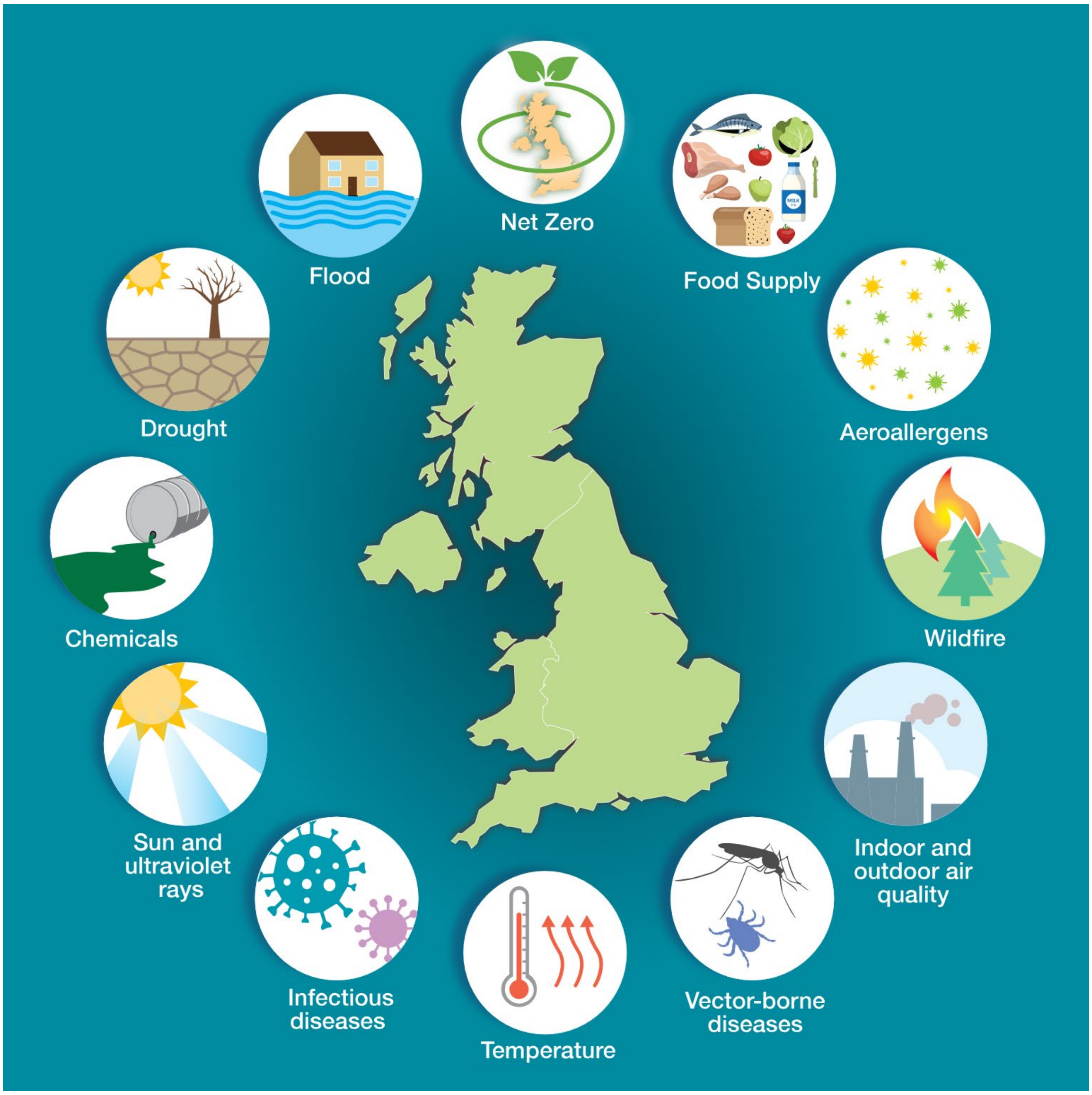
Health Effects of Climate Change (HECC) in the UK: 2023 report

Chapter 6. Outdoor airborne allergenic pollen and fungal spores



Summary

Aeroallergens are airborne particles that can cause or exacerbate allergic disorders including pollen and fungal spores. Aeroallergens can trigger hay fever and exacerbate asthma which affects about 11% of the UK population. Chapter 6 considers the seasonality of these allergens and how they may be impacted by climate change. The chapter was led by academic experts from University of Leicester, with contributions from the University of Worcester, University of Exeter and UKHSA.

Weather and climate are well-recognised drivers of aeroallergen production. Climate also impacts atmospheric transport of pollen grains, including atmospheric transport of allergenic pollen from the continent. There is thus significant potential for a changing climate to shift the start-date, duration, and severity of pollen seasons and associated health risks. The authors present new empirical analyses assessing the relationship between fungal spores and temperature using a 52-year data set (1970 to 2021) and review the published evidence and surveillance data for oak, alder, birch, and grass pollen at 6 sites across the UK (1995 to 2020).

The link between aeroallergen production, seasonality and temperature differs widely between species. Current evidence outlined in this chapter suggests that there has been a significant trend towards higher concentrations of pollen (such as birch) or increased length of the pollen season (such as oak). Other species (such as alder and grass pollen) show a mixed picture, however for grass pollen, this is likely due to the high number of different grass species and interacting variables that affect these seasons. The occurrence of the first high day for grass pollen annually is getting earlier, however, and heatwaves are predicted to shorten the season duration. The authors note that trends over time are most pronounