Estimating *Aspergillus fumigatus* exposure from outdoor composting activities in England between 2005 and 14

B. Williams [a,*,1], P. Douglas [b,c,d,1], A. Roca Barcelo [b,d], A.L. Hansell [b,d,e,f], E. Hayes [a]

[a] Air Quality Management Resource Centre, University of the West of England, Faculty of Environment and Technology, Coldharbour Lane, Bristol BS16 1QY, UK
[b] UK Small Area Health Statistics Unit, MRC-PHE Centre for Environment and Health, Imperial College London, London W2 1PG, UK
[c] Population Health and Occupational Disease, National Heart and Lung Institute, Imperial College, London SW3 6LR, UK
[d] National Institute for Health Research Health Protection Research Unit (NIHR HPRU) in Health Impact of Environmental Hazards, Department of Epidemiology and Biostatistics, Imperial College London, London W2 1PG, UK
[e] Directorate of Public Health and Primary Care, Imperial College Healthcare NHS Trust, London W2 1NY, UK
[f] Centre for Environmental Health and Sustainability, George Davies Centre University of Leicester, University Road, Leicester LE1 7RH, UK

ARTICLE INFO

ABSTRACT

Bioaerosols, ubiquitous in ambient air, are released in elevated concentrations from composting facilities with open-air processing areas. However, spatial and temporal variability of bioaerosols, particularly in relation to meteorology, is not well understood. Here we model relative concentrations of *Aspergillus fumigatus* at each postcode-weighted centroid within 4 km of 217 composting facilities in England between 2005 and 2014. Facilities were geocoded with the aid of satellite imagery. Data from existing bioaerosol modelling literature were used to build emission profiles in ADMS. Variation in input parameters between each modelled facility was reduced to a minimum. Meteorological data for each composting facility was derived from the nearest SCAIL-Agriculture validated meteorological station. According to our results, modelled exposure risk was driven primarily by wind speed, direction and time-varying emissions factors incorporating seasonal fluctuations in compostable waste. Modelled *A.fumigatus* concentrations decreased rapidly from the facility boundary and plateaued beyond 1.5–2.0 km. Where multiple composting facilities were within 4 km of each other, complex exposure risk patterns were evident. More long-term bioaerosol monitoring near facilities is needed to help improve exposure estimation and therefore assessment of any health risks to local populations.

1. Introduction

The European Union Waste Framework Directive (2008/96/EC), transposed into UK law as the Waste (England and Wales) (Amendment) Regulations, 2012, requires the UK and other Member States to recycle 50% of their Waste from Households by 2020 (currently at 45.2% in the UK (Department of Environment, Food and Rural Affairs ((Defra), 2018a)), resulting in a significant increase in waste previously destined for landfill being recycled and composted. Industrial-scale composting, more widespread as a result of the Directive, contributes to elevated emissions of bioaerosols, particularly when compost is agitated (e.g. shredded, turned or screened) (Danneberg, 1997; Taha et al., 2006).

Bioaerosols, sometimes referred to as airborne biological agents, primary biological aerosol particles, and biological air pollution, are ubiquitous in the ambient environment, comprise a complex mixture of bacteria, fungi, pollen, particulate matter and fragments, constituents and by-products of cells, including endotoxin (Pearson et al., 2015). In occupational settings, bioaerosols have been widely associated with adverse health outcomes, particularly respiratory-related illnesses, such as increased cough, phlegm, frequency of developing a cold, bronchitis, and shortness of breath (Aatamilla et al., 2011; Herr et al., 2003a; Pearson et al., 2015; Searl, 2008). In the UK, these activities are mostly outdoor and consequently emission and dispersion is difficult to contain and control and thus may reach nearby communities (Douglas et al., 2016a). Unfortunately, research assessing health impacts on these communities is scarce. A systematic review conducted by Pearson et al. (2015) summarised the evidence from the few available studies, some of which have reported a higher risk of developing respiratory-related illness in communities living near a composting facility (Aatamilla et al., 2011; Herr et al., 2003a and b). A recent ecological study examined risk of respiratory-related hospital admissions in relation to distance from composting

* Corresponding author.
E-mail address: Ben3.Williams@uwe.ac.uk (B. Williams).
[1] Joint first authors.

facilities, and found a small non-statistically significant increased risk nearer to the site, using a continuous measure of distance (Douglas et al., 2016a). However, these studies relied on distance from composting facility as a proxy for bioaerosol exposure, did not account for seasonal effects, wind direction or other local differences between composting facilities, which would have led to some exposure misclassification and may have made associations harder to detect.

Bioaerosol sampling is an important tool to understand the biological composition of emissions from sites and the potential impact of a site on its environment. However, current monitoring regimes are very infrequent and are unlikely to truly represent the variability in emissions and dispersion temporally or spatially. In addition, running a monitoring campaign using currently available instruments and analytical frameworks would be expensive and likely cost prohibitive to many operators.

Dispersion models have the potential to estimate bioaerosol concentrations at high spatial and temporal resolution, and thus provide an improved exposure assignment (Douglas et al., 2017b). Recent developments include a sensitivity analysis and a model validation study (Douglas et al., 2016b; 2017a). These studies determined which *A. fumigatus* modelling inputs are most important when estimating bioaerosol emissions from composting facilities and what model input values resulted in the best fit between modelled outputs and bioaerosol measurement data. Although these studies were conducted using the limited monitoring data available, results suggested that dispersion modelling can be applied to multiple composting facilities to make reasonable predictions of *A. fumigatus* dispersion resulting from outdoor composting activities.

The aim of this study was to produce the first population exposure estimates, derived using a dispersion model, near all operating large-scale outdoor composting facilities in England between 2005 and 2014 using existing *A. fumigatus* modelling parameters. We hypothesise that airborne micro-organism dispersion is primarily driven by wind speed and direction, therefore we investigated spatial patterns of *A. fumigatus* dispersion around each facility (4 km), with specific emphasis on the influence of wind speed and direction on exposure estimates.

2. Materials and methods

2.1. Study area, facility selection and geocoding

In England, composting facilities require a permit to operate if they store or treat >60 tonnes of compost at any one time (Defra, 2014). All permitted composting facilities in England operating between 2005 and 2014 were included in the study using information provided by, and data interpretation discussed with, the Environment Agency (EA). The data included permit number, operator, permitted throughput of waste, composting activity type (e.g. open windrow, in-vessel etc.), facility address and a grid reference (8 digit British national grid reference) for 313 facilities that had a valid permit to operate at the end of 2014. The date a composting facility obtained a permit to operate was the assumed operational start date. The data contained no information on closing date, so it was assumed that once opened, the facility did not close. Only facilities that had an outdoor composting component (i.e. open windrow facilities, or enclosed facilities with an outdoor composting element), were included, as per Douglas et al. (2016a). National grid references and facility addresses were used to accurately locate facilities using aerial maps in Google Earth Pro (Douglas et al., 2016a). Outdoor composting areas were geocoded by tracing the perimeter of the outdoor composting activity areas: 217 facilities were geocoded; 96 facilities were excluded either because

they did not contain an outdoor component, were duplicated, or it was not possible to locate the facility based on the information provided. Of the geocoded facilities, 152 (70%) were fully open windrow facilities, of which 53 were assumed operational during the entire study period. 65 (30%) of the geocoded facilities were outdoor elements of a facility with an in-vessel composting component, of which 13 were assumed operational during the entire study period (Fig. 1).

Postcodes within 4 km radius of each geocoded composting facility were studied. Douglas et al. (2016a) noted that bioaerosol concentrations were likely to reach background concentrations by ~2.5 km; however, wind speed and direction were not included in their analysis as their study focussed on exposure by distance only and not the influence of wind speed and direction. Consequently, the radius in this study was increased to 4 km to capture the impact of including these parameters on dispersion.

2.2. Dispersion modelling

Modelling was undertaken using Atmospheric Dispersion Modelling System (ADMS) (Version 5.1) as it has been extensively used and is considered, at present, to be the most appropriate tool to assess bioaerosol dispersion from composting facilities (Douglas et al., 2017b). Modelling focussed on *A. fumigatus,* a pathogenic thermophilic filamentous fungi which is; (i) associated with the onset of, or exacerbations of, many diseases (Klich, 2009); (ii) is known to often be in elevated concentrations during specific activities at composting facilities (Pankhurst et al., 2011); (iii) is included in the EA's position statement on acceptable levels from composting (Defra, 2018b); (iv) is widely monitored at composting facilities (Pearson et al. 2015).

2.2.1. ADMS source parameters

A source height of 3 m, a pollutant exit velocity of 2.95 m s^{-1} and pollutant temperature of 29 °C, found to be optimal model inputs in a recent dispersion model validation study (Douglas et al., 2016b), was assumed for every composting facility.

Emissions from composting facilities were represented in ADMS as area sources, as considered appropriate in Douglas (2016b) based on the geocoded perimeter described in Section 2.1. ADMS requires all polygons to be convex (CERC, 2016), however 81 (out of 217) composting facilities included concave boundaries. As a result, these were manually adjusted using ArcMap version 10.4 to remove concavity, consequently increasing the area of 81 facilities. The change in area ranged from 2% to 176% whilst, on average it increased by 21.6%.

2.2.2. ADMS pollutant parameters and emission rate

A. fumigatus cells collected from compost sources were measured as <2 μm by Tamer-Vestlund et al. (2014) and considered to be 2–3 μm by Williams et al. (2013). Consequently, PM$_{2.5}$ was considered an appropriate proxy for modelling purposes. Bioaerosol concentrations are commonly derived by using culture-based analytical methods, resulting in concentrations reported with units of Colony Forming Units per cubic metre (CFU m^{-3}); however ADMS (among other models) does not have the option to model concentrations in these units. In line with Douglas et al. (2017a) and Stocker et al. (2015), a direct conversion to g m^{-3} (i.e. 1 CFU m^{-3} = 1 g m^{-3}) was used instead.

Time varying emission factors (TVEF) were added to reflect daily and seasonal variability in bioaerosol emission rates dispersion based on facility activity. To reflect daily variability, an emission rate of 9×10^6 g m^{-2} s^{-1} was used for operational periods (assumed to be 8 am and 5 pm from Monday to Friday), as per (Douglas et al., 2017a); and an emission rate of 11×10^3 g m^{-2} s^{-1} for dormant hours (the rest of the time), based on Taha et al.
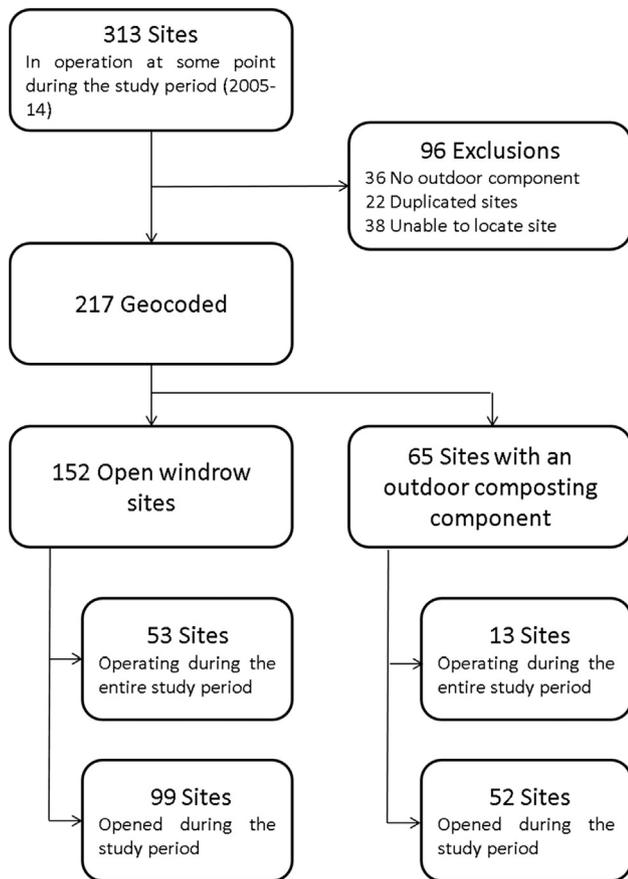
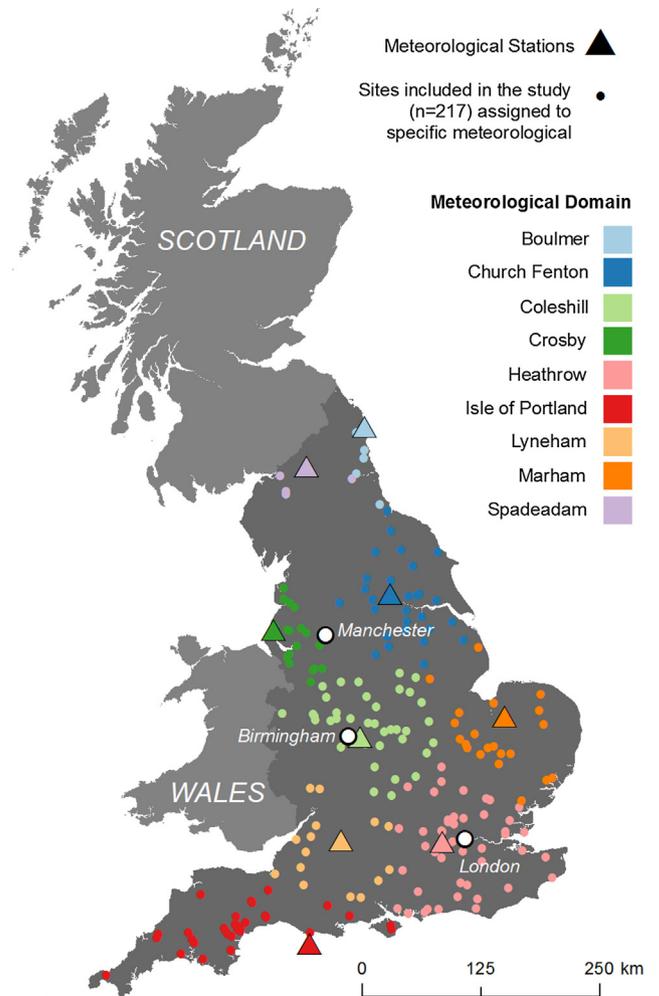Fig. 1. The number of composting facilities with an outdoor composting component included in the study.

Fig. 2. Locations of composting facilities included in the study. The locations of the meteorological stations used in the study are also depicted, highlighting which composting facilities were assigned to each by comparative colour.

(2006). To reflect seasonal variability, monthly variations were developed using monthly recycling statistics on composting tonnage obtained from Defra (Defra, 2015, 2016, 2017), which were offset by a month to account for retention of waste on site.

2.2.3. ADMS meteorological inputs

As a minimum, ADMS requires wind speed, wind direction, the Julian day number, time of day and cloud cover (wind speed, wind direction and sensible heat flux, or reciprocal of Monin-Obukhov length may also be used) (CERC, 2016). Data were obtained from nine meteorological stations across England assigned to each composting facility based on their proximity. The approach followed was as used in the Simple Calculation of Atmospheric Impact Limits agriculture (SCAIL-Agriculture) screening tool (SCAIL, 2018) and prompted by the lack of on-site meteorological stations. SCAIL-Agriculture statistically-selects meteorological data that is representative of the weather in that area (Hill et al., 2014). The nine meteorological stations used were Boulmer, Church Fenton, Coleshill, Crosby, Heathrow, Isle of Portland, Lyneham, Marham and Spadeadam (Fig. 2).

In this study, rainfall was not considered as a meteorological variable as; (i) the impact of rainfall on bioaerosols emitted from composting facilities is unknown; and (ii) we are unable to validate the effects of rainfall as current established bioaerosol monitoring techniques (set out in the M9 Technical Guidance note (Monitoring M9): Environmental modelling of bioaerosols at regulated facilities, (EA, 2017)), forbids samples to be taken in wet weather conditions.

Daily Meteorological data from each meteorological station were downloaded for the entire study period from the Centre for Environmental Data Archival (CEDA) (CEDA, 2017) in surface synoptic observations (SYNOP) format. Data were cleaned and transformed into the correct format for ADMS. Data from Boulmer and Church Fenton meteorological stations were missing for the last 19 and 377 days of the 2014 respectively, and therefore data from the next nearest meteorological station (Albemarle for Boulmer and Dishforth for Church Fenton) was used for these periods. To assess comparability, Spearman's correlations of data from the original and replacement stations were conducted.

Urban facilities were assigned a surface roughness of 1 m and rural areas were assigned a surface roughness of 0.3 m, representing pre-defined surface roughness values based on land use within ADMS (a surface roughness of 1 m representing cities and woodland areas, and a surface roughness value of 0.3 m representing agricultural areas) (CERC, 2016). 171 facilities were classed as rural, and 46 as urban, using the 2011 Office for National Statistics (ONS) urban-rural classification for the census output area (COA) that ach respective composting facility was located within. Three composting facilities fell within two COAs with different rural-urban classifications. In this case, the study team made an informed decision based on the land-use around the facility as observed from aerial maps.

2.2.4. ADMS pollutant prediction area

ADMS was set up to produce bioaerosol concentration estimates at residential postcodes (average 12 households per

postcode), whose area centroid was within 4 km of a geocoded composting facility. This exposure assessment was designed with a small area epidemiological study in mind and consequently, estimated concentrations were modelled at postcode, not across a grid or at address level. The X- and Y- coordinates of geometric postcode centroids were obtained from ONS. As X- and Y- coordinates of postcodes may change over time, data were extracted on a yearly basis for the 2005–2014 study period. Any duplicates (i.e. repeats of postcodes with the same X- and Y-coordinates) were removed. Remaining postcodes were imported into a Geographical Information System (ArcMap version 10.2, ESRI Inc.), and cropped so that only postcodes within 4 km of the 217 composting facilities included in the study remained.

2.2.5. ADMS advanced inputs

ADMS features advanced inputs to account for pollutant dispersion in complex terrain, or around buildings. It was not practical to include the effects of buildings or complex terrain within ADMS, as the study area was large (217 facilities, 4 km around each). Instead, surface roughness was altered to represent effects on pollutant turbulence and dispersion (see Section 2.2.3).

2.2.6. ADMS model outputs

ADMS outputs were presented as short term hourly sequential, enabling an estimated daily *A. fumigatus* concentration in g m^{-3} at each postcode included in the study area to be calculated (see Section 2.2.4).

3. Results

3.1. Study area

Table 1 summarizes the main characteristics of the study area, overall and stratified by the meteorological station the composting facilities were assigned to. Overall, the study covered a total surface area of 10,908 km^2, the study area was mostly rural (79.5%), and included 204,428 postcodes in England. Of all the included postcodes, 11,931 (5.8%) fell within 4 km of more than one composting facility (i.e. overlapping areas). The number of composting facilities assigned to each meteorological station ranged from a minimum of 4 around Spadeadam to a maximum of 47 around Heathrow.

3.2. Meteorology

As shown in Table 2, the mean temperature across the entire study period and area was 10.1 °C. In general, temperatures in July, August and September were double those recorded between October and March. The mean wind speed was 4.9 m s^{-1} and did not show much variability across the meteorological stations except for Coleshill and Isle of Portland which showed especially low (2.5 m s^{-1}) and high (7.2 m s^{-1}) wind speed, respectively. The predominant wind direction was from South/South-West, with the exception of the Isle of Portland with winds primarily from the East.

Table 1
Summary statistics for the study area and meteorological data for all composting facilities, stratified according to the meteorological station the facilities were assigned to.

	Total	Meteorological Station								
		Coleshill	Lyneham	Heathrow	Crosby	Boulmer	Isle of Portland	Spaed-adam	Marham	Church Fenton
No. of composting facilities, n(%)[*]	217 (100.0)	40 (18.4)	15 (6.9)	47 (21.7)	18 (8.3)	5 (2.3)	39 (18.0)	4 (1.8)	21 (9.7)	28 (12.9)
No. of postcodes, n(%)[*]	204,428 (100.0)	26,984 (13.2)	7170 (3.5)	102,619 (50.2)	17,399 (8.5)	4879 (2.4)	14,673 (7.2)	778 (0.4)	11,426 (5.6)	18,500 (9.0)
No. of postcodes in an overlap area, n(%)[*]/[**]	11,931 (5.8)	2346 (8.7)	0 (0)	5191 (5.1)	1376 (7.9)	10 (0.2)	2497 (17.0)	53 (6.8)	381 (3.3)	77 (0.4)
No. of facilities in rural areas, n(%)[***]	171 (79.5)	33 (82.5)	12 (80.0)	35 (77.8)	13 (72.2)	3 (60.0)	37 (94.9)	4 (100.0)	18 (85.7)	20 (71.4)
Study area (km^2)[****]	10,908	2011	754	2362	905	251	1960	201	1056	1407

[*] Percentage of the total modelled postcodes (unique postcodes over study period only, duplicates excluded).
[**] Postcodes that are within 4 km of more than one included composting sites.
[***] As defined by ONS rural/urban classification at census output area level for 2011?.
[****] Rounded to the nearest whole number.

Table 2
Summary statistics of the meteorological data for all composting facilities, stratified according to the meteorological station the facilities were assigned to.

