\alpha, \beta)x^{\alpha-1}e^{(-x/\beta)}, \quad x > 0$$

where $C(\alpha, \beta)$ was a constant standardization (the integration of the function $f(x)$ must be equal to one).

This model was made up of two parameters, one related to the curve shape (alpha, α), which did not have units. The α parameter was estimated as the inverse of the square of the coefficient of variation of the dataset, so that its stability throughout time became an indicator of the concentration variability of the studied taxon. In this sense, the higher α , the more homogenous the concentration was throughout a series of annual data. The α parameter always showed values higher than zero. For those values closer to zero, the curve was presented as asymptote to the ordinate axis, whose slope decreases as the value of α increases. Conversely, for $\alpha \geq 1$ the curve appeared as a growth asymptote to the axis of the ordinate, until reaching the maximum value, where it showed an exponential curve decrease with a similar behavior to $\alpha < 1$.

On the other hand, β parameter corresponds to the amplitude or propagation of the curve, whose units are, in this case, the same ones that express the concentration (Belmonte and Canela 2003). This β parameter is calculated by dividing the standard deviation square by the mean of the annual series, and its value indicates the airborne spore concentrations. In the model, the α and β parameters were calculated per each series through the so-called moment estimator, exploiting the relationship between the mean and standard deviation and the α and β parameters. Since the mean and the variance equal to $\alpha\beta$ and $\alpha\beta^2$, respectively, the coefficient of variation, CV (i.e. the standard deviation divided by the mean) was equal to $\alpha^{-1/2}$. Both α and CV were scale-free parameters, so changing the units did not affect the parameter value. With α parameter we made an analysis of the stability of the annual series on a temporal scale (the same station and taxa through the time) and on a spatial scale (the same year and taxa in all stations) from mean values per each station and taxon.

The significance level of the gpdf was made with Chi-square test. As a result, 5 categories were established for the concentration thresholds (null, low, medium, high and very high; Vélez-Pereira 2017) and the α and β parameters, which generate two degrees of freedom; enough to validate the test. However, due to the high variability on the number of data available in each data series, the test was considered significant if in all expected portions, a frequency equal or higher than 1% was obtained. The Chi-square test was mainly employed to establish the degree of fit, and it was not performed as a validation to accept or reject the gamma model.

The calculations were developed with R v3.0.3, while the spatial representation of the generic classification was elaborated with Golden SURFER®. In the latter case, an interpolation tool known as the “Nearest Neighbor” was used. This method established a potential area of influence based on the value of the nearest point (aerobiological station) to each grid node.

3 Results

Among the studied fungal taxa (Table 1), the most abundant airborne spores corresponded to *Cladosporium* sp., followed by Coprinaceae and *Agroclybe* sp. And the less abundant taxa were *Curvularia* sp., *Pithomyces* sp. and *Chaetomium* sp. In regard to the NND parameter, the more frequent taxa in the atmosphere throughout the year was *Alternaria* sp., followed by Coprinaceae and *Cladosporium* sp., while *Curvularia* sp., Venturiaceae and *Chaetomium* sp. were the less frequent ones. With respect to the spatial distribution, it was observed that the inland stations had the largest ASIn (from highest to lowest: Lleida, Manresa, Girona and Bellaterra), followed by coastal (Roquetes-Tortosa, Tarragona and Barcelona) and the mountain station (Vielha).

A summary of gamma model parameters and NND obtained per each fungal taxon is shown in Table 2. Taking into account the rule of considering only the taxon station series that did not present more than two annual series with less than 10 NND, we removed the taxa *Curvularia* sp. and Venturiaceae in all stations and *Chaetomium* sp. in Vielha.

The results of the gamma model showed that airborne spores of *Cladosporium* sp., *Agroclybe* sp. and

Table 1 Summary of the average Annual Spore Integral—ASIn (spore*day/m³) and number of non-null days—NND (gray background) of the studied taxa per station

Taxa	Stations								Mean
	Barcelona	Bellaterra	Girona	Lleida	Manresa	Tarragona	Roquetes-Tortosa	Vielha	
<i>Agaricus</i> sp.	2543	5653	7820	2546	2615	1794	2435	2035	3430
	143	187	168	125	162	113	177	103	147
<i>Agrocybe</i> sp.	10,974	30,712	23,383	7928	23,330	14,422	14,947	25,717	18,927
	245	264	256	204	249	214	224	199	232
<i>Alternaria</i> sp.	9383	11,700	13,051	36,182	21,068	10,242	14,097	2027	14,719
	301	321	277	300	322	299	321	165	288
<i>Arthrinium</i> sp.	1323	1718	1028	1515	1968	1352	1096	200	1275
	130	163	120	145	164	126	122	31	125
<i>Asper.-Penic</i>	5212	5638	6981	4928	5435	4570	5364	3298	5178
	95	100	110	95	94	80	99	69	93
<i>Chaetomium</i> sp.	224	178	140	182	165	240	79	43	156
	47	33	33	42	34	33	22	11	32
<i>Cladosporium</i> sp.	199,677	305,264	356,063	577,936	463,408	218,094	323,553	161,883	325,735
	238	283	258	279	292	234	272	168	253
Coprinaceae	11,655	36,867	45,448	27,368	27,490	13,331	19,749	30,511	26,552
	296	304	288	265	265	261	279	233	274
<i>Curvularia</i> sp.	49	89	78	72	231	40	36	65	83
	9	13	12	16	22	9	10	8	12
<i>Dresh.-Helmi</i>	2144	2218	2319	3956	3711	2700	1679	620	2418
	193	204	187	218	220	206	188	95	189
<i>Epicoccum</i> sp.	1498	1406	2984	3777	1869	944	806	1147	1804
	155	170	193	216	185	130	126	114	161
<i>Ganoderma</i> sp.	1690	4004	6708	1760	1297	1568	1355	14,761	4143
	170	192	195	150	128	152	142	150	160
<i>Leptosphaeria</i> sp.	2022	6124	6151	3647	7681	4114	3762	1932	4429
	158	192	165	160	174	180	161	124	164
<i>Pithomyces</i> sp.	156	153	231	125	159	114	114	191	155
	32	35	50	33	37	28	32	44	36
<i>Pleospora</i> sp.	1864	2810	1747	5807	4163	3052	3090	814	2918
	188	203	160	198	207	208	195	112	184
<i>Stemphylium</i> sp.	875	961	862	1926	1679	850	822	101	1010
	137	148	127	188	169	136	140	31	135
Thelephoraceae	1259	2643	4001	389	3310	1203	1090	1893	1974
	124	161	161	74	167	114	121	116	130
<i>Torula</i> sp.	753	729	1173	2618	1120	750	772	326	1030
	102	104	128	185	128	101	117	53	115
Venturiaceae	138	257	128	33	204	103	80	451	174
	25	31	20	11	24	15	20	24	21
Xylariaceae	634	1812	3165	588	1153	594	481	2898	1416
	105	152	177	96	135	98	90	153	126

Table 1 continued

Taxa	Stations								Mean
	Barcelona	Bellaterra	Girona	Lleida	Manresa	Tarragona	Roquetes-Tortosa	Vielha	
Total	254,071	420,935	483,460	683,283	572,056	280,078	395,407	250,913	417,526

Data yearly periods: Barcelona and Bellaterra (1995–2014), Girona, Lleida, Manresa and Tarragona (1996–2014), Vielha (2004–2014) and Roquetes-Tortosa (2006–2014). *Asper.-Penic*: *Aspergillus* sp.-*Penicillium* sp.; *Dresh.-Helmi*: *Drechslera* sp.-*Helminthosporium* sp

Alternaria sp. presented the highest values of α , while *Chaetomium* sp., *Pithomyces* sp. and *Leptosphaeria* sp. the lowest (Table 2). With regard to the taxa, it was also observed that the conidiospores types showed high and medium values of α , followed by the basidiospores types with medium values, and ending with the ascospore types with low values. Considering that the α parameter was an indirect measurement of the CV of the daily concentration in the annual series, it was also established that the taxa with the highest values in this parameter had less heterogeneity in their concentration throughout the year. This coincided with the taxa which reported an higher α for being present more days in a year, except for Coprinaceae (NND upper than 270) which presented a more heterogeneous distribution in its concentrations (Table 2).

In general, the results of fit of Chi-square test (Supplementary material) showed high values of significance in all taxa, being *Alternaria* sp., *Pleospora* sp. and Coprinaceae the ones showing the best fit to the gamma distribution, while *Aspergillus* sp.-*Penicillium* sp., *Agrocybe* sp. and *Drechslera* sp.-*Helminthosporium* sp. presented the worst fit. In regard to the results by stations, we observed that Tarragona and Roquetes-Tortosa presented the highest fits, whereas Barcelona and Bellaterra reported the lowest ones.

The generic classification based on the α values is shown in Table 3. The first category was made up of *Cladosporium* sp. in all stations, with mean α values greater than 0.60 and 253 NND. The second category was made up of nine taxa, with *Alternaria* sp. and *Ganoderma* sp. the only ones which presented the same behavior in the eight stations. The α values varied between 0.30 and 0.59, and 149 and 288 NND.

The third category consisted of 10 taxa, being *Pleospora* sp. the taxon with the same behavior in all sampling localities. The α values ranged from 0.20 to 0.29 with mean NND values between 104 and 278. The fourth category was made up of 11 taxa, where *Leptosphaeria* sp. and *Aspergillus* sp.-*Penicillium* sp. were classified equally for all stations. The α value varied between 0.10 and 0.19, and the NND between 42 and 164. Finally, the fifth category was comprised of four taxa showing α values under 0.10 and NND close to 30.

A representation of the spatial distribution in Catalonia of the 18 fungal spore taxa selected based on the five levels established for α and the NND values is shown in Fig. 3. The α parameter was employed as the criteria to classify, while NND was employed as secondary parameter to define the categories. In order to understand the information shown in this figure, it is necessary to check Table 3. Six taxa were framed on the same level of α in all stations (*Cladosporium* sp., *Alternaria* sp., *Ganoderma* sp., *Pleospora* sp., *Leptosphaeria* sp. and *Aspergillus* sp.-*Penicillium* sp.), eight taxa in two levels of α (*Drechslera* sp.-*Helminthosporium* sp., *Stemphylium* sp., Coprinaceae, *Pithomyces* sp., *Chaetomium* sp., Thelephoraceae, *Agrocybe* sp. and *Agaricus* sp.) and four of them in three α levels (*Arthrinium* sp., *Epicoccum* sp., Xylariaceae and *Torula* sp.).

4 Discussion

Fungi are an important component of ecosystems. Some fungi are widely distributed, while other are limited to certain habitats. The studies based on airborne fungal spores can help to define the

Table 2 Summary of the α , β and NND parameters per taxa studied that presented less than two annual series with less than 10 NND

Taxon (spore type)	α Mean (min–max)	β Mean (min–max)	NND Mean (min.–max.)
<i>Agaricus</i> sp. (B)	0.198 (0.012–0.874)	71.5 (5.1–740.9)	152 (18–309)
<i>Agrocybe</i> sp. (B)	0.773 (0.047–1.330)	500.3 (0.3–6356.5)	238 (20–362)
<i>Alternaria</i> sp. (C)	0.511 (0.116–1.072)	97.6 (10.4–712.3)	293 (78–358)
<i>Arthrimum</i> sp. (C)	0.201 (0.013–0.776)	22.8 (3.8–77.0)	132 (16–231)
<i>Aspergillus</i> sp.- <i>Penicillium</i> sp. (C)	0.203 (0.010–5.621)	162.2 (21.5–996.6)	95 (12–246)
<i>Chaetomium</i> sp. (A)	0.080 (0.005–0.254)	12.5 (2.4–448.8)	36 (10–94)
<i>Cladosporium</i> sp. (C)	0.798 (0.324–2.340)	1391.7 (245.0–10,620.0)	256 (66–361)
Coprinaceae (B)	0.289 (0.047–1.141)	357.2 (5.6–1843.2)	279 (23–356)
<i>Drechslera</i> sp.- <i>Helminthosporium</i> sp. (C)	0.026 (0.003–0.114)	17.1 (2.7–101.7)	197 (19–314)
<i>Epicoccum</i> sp. (C)	0.446 (0.032–0.973)	19.5 (2.8–92.3)	166 (13–305)
<i>Ganoderma</i> sp. (B)	0.313 (0.026–1.027)	33.3 (3.4–255.3)	166 (10–275)
<i>Leptosphaeria</i> sp. (A)	0.356 (0.030–0.679)	96.6 (3.1–1024.1)	167 (13–324)
<i>Pithomyces</i> sp. (C)	0.164 (0.028–0.411)	5.6 (2.6–24.3)	38 (13–78)
<i>Pleospora</i> sp. (A)	0.088 (0.011–0.187)	42.3 (7.2–397.1)	187 (27–278)
<i>Stemphylium</i> sp. (C)	0.266 (0.089–0.525)	10.3 (2.7–48.3)	140 (11–250)
Thelephoraceae (B)	0.328 (0.043–0.748)	33.8 (2.7–607.4)	135 (22–261)
<i>Torula</i> sp. (C)	0.222 (0.017–0.979)	14.3 (5.5–98.4)	119 (10–272)
Xylariaceae (A)	0.225 (0.010–0.752)	20.7 (4.1–269.3)	129 (22–265)

NND: Non-null days. Min: minimum. Max: maximum.
Spore type: A, ascospore;
B, basidiospore; C,
conidiospore

geographical distribution of fungi in a region. For each fungal taxon, the seasonal and interannual behavior of its airborne spores may vary considerably so that the spatial–temporal comparisons are very difficult to obtain. In this work, we used a gamma distribution model because it can describe the distribution of an annual data series and, additionally, allows the

comparison of two or more taxa from two or more places with similar or different behavior. The results of our study showed that airborne spores of *Cladosporium* sp., Coprinaceae and *Agrocybe* sp. were the most abundant in Catalonia, a fact that coincided with other studies (Li and Kendrick 1995; Díaz et al. 2006; Oliveira et al. 2009, 2010; Mallo et al. 2011; Recio

Table 3 Generic classification of taxa through the α parameter of the gpdf model

	Taxon	Station in the category	Mean of the category		
			α	β	NND
Categories according to α	<i>Cladosporium</i> sp.	All	0.780	1396.5	253
	<i>Alternaria</i> sp.	All	0.504	94.7	288
	Drech.-Helmi. (I)	Except VIE	0.476	17.7	204
	<i>Torula</i> sp. (I)	LLE	0.433	20.1	197
	<i>Epicoccum</i> sp. (I)	BTU/GIC/LLE/MAN	0.385	22.3	191
	<i>Ganoderma</i> sp.	All	0.353	38.9	164
	Coprinaceae (I)	BCN/GIC/VIE	0.351	316.9	272
	<i>Stemphylium</i> sp. (I)	Except VIE	0.348	10.9	149
	Xylariaceae (I)	GIC	0.327	38.3	177
	<i>Agrocybe</i> sp. (I)	BTU/GIC/LLE/MAN	0.317	561.1	246
	<i>Pleospora</i> sp.	All	0.259	42.2	184
	Coprinaceae (II)	Except BCN/GIC/VIE	0.249	398.2	278
	Xylariaceae (II)	Except GIC/VIE	0.246	20.8	125
	<i>Arthrimum</i> sp. (I)	BTU/GIC/LLE/MAN	0.246	22.5	148
	<i>Epicoccum</i> sp. (II)	BCN/TAU/TOR	0.239	13.8	137
	<i>Agrocybe</i> sp. (II)	BCN/TAU/TOR/VIE	0.236	442.7	224
	<i>Agaricus</i> sp. (I)	Except LLE/TAU/VIE	0.234	73.7	167
	Thelephoraceae (I)	Except LLE	0.232	37.4	142
	<i>Torula</i> sp. (II)	BTU/GIC/MAN/TOR	0.229	14.0	123
	Drech.-Helmi. (II)	VIE	0.220	9.7	104
	<i>Epicoccum</i> sp. (III)	VIE	0.190	23.8	114
	<i>Arthrimum</i> sp. (II)	BCN/TAU/TOR	0.171	24.3	126
	Xylariaceae (III)	TOR	0.169	9.5	90
	Thelephoraceae (II)	LLE	0.168	7.7	74
	<i>Leptosphaeria</i> sp.	All	0.163	94.3	164
	<i>Torula</i> sp. (III)	BCN/TAU/VIE	0.159	11.9	85
	<i>Agaricus</i> sp. (II)	LLE/TAU/VIE	0.150	64.9	122
	Asper.-Penic	All	0.133	163.9	94
	<i>Chaetomium</i> sp. (I)	LLE	0.129	9.7	42
	<i>Pithomyces</i> sp. (I)	GIC/VIE	0.114	6.4	48
	<i>Pithomyces</i> sp. (II)	Except GIC/VIE	0.086	5.2	35
	<i>Stemphylium</i> sp. (II)	VIE	0.086	4.0	31
	<i>Chaetomium</i> sp. (II)	Except LLE/VIE	0.077	13.6	35
	<i>Arthrimum</i> sp. (III)	VIE	0.045	16.6	33

BCN: Barcelona; BTU: Bellaterra; GIC: Girona; LLE: Lleida; MAN: Manresa; TAU: Tarragona; TOR: Roquetes-Tortosa; VIE: Vielha. NND: non-null days. Asper.-Penic.: *Aspergillus* sp.-*Penicillium* sp.; Dresh.-Helmi.: *Drechslera* sp.-*Helminthosporium* sp.

et al. 2012). The ASIn variation observed across the study region can be explained by the complexity of factors that affected the presence of these airborne spores such as the physiology of the taxon, the weather conditions or the land use (Carlile et al. 2001; Boddy

et al. 2014). The highest spore concentration values reported at inland in Catalonia, especially in Lleida, can be attributed to the land use (mainly agricultural), whereas the lowest annual concentration values at the mountain and coastal regions can be attributed to the

respective temperatures likely to be out of the optimum range of sporulation for the taxa studied (Skjoth et al. 2016; Vélez-Pereira et al. 2016).

One of our objectives when applying the gamma distribution model was to use the values of α to show the aerobiological behavior of each taxon over the years in the same aerobiological station (temporal variation) as well as to compare their behavior between aerobiological stations (spatial variation). Airborne fungal spore *Cladosporium* sp. was the most stable throughout the years, while *Aspergillus* sp.-*Penicillium* sp. presented a sporadic behavior (α min-max, Table 2), a fact that was also indicated in Oliveira et al. (2010). Likewise, Girona was the station with the highest annual heterogeneity, while Barcelona and Vielha were the most homogeneous (Supplementary material). The greatest variability showed by Girona can be attributed to the greatest variation observed between the minimum and maximum temperatures during the study period (Fig. 2), which could be causing changes in sporulation. In the case of Barcelona and Vielha, the behavior of the temperature and water availability may favor the stability in the emissions. Barcelona showed the lowest thermal oscillation and Vielha the lowest temperature value, which could be limiting the increase in spore concentrations, and therefore, the annual variation. Similarly, the high records of annual rainfall and days with rainfall at both stations (Fig. 2) could be regulating the sporulation processes.

On the other hand, spatial comparisons are shown in Fig. 3. The six taxa distributed homogeneously in all stations were *Cladosporium* sp., *Alternaria* sp., *Ganoderma* sp., *Pleospora* sp., *Leptosphaeria* sp. and *Aspergillus* sp.-*Penicillium* sp. All of them were considered as cosmopolitans, reported frequently in the fungal aerobiological spectrum, except for the taxa *Aspergillus* sp.-*Penicillium* sp., which was reported with less frequency (Díaz et al. 2006; Mallo et al. 2011; Hasnain et al. 2012; Almaguer et al. 2013; Damialis et al. 2015). All of them were strongly influenced by the change of humidity in the Mediterranean climate, and their sporulation could be favored by the rainfall, though, especially in the taxa *Cladosporium* sp., *Alternaria* sp., *Pleospora* sp. and *Leptosphaeria* sp. (Rúa-Giraldo 2013).

With regard to the taxa that were present in two categories of the α values scale, *Drechslera* sp.-*Helminthosporium* sp. and *Stemphylium* sp. taxa stand

out because Vielha station showed a different behavior to the rest of stations of the study area. This can be explained by the need for warm temperatures for these taxa to achieve an optimum sporulation (Rossi et al. 2005; Grinn-Gofroń and Bosiacka 2015).

In regard to Coprinaceae taxon, its spatial distribution might respond more to the precipitation in the area, which favors its sporulation (Morales et al. 2006), than to the environment where many of its species grow (well-fertilized pastures, parks, roadsides, cleared land, forests in general). In this particular case, the highest α values were recorded in Vielha, Girona and Barcelona, the three stations which presented the highest values of annual rainfall (Fig. 2).

Despite *Pithomyces* sp. being recognized as a taxon of dry air and less frequent in the aerobiological spectrum (Rúa-Giraldo 2013), our results show a greater stability in the stations of Girona and Vielha, with the highest values of rainfall, days with rainfall and humidity of the studied stations. This coincided with Domsch et al. (2007), who claimed that the largest sporulations of *Pithomyces* sp. happen after the rainfall. The difference among the various studies can be explained in terms of the low frequency of the taxon in the spectrum and in terms of being reported with the highest concentrations during the summertime (Kasprzyk et al. 2004; Stepalska and Wołek 2005; Oliveira et al. 2009; Mallo et al. 2011; Hasnain et al. 2012), when rainfall was less intense and frequent, and the temperatures were the highest (Fig. 2).

Chaetomium sp. was described as a fungi indicator of humidity, especially in indoor places (Codina et al. 2008; Andersen et al. 2011; McMullin et al. 2012), as well as an opportunistic colonizer in plant debris, cereal crops or their seeds and its sporulation temperature oscillated between 18 °C and 20 °C (Domsch et al. 2007). These characteristics allowed us to explain the big difference in the α values at Lleida station with respect to the other stations, which showed low frequency and low levels of this taxon (Table 1). Apart from the high agricultural land use in Lleida, with cereal plantations and forage grasses (Departament d'Agricultura, Ramaderia, Pesca i Alimentació et al. 2014), the highest values of relative humidity during the autumn and the winter can benefit the presence of this taxon in this specific area.

The Thelephoraceae taxon showed a similar spatial distribution to *Chaetomium* sp. (except for Vielha), but with inverse values, with less stability in the



◀ **Fig. 3** Spatial representation of the average of α by taxon in the study area. D. Station discarded in the generic classification

concentrations in Lleida than in the rest of localities. This can be attributed to the water availability in the study area, as Thelephoraceae required a minimum accumulation of rainfall and high values of humidity to enable the growth of the basidioma (Ramírez-López et al. 2013). These conditions may be present in all stations (except Lleida) toward the end of the summertime and beginning of autumn, favoring the formation of the basidioma and later on the sporulation.

The ecology of *Agrocybe* sp. was complex to establish due to the high resistance to environmental stress of the species of this taxon and because they are saprobic mushrooms in localities with anthropogenic impact such as fields and pastures, borders with pastures and gardens, among others (Malysheva and Kiyashko 2011). These characteristics allowed us to partially explain the α distribution obtained, showing greater concentration stability in the inland area, and varying in the mountain area (Vielha), because the colder conditions, and in the coastal area (Barcelona, Tarragona y Roquetes-Tortosa) because the warmer environment.

Agaricus sp. was reported as saprobic of litter and remains of decaying vegetables (Kerrigan et al. 1998). These characteristics explained the behavior of the α parameter with greater stability in rural/urban environments, except for Girona, which in addition to be considered an urban area, is located in the area with the second greatest forest cover in Catalonia (Institut d'Estadística de Catalunya 2014).

As for the taxa that were present in three α values of the scale, the behavior of *Arthrinium* sp. and *Epicoccum* sp. stand out. Both taxa were established as fungi with a frequency ranging from moderate to low in the aerobiological spectrum in Asia and South America (Hasnain et al. 2005; Ho et al. 2005; Mallo et al. 2011), although in Europe *Epicoccum* was presented more frequently (Kasprzyk et al. 2004; Oliveira et al. 2009). Both taxa showed more frequencies in warm climate, although *Epicoccum* sp. showed greater facility to sporulate in warm temperatures than *Arthrinium* sp. (Stępańska and Wołek 2005; Domsch et al. 2007; Crous and Groenewald 2013). These relationships

with temperature could explain the behavior of α . The inland stations (Bellaterra, Girona, Manresa and Lleida) showed greater α values, due to their temperate climate, followed by medium values of α in the coastal zone (Barcelona, Tarragona, Roquetes-Tortosa) with warm temperatures and ending with lowest α values in the mountain area (Vielha) with cold temperatures. All this information supports that these taxa can be used as bioclimatic indicators of temperature.

The habitat of the taxon Xylariaceae is bark of decaying trees, trees or branches of trees, leaf litter and animal manure (Whalley 1985, 1996). Likewise, it was reported in a great variety of climatic areas, even though some species from this family showed restrictive characteristics, requiring freezing temperatures for ascospore germination and low temperatures for their growth (Whalley 1985, 1996). Girona was the station with mean low temperature values close to freezing and it was the one showing the greatest values of α , while Roquetes-Tortosa showed the highest average temperature in the sampling area and showed the lowest values in the α parameter.

Finally, *Torula* sp. was reported as a saprobic taxon of temperate zones, with preference for grasses, but it was also recognized as a cosmopolitan taxon (Domsch et al. 2007). This last characteristic was confirmed by the aerobiological studies carried out by Stępańska and Wołek (2005), Oliveira et al. (2010) and Mallo et al. (2011) who reported that this taxon was present in the air with moderate to high frequency. However, in our study, the behavior of the α parameter was the most variable appearing as the only fungal taxon with four levels of α . It could be justified by the land use by grass crops. According to the Departament d'Agricultura, Ramaderia, Pesca i Alimentació et al. (2014), Lleida was the area with greater land use with crops followed by Manresa, Girona, Roquetes-Tortosa, Bellaterra, Tarragona, Barcelona and Vielha. The α values obtained in this study correspond to this distribution of crops across Catalonia.

In general, with the obtained results of the α parameter, it can be observed that the level of airborne fungal spores can be used as an indicator of bioclimatic factors such as temperature (*Agrocybe*, *Drechslera* sp.-*Helmintosporium* sp. and *Stemphylium* sp.), water availability (Coprinaceae, *Pithomyces* sp., Thelephoraceae and Xylariaceae) or the interaction of several of them (*Arthrinium* sp. and *Epicoccum* sp.), as

well as to indicate certain types of land use (*Agaricus* sp., *Chaetomium* sp. and *Torula* sp.). Moreover, based on the results of this study, we can establish a generic classification of spore types grouped by the similarity of their α parameter. In this way, in Catalonia, the number of taxa needed to understand the general airborne fungal dynamic can be reduced to five representative taxa (one for each α category). This would facilitate the management of aerobiological databases and would also allow us to more efficiently study the atmospheric dynamics of the different taxa. Focusing on the aerobiological study of *Cladosporium* sp., *Alternaria* sp., *Pleospora* sp., *Lepthosphaeria* sp. and *Phytomyces* sp. we could interpret the behavior of 20 taxa present in the atmosphere of Catalonia.

5 Conclusions

The gamma distribution model was valid when describing the behavior of annual series of daily concentrations of airborne fungal spores in Catalonia, which allowed us to undertake spatiotemporal comparisons. Taking the results of the α parameter into consideration, a generic classification into five categories had been proposed. The results identified the taxa that indicate land use or the bioclimate. The proposed generic classification could help to make more efficient the management of the aerobiological database of Catalonia, since the study of the annual dynamics can be reduced to a smaller number of representative taxa, one for each category, and this could also be applied in the development of prediction models.

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Availability of data and materials Authors declare that if required, they can send their datasets as supplementary material.

Compliance with ethical standards

Conflict of interest Authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethics approval For this type of study, an approval of an Ethical Committee is not necessary.

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