	Total	Meteorological station								
		Coleshill	Lyneham	Heathrow	Crosby	Boulmer	Isle of portland	Spaed-adam	Marham	Church Fenton
Mean temperature for entire study period (°C, (SD))	10.1 (5.2)	10.0 (5.4)	9.9 (5.3)	11.5 (5.6)	10.6 (5.0)	9.3 (4.4)	11.3 (4.3)	7.5 (4.9)	10.2 (5.6)	9.9 (5.3)
Mean temperature for winter period (°C, (SD))[*]	5.2 (3.3)	5.1 (3.4)	4.9 (3.4)	8.9 (4.4)	5.8 (3.0)	5.2 (2.7)	6.8 (2.7)	2.9 (2.9)	4.9 (3.4)	5.1 (3.4)
Mean temperature for spring period (°C, (SD))[*]	11.5 (3.6)	11.8 (3.7)	11.7 (3.6)	6.2 (3.3)	12.1 (3.2)	10.3 (2.9)	11.8 (2.7)	9.0 (3.5)	12.1 (3.7)	11.6 (3.5)
Mean temperature for summer period (°C, (SD))[*]	15.5 (2.6)	15.6 ((2.6)	15.4 (2.5)	17.4 (2.7)	16.0 (2.1)	14.3 (1.9)	16.1 (1.4)	12.7 (2.4)	16.1 (2.7)	15.6 (2.4)
Mean temperature for autumn period (°C, (SD))[*]	7.9 (4.4)	7.6 (4.4)	7.6(4.3)	8.9 (4.4)	8.6 (4.2)	7.5 (3.6)	10.5 (3.7)	5.3 (4.0)	7.7 (4.5)	7.5 (4.4)
Mean wind speed, for entire study period (m s^{-1} (SD))	4.9 (2.5)	2.5 (1.5)	4.4 (1.7)	4.2 (1.7)	5.9 (3.0)	5.1 (2.2)	7.2 (3.0)	5.1 (2.5)	4.7 (2.1)	4.3 (2.0)
Dominant wind direction for entire study period (°)	197.8 (SSW)	197.5 (SSW)	190.3 (S)	194.6 (SSW)	196.3 (SSW)	205.2 (SSW)	79.6 (E)	185.6 (S)	192.9 (SSW)	210.2 (SSW)

[*] Seasons defined as follows: winter (January–March), spring (April–June), summer (July–September), and autumn (October–December).

3.3. Predicted Aspergillus fumigatus concentrations

Across all postcodes included in the study, the mean average modelled concentrations of *A. fumigatus* (Table 3) calculated across the study period, was 197.7 g m^{-3}, equivalent to 197.7 CFU m^{-3}, following the direct 1:1 comparison described by Douglas et al. (2017a). The 5th, 25th, 50th, 75th and 95th percentiles are also provided to illustrate the distribution of the daily average modelled concentrations. Table 3 indicates a large difference in predicted average *A. fumigatus* concentrations between the 95th percentile and the maximum value. This is likely to reflect the spatial distribution of estimated emissions, that there are a small number of postcodes with extremely high exposure estimates, as the table presents averaged estimated concentrations of all postcodes across the study period. There is variability in bioaerosol concentrations across the nine meteorological stations, which is likely to reflect the influence of meteorological indicators or area roughness on the modelled concentrations.

3.3.1. Temporal variability

Fig. 3 shows the average daily modelled concentrations for the entire study area and period. The lowest concentrations were recorded between day 30 and day 90 (chiefly February-March), whereas the highest concentrations occurred between days 190 and 210 (July). The clear discontinuity between seasons reflects the assigned TVEFs introduced into ADMS (see Section 2.2.2). Modelled concentrations were also closely related with fluctuations in ambient temperature; where annual average temperatures were higher, bioaerosol concentrations tended to be elevated (Spearman correlation coefficient r = 0.42, p-value <0.005).

3.3.2. Spatial variability

Fig. 4 shows the average bioaerosol concentration as modelled in each postcode by proximity to the nearest composting facility. Modelled concentrations were very high close to source, depleting rapidly, and then plateaued at approximately 1500–2000 m.

Table 3
Total mean (SD), minimum, maximum and percentiles (5th, 50th, 25th, 50th, 75th and 95th) of the average modelled concentrations of *Aspergillus fumigatus* (CFU m^{-3})[*] over the study period (only operating years included) across all postcodes[**]. Data provided for all composting facilities and by assigned meteorological station.

| | Meteorological station | | | | | | | | | |
	Total	Coleshill	Lyneham	Heathrow	Crosby	Boulmer	Isle of Portland	Spaedadam	Manham	Church Fenton
Mean (SD)	197.7 (602.4)	269.5 (411.2)	165.0 (237.5)	169.3 (803.1)	237.0 (225.0)	109.7 (338.5)	184.1 (277.7)	143.5 (206.2)	208.8 (427.0)	237.4 (291.4)
Minimum	0.2	0.4	12.7	19.3	5.7	0.2	13.8	20.4	26.1	39.7
5th percentile	51.5	103.6	55.4	65.0	35.5	5.5	34.2	35.7	44.5	95.7
25th percentile	90.0	160.3	86.5	84.4	91.5	7.3	93.1	57.9	80.0	136.2
50th percentile	155.2	240.3	135.4	117.6	236.3	51.7	138.4	85.1	167.5	197.6
75th percentile	249.4	333.5	193.3	212.1	295.3	115.2	203.7	127.0	258.6	291.9
95th percentile	417.2	467.6	303.3	341.1	491.3	340.0	405.7	542.7	486.2	460.7
Maximum	176034.6	58725.6	10249.9	176034.6	11718.9	10093.8	10806.8	3284.2	39070.5	23894.0

[*] PM$_{2.5}$ (g m^{-3}) was used as a proxy for *Aspergillus fumigatus* (see Section 2.2).
[**] Postcodes that are within 4 km of more than one composting facility included.
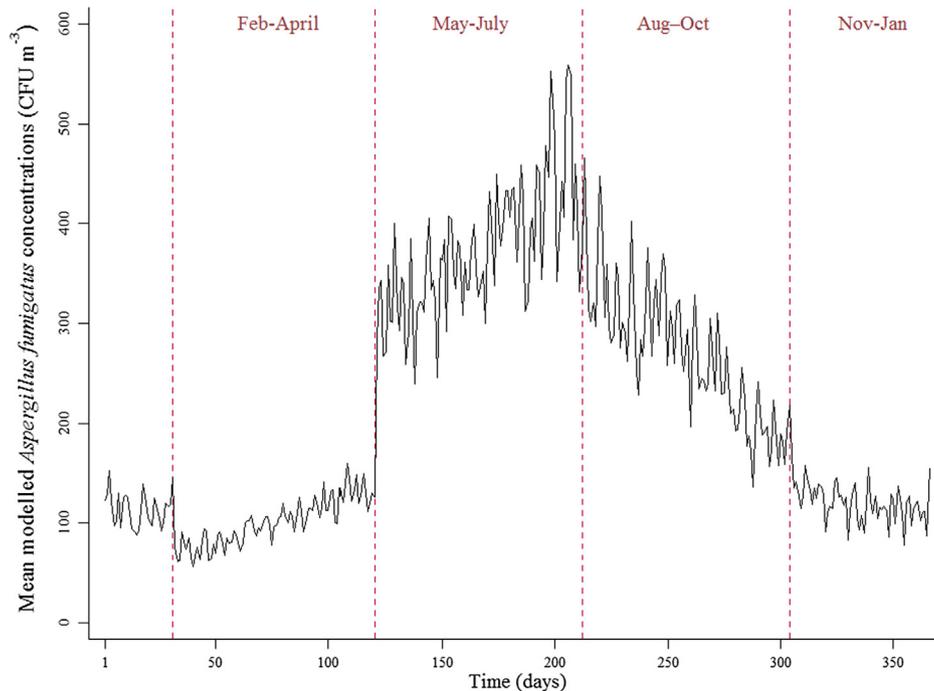
Fig. 3. Mean average daily modelled *A. fumigatus* concentration estimates for areas within 4 km of a composting facility, 2005–2014. Red dotted lines depict quarterly windows. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
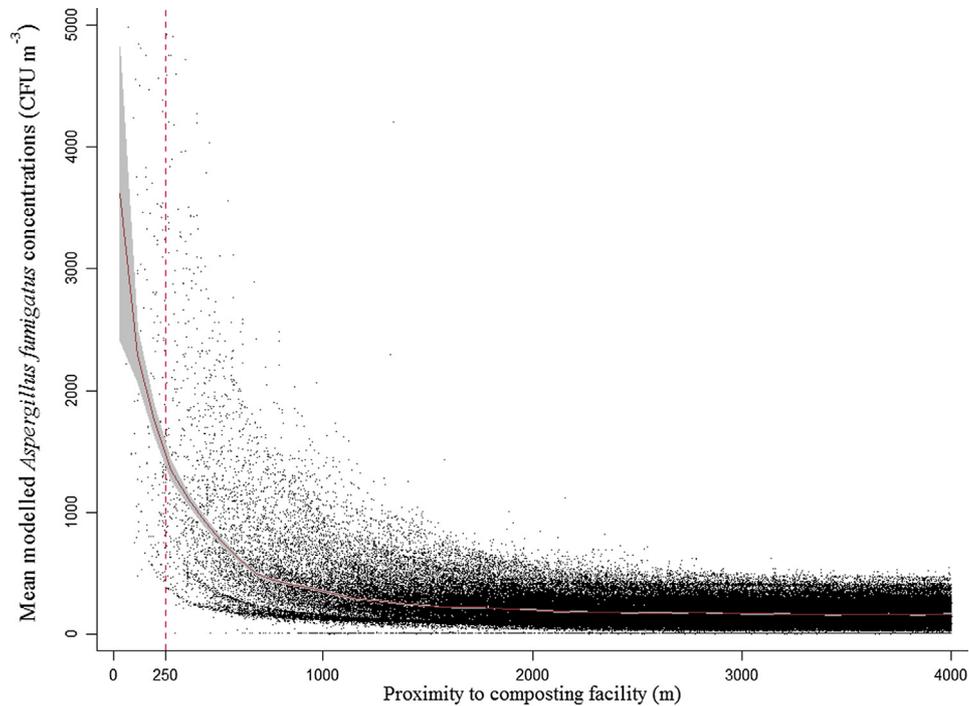
Fig. 4. Estimated mean *Aspergillus fumigatus* concentration at each postcode by proximity to composting facility, for the entire study period (2005–2014). The red line depicts the average (and the greyed area 95% confidence intervals) across all postcodes, estimated using the Kernel-weighted local polynomial regression (*Local cubic polynomial (degree = 3); bandwidth obtained using the rule-of-thumb (ROT) method; default Epanechnikov Kernel functions*). The red dotted line at 250 m represents the current set-back distance recommended by the EA (EA, 2017). (Note that this excludes estimated concentrations in areas that overlapped to avoid double counting). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Whilst most input parameters remained constant across each facility, meteorological data and TVEFs were variable and resulted in marked differences in the spatial dispersion of bioaerosols between facilities. Dispersion was driven mainly by wind speed and direction (dominant wind direction was SSW). Some postcodes in the highest quintile of modelled concentrations were in the furthest distance band modelled (3–4 km) (Fig. 5). This suggests that distance bands do not equate well with bioaerosol dispersion.

Complex dispersion patterns were observed where the 4 km radii around composting facilities overlapped (Fig. 6). The contribution of multiple emission sources alters the patterns of dispersion. Consequently, postcodes located downwind of both composting facilities receive a higher concentration. Overall, there were 11,931 postcodes (5.8%) within 4 km of more than one composting facility. Most of the overlaps were concentrated in SE England, more specifically within the meteorological station of Isle of
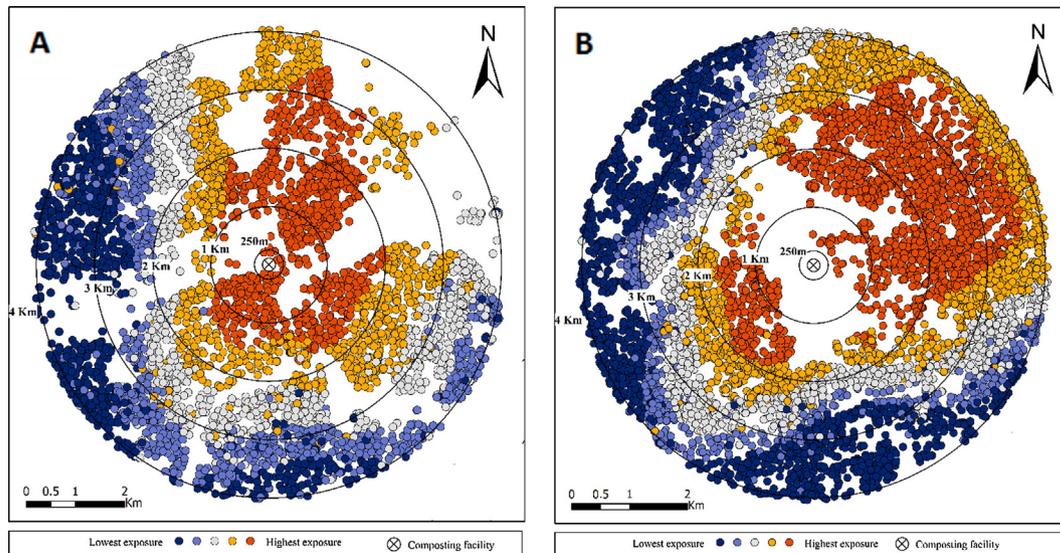
Fig. 5. Mean average modelled concentrations for the entire study period (presented as quintiles) at postcodes for two composting facilities for (A) a composting facility located in an urban area and (B) a composting facility located in a rural area. The black concentric circles represent distance bands at 250 m, 1000 m, 2000 m, 3000 m and 4000 m from the composting facility.
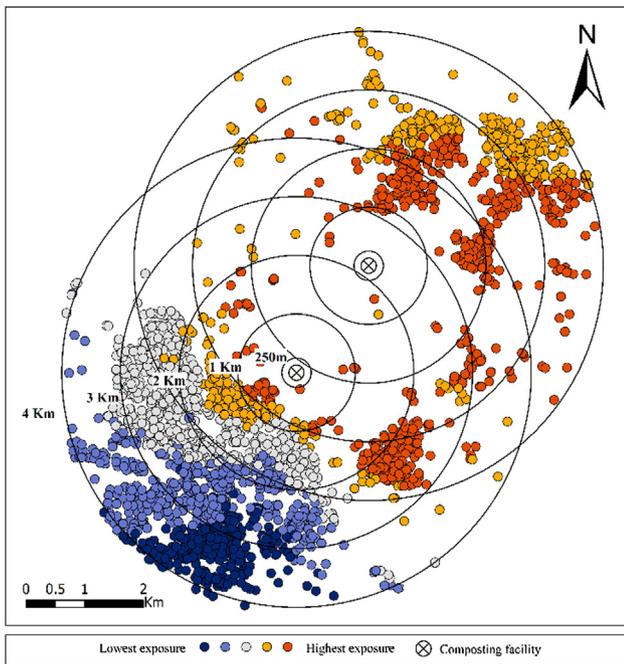
Fig. 6. Quintiles of the average modelled A. *fumigatus* concentrations at the postcode level for two composting facilities (A and B) with overlapping areas. The black concentric circles represent distance bands at 250 m, 1000 m, 2000 m, 3000 m and 4000 m from the composting facility, and each dot represents a postcode centroid.

Portland with a cluster of over 26 composting facilities, accounting for over 17% of the affected postcodes. ADMS automatically calculated concentrations in overlapping areas, as the area sources representing each site were entered into a single model run.

4. Discussion

This study attempted to comprehensively model bioaerosol concentrations due to emissions from composting facilities with open-air processes across an entire country using daily ADMS emissions modelling and selecting A. *fumigatus* as an indicator of bioaerosol exposure. Given computational challenges, we used well defined time-varying emissions and facility parameters and focussed particularly on the impact of meteorological and seasonal factors on spatial and temporal variability in exposure. This contribution represents the first time a screening assessment of A. *fumigatus* from composting facilities has been undertaken, on a national scale. Whilst it is recognised that dispersion modelling is a simplification of reality, this paper has used the best available evidence from the A. *fumigatus* modelling literature to carry out a rapid assessment of A. *fumigatus* exposure.

Our models predicted highest concentrations in July and lowest in February-March. These fluctuations were driven mainly by the TVEFs, but also by ambient temperature, as bioaerosol concentrations raised with increasing temperatures. Our results also showed that, in keeping with another exposure assessment study of incinerator emissions (Douglas et al., 2017c), distance bands are poor indicators of areas of highest exposure mainly due to the effect of wind speed and direction on dispersion patterns. This suggests that accounting for meteorological events provides a better estimate of spatial gradient in exposure for use in epidemiological studies compared to using distance from facility as a proxy for exposure, as previously used in Douglas et al. (2016a). In relation to distance, and in line with data summarised in Pearson et al., 2015, our model suggest that concentrations of bioaerosols drop

rapidly with distance, reaching background levels at approximately 2 km downwind. In addition, we found that exposure patterns become more complex when multiple facilities are present in close geographical proximities to each other (Fig. 5). Therefore, regulators should consider the presence of other anthropogenic sources of bioaerosols (e.g. intensive farming and sewage treatment facilities etc.) when assessing bioaerosol risk. Failure to account for these may lead to an underestimation of potential health hazards.

The range of the modelled concentrations, are within that reported in other studies. For example, Millner et al. (1980) modelled A. *fumigatus* dispersion and found that the number of particles per metre cubed (understood to be $CFU\ m^{-3}$) downwind from 'agitated compost piles' ranged from $1.2 \times 10^4\ CFU\ m^{-3}$ at 100 m to $990\ CFU\ m^{-3}$ at 1 km under stable atmospheric conditions. In addition, Taha et al. (2007) modelled A. *fumigatus* and found concentrations of $1 \times 10^4\ CFU\ m^{-3}$ within 100 m of the facility, reducing to $1 \times 10^2\ CFU\ m^{-3}$ at 1 km.

4.1. Strengths and limitations

Dispersion modelling is a simplification of reality. ADMS, a well-validated and widely used dispersion model, was used in this study. Model errors were reduced as much as possible by utilising the best available evidence from the modelling literature (Taha et al., 2007; Douglas, 2017a). However, there are several limitations when modelling bioaerosol emissions from composting facilities, as previously discussed in Douglas et al. (2017b) and detailed below. Consequently, resultant predicted concentrations should not be considered as quantitative but as a qualitative estimate of bioaerosol exposure, and viewed as a screening approach of relative risk associated with proximity to composting facilities. The model presented herein allows for an assessment of the impact of meteorological data on space-time patterns of bioaerosol concentrations, providing a more comprehensive assessment of bioaerosol exposure than distance from site as an exposure proxy, as used in previous studies (Aatamilla et al., 2011; Douglas et al., 2016a; Herr et al., 2003b).

An assessment of model performance was attempted using an existing dataset (Williams et al., 2013), however these data were considered unsuitable because of (i) a very small number of samples, (ii) inconsistent length of sampling durations, and (iii) frequent relocation of samplers with wind direction.

4.1.1. Study area, facility selection and geocoding

A major strength of this model is that it was conducted at the national level, including all permitted composting facilities in England which had an outdoor composting component and that were identifiable in the geocoding process; a similar approach was adopted in Douglas et al. (2016a). Composting site information were obtained from permit data provided by the EA of composting facilities with valid permits to operate in 2014. The permit issue date was considered the operational start and facilities were assumed to remain operational for the rest of the study period, as per Douglas et al. (2016a).

4.1.2. Source parameters, pollutant parameters and emission rate

A. *fumigatus* is the most commonly enumerated airborne microorganism species and frequently included in bioaerosol modelling and monitoring exercises (Domingo et al., 2015; Deacon et al., 2009; Douglas et al., 2017a). Despite this, the pollutant parameters and its dispersion properties are not well understood. For example, whilst the direct conversion of $CFU\ m^{-3}$ to $g\ m^{-3}$ is recommended in the literature (Douglas et al., 2017a; Stocker et al., 2015) it may not be representative of A. *fumigatus,* as CFU is a count of the presence, or lack thereof, of colonies and not their mass or size.

To account for daily and seasonal fluctuations in emission rates, TVEFs were included, allowing more nuanced modelling of bioaerosols year-round. However, more information is needed to develop these to reflect the wide variation across composting facilities, as each facility will have different characteristics (feedstocks, tonnage of waste handled, management practises, operational hours etc.) that may influence these. Determination of variations in facility-specific data were beyond the scope of this study. These assumptions in the emission rates and their daily and seasonal fluctuations are likely to have introduced some errors in dispersion concentrations. Despite this limitation, the spatial dispersion patterns described by our model should represent a reasonable approximation of reality and consequently, are adequate for use in epidemiological studies as a screening tool providing that resultant estimated concentrations are used as a qualitative measure of bioaerosol exposure.

Every care was taken to ensure that site boundaries identified using Google Earth Pro were delineated accurately. The geometry of composting facilities and the location of site activities may change over time from that identified in this study as sites expand and contract both seasonally and annually. Sites without wholly convex boundaries required adjustment to allow for their modelling, introducing an increase in area at affected sites and consequently a likely increase in modelled concentrations at respective postcode centroids. Whilst absolute concentrations are likely to increase, the spatial dispersion pattern will be largely unaffected as wind speed and direction are the primary drivers.

4.1.3. Meteorological data

Meteorological data from nine meteorological stations used in the SNIFFER study (Hill et al., 2014) were used in this study. Whilst this approach does not take into account local changes in meteorology at every composting facility, it does account for regional variations and is more robust than assuming a single, national prevailing wind direction or discounting meteorological conditions completely. Some data from two meteorological stations were missing (Boulmer and Church Fenton), and were replaced with data from the next nearest meteorological station with complete data (Albemarle and Dishforth respectively). A similar approach was adopted in a recent study estimating particulate exposure from municipal waste incinerators, whereby missing cloud cover was obtained from the nearest meteorological station (Douglas et al., 2017c) To assess comparability, Spearman's correlations of data from the original and replacement stations were conducted, and was found to be well correlated (Spearman's r = 0.558–0.989, p < 0.001).

Rainfall was not included in the study. If it had been included, predicted concentrations would have decreased according to the pollutant's respective washout coefficient. However, this may not truly account for the impact of rainfall on *A. fumigatus* release. For example, Rathnayake et al. (2017) found that fungal spore tracers peaked in concentration following spring rain events. However the impacts of rainfall on bioaerosol emissions from composting facilities is not well understood, and difficult to measure with current established sampling methods and therefore further investigation is required.

4.1.4. Pollution prediction area

ADMS is capable of predicting concentrations at finer spatial resolutions (e.g. grid or address level), at the user's discretion. In this study, modelled concentrations were predicted at postcode centroids within 4 km of each composting facility. The aim of this study was to produce exposure estimates at population level; postcodes were chosen as this reflects the finest spatial resolution that routine population health data are available (e.g. hospital episode statistics) (Health and Social Care information Centre, 2013). The

dispersion modelling results from this study will be used in an epidemiological study assessing the associations between bioaerosol emissions from composting facilities and respiratory health effects.

4.2. Impact and policy implications

At present, in England the EA take a precautionary approach to composting facility regulation in terms of bioaerosol emissions (Defra 2018b). Permitted facilities need to demonstrate that acceptable levels of bioaerosols above upwind background concentrations are maintained at 250 m or at the nearest sensitive receptor (such as a dwelling) (Defra, 2018b). Acceptable levels are 300, 1000, and 500 colony forming units per metre cubed (CFU m^{-3}) above background concentrations for gram-negative bacteria, total mesophilic bacteria, and *A. fumigatus* respectively, measured following the M9 sampling guidelines (EA, 2017). Established bioaerosol measurement methods (i.e. those suggested in the M9 guidance) are expensive, laborious and provide only a spatial and temporal snapshot of bioaerosol concentrations (Douglas et al., 2017b). This study presents the first steps towards developing a screening tool, using dispersion models to provide a cheaper and quicker risk assessment method. If further developed and tested, this could be used in the permitting process as a means to assess bioaerosol risk, alleviating some of the cost burden to facility managers.

However, more work is needed on long-term bioaerosol monitoring around facilities to help further develop modelling approaches. This approach potentially provides a pathway for the inexpensive assessment of bioaerosol dispersion on a facility-specific basis and, where risks are suspected, targeted periods in which monitoring can be undertaken to assess actual concentrations of bioaerosols. This could also provide a tool for facility managers to implement mitigation methods to reduce emissions on days where estimated bioaerosol concentrations in nearby communities are higher. The EA's Bioaerosol Monitoring Technical Guidance Note (M9) could be updated to incorporate such an approach, helping both facility operators and regulators manage and assess bioaerosol dispersion on a flexible and yet defined basis. Furthermore, this approach can provide the basis of standardising the modelling of bioaerosols, providing a platform and rigorous framework for the ongoing development of the bioaerosol modelling field.

4.3. Further considerations

This contribution provides a valuable first step in the screening of exposure risk associated with composting facilities. Future studies following this approach should consider (i) incorporating facility-specific meteorological data, (ii) geo-locating specific on-site activities at each facility, (iii) determining facility-specific opening hours, on-site waste statistics, and management practices, and (iv) incorporating facility-specific surface roughness. For the improvement of bioaerosol modelling generally, the following additional challenges should be addressed; (v) improving the understanding between CFU and mass, and (vi) developing robust high resolution bioaerosol monitoring protocols for the assessment of model performance.

5. Conclusions

This is the first time that a population exposure model for large-scale outdoor composting facilities has ever been attempted nationally. We have used ADMS to predict bioaerosol concentrations at postcode centroids within 4 km of 217 composting facilities in England between 2005 and 2014. We found that:

- The highest estimated bioaerosol concentrations were found in July, and lowest in February and March, which reflect TVEFs and ambient temperatures;
- Bioaerosol concentrations deplete rapidly with distance, reaching background levels at approximately 2 km;
- Dispersion patterns were mainly driven by wind speed and direction, emphasising the limitations of using distance from facility as a proxy for bioaerosol exposure, as previously used in community health studies; and
- Complex dispersion patters were observed in overlapping areas, highlighting the importance of considering all bioaerosol sources when assessing health risks.

The limitations set out in this study demonstrate that bioaerosol dispersion is still not sufficiently understood. In particular, more monitoring datasets are needed in formats conducive to modelling applications.

Acknowledgements

Competing interests

The authors declare that they have no competing interests.

Declaration of interest

None.

References

Aatamila, M., Verkasalo, P., Korhonen, M., Suominen, A., Hirvonen, M., Viluksela, M., Nevalainen, A., 2011. Odour annoyance and physical symptoms among residents living near waste treatment centres. Environ. Res. 111 (1), 164–170.

CEDA, 2017. Web Processing Service. [Online] Available at: http://wps-web1.ceda.ac.uk/ui/home (accessed 19 Jul. 2018).

CERC, 2016. ADMS 5 Atmospheric Dispersion Modelling System User Guide. [Online] Available at: http://www.cerc.co.uk/environmental-software/assets/data/doc_userguides/CERC_ADMS_5_2_User_Guide.pdf (accessed 19 Jul. 2018).

Danneberg, G., Gruneklee, E., Seitz, M., Hartung, J., Driesel, A., 1997. Microbial and endotoxin immissions in the neighborhood of a composting plant. Annals Agri. Environ. Med. 4 (1), 169–173.

Deacon, L., Pankhurst, L., Drew, G., Hayes, E., Jackson, S., Longhurst, P., Longhurst, J., Liu, J., Pollard, S., Tyrrel, S., 2009. Particle size distribution of airborne Aspergillus fumigatus spores emitted from compost using membrane filtration. Atmos. Environ. 43 (35), 5698–5701.

Department of Environment Food and Rural Affairs, 2014. Waste Exemption: T23 Aerobic Composting and Associated Prior Treatment. [Online] Available at: https://www.gov.uk/guidance/waste-exemption-t23-aerobic-composting-and-associated-prior-treatment (accessed 19 Jul. 2018).

Department of Environment Food and Rural Affairs, 2015. Tonnage Report – Residual and Recycling Waste 2014/15 – data.gov.uk. [Online] Available at: https://data.gov.uk/dataset/tonnage-report-residual-and-recycling-waste-2014-15 (accessed 20 Jul. 2018).

Department of Environment Food and Rural Affairs, 2016. Tonnage Report – Residual and Recycling Waste 2015–16 – data.gov.uk. [Online] Available at: https://data.gov.uk/dataset/tonnage-report-residual-and-recycling-waste-2015-16 (accessed 20 Jul. 2018).

Department of Environment Food and Rural Affairs, 2017. Tonnage Report – Residual and Recycling Waste 2016–17 – data.gov.uk. [Online] Available at: https://data.gov.uk/dataset/tonnage-report-residual-and-recycling-waste-2016-17 (accessed 20 Jul. 2018).

Department of Environment Food and Rural Affairs, 2018a. UK Statistics on Waste. [Online] Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/683051/UK_Statisticson_Waste_statistical_notice_Feb_2018_FINAL.pdf (accessed 20 Sep. 2018).

Department of Environment Food and Rural Affairs, 2018b. Bioaerosol Monitoring at Regulated Facilities – Use of M9: RPS 209. [Online] Available at: https://www.gov.uk/government/publications/bioaerosol-monitoring-at-regulated-facilities-use-of-m9-rps-209/bioaerosol-monitoring-at-regulated-facilities-use-of-m9-rps-209 (accessed 19 Jul. 2018).

Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives, 2008.

Domingo, J., Rovira, J., Vilavert, L., Nadal, M., Figueras, M., Schuhmacher, M., 2015. Health risks for the population living in the vicinity of an integrated waste management facility: screening environmental pollutants. Sci. Total Environ. 518–519, 363–370.

Douglas, P., Bakolis, I., Fecht, D., Pearson, C., Leal Sanchez, M., Kinnersley, R., de Hoogh, K., Hansell, A., 2016a. Respiratory hospital admission risk near large composting facilities. Int. J. Hyg. Environ. Health 219 (4–5), 372–379.

Douglas, P., Tyrrel, S., Kinnersley, R., Whelan, M., Longhurst, P., Walsh, K., Pollard, S., Drew, G., 2016b. Sensitivity of predicted bioaerosol exposure from open windrow composting facilities to ADMS dispersion model parameters. J. Environ. Manage. 184, 448–455.

Douglas, P., Tyrrel, S., Kinnersley, R., Whelan, M., Longhurst, P., Hansell, A., Walsh, K., Pollard, S., Drew, G., 2017a. Predicting Aspergillus fumigatus exposure from composting facilities using a dispersion model: a conditional calibration and validation. Int. J. Hyg. Environ. Health 220 (1), 17–28.

Douglas, P., Hayes, E., Williams, W., Tyrrel, S., Kinnersley, R., Walsh, K., O'Driscoll, M., Longhurst, P., Pollard, S., Drew, G., 2017b. Use of dispersion modelling for environmental impact assessment of biological air pollution from composting: progress, problems and prospects. Waste Manage. 70, 22–29.

Douglas, P., Freni-Sterrantino, A., Leal Sanchez, M., Ashworth, D., Ghosh, R., Fecht, D., Font, A., Blangiardo, M., Gulliver, J., Toledano, M., Elliott, P., de Hoogh, K., Fuller, G., Hansell, A., 2017c. Estimating particulate exposure from modern municipal waste incinerators in great britain. Environ. Sci. Technol. 51 (13), 7511–7519.

EA, 2017. Technical Guidance Note (Monitoring) M9: Environmental Monitoring of Bioaerosols at Regulated Facilities.

Health and Social Care Information Centre, 2013. Hospital Episode Statistics (HES) Analysis Guide. [Online] Available at: http://docs.adrn.ac.uk/888040/mrdoc/pdf/888040_hes-analy-guide-apr13.pdf (accessed 2 Nov. 2018).

Herr, C., Nieden, A., Bödeker, R., Gieler, U., Eikmann, T., 2003a. Ranking and frequency of somatic symptoms in residents near composting facilities with odor annoyance. Int. J. Hyg. Environ. Health 206 (1), 61–64.

Herr, C., zur Nieden, A., Jankofsky, M., Stilianakis, N., Boedeker, R., Eikmann, T., 2003b. Effects of bioaerosol polluted outdoor air on airways of residents: a cross sectional study. Occ. Environ. Med. 60 (5), 336–342.

R. Hill, B. Bealey, C. Johnson, A. Ball, K. Simpson, A. Smith, M. Theobald, C. Braban, I. Magaz, T. Curran, SCAIL-Agriculture update. [Pdf] Sniffer, 2014 http://www.scail.ceh.ac.uk/agriculture/Sniffer%20ER26_SCAIL-Agriculture%20Final%20report_Issue_11032014.pdf (accessed 19 Jul. 2018).

Klich, M., 2009. Health effects of aspergillus in food and air. Toxicol. Ind. Health 25 (9–10), 657–667.

Millner, P., Bassett, D., Marsh, P., 1980. Dispersal of Aspergillus fumigatus from sewage sludge compost piles subjected to mechanical agitation in open air. Appl. Environ. Microbiol. 39 (5), 1000–1009.

Pankhurst, L., Whitby, C., Pawlett, M., Larcombe, L., McKew, B., Deacon, L., Morgan, S., Villa, R., Drew, G., Tyrrel, S., Pollard, S., Coulon, F., 2011. Temporal and spatial changes in the microbial bioaerosol communities in green-waste composting. FEMS Microbiol. Ecol. 79 (1), 229–239.

Pearson, C., Littlewood, E., Douglas, P., Robertson, S., Gant, T., Hansell, A., 2015. Exposures and health outcomes in relation to bioaerosol emissions from composting facilities: a systematic review of occupational and community studies. J. Toxicol. Environ. Health, Part B 18 (1), 43–69.

Rathnayake, C., Metwali, N., Jayarathne, T., Kettler, J., Huang, Y., Thorne, P., Shaughnessy, P., Stone, E., 2017. Influence of rain on the abundance of bioaerosols in fine and coarse particles. Atmos. Chem. Phys. 17 (3), 2459–2475.

SCAIL, 2018. SCAIL - Simple Calculation of Atmospheric Impact Limits. [Online] Available at: http://www.scail.ceh.ac.uk/cgi-bin/agriculture/input.pl (accessed 19 Jul. 2018).

Searl, A., 2008. Exposure-Response Relationships for Bioaerosol Emissions from Waste Treatment Processes. Defra Contract: 611-00319. Institute of Occupational Medicine.

Stocker, J., Ellis, A., Smith, S., Carruthers, D., Venkatram, A., Attree, M., Dale, W., 2015. A Review of the Limitations and Uncertainties of Modelling Pollutant Dispersion from Non-point Sources. Cambridge Environmental research Consultants. ADMLC/2015/06.

Taha, M., Drew, G., Longhurst, P., Smith, R., Pollard, S., 2006. Bioaerosol releases from compost facilities: evaluating passive and active source terms at a green waste facility for improved risk assessments. Atmos. Environ. 40 (6), 1159–1169.

Taha, M., Drew, G., Tamer, A., Hewings, G., Jordinson, G., Longhurst, P., Pollard, S., 2007. Improving bioaerosol exposure assessments of composting facilities — Comparative modelling of emissions from different compost ages and processing activities. Atmos. Environ. 41 (21), 4504–4519.

Tamer Vestlund, A., Al-Ashaab, R., Tyrrel, S., Longhurst, P., Pollard, S., Drew, G., 2014. Morphological classification of bioaerosols from composting using scanning electron microscopy. Waste Manage. 34 (7), 1101–1108.

M. Williams, B. Lamarre, D. Butterfield, S. Tyrrel, P. Longhurst, G.H. Drew, R. Al-Ashaab, A. Nelson, T. Gladding, A. Simpson, D. Coughlin, A. Hansell, 2013. DEFRA (Department for Environment, Food & Rural Affairs) Report WR1121 Bioaerosols Odour Emissions Compos. Facilities 2013 [Online] http://oro.open.ac.uk/39330/2/WR1121Bioaerosols-FINALREPORT.pdf (accessed 19 Jul. 2018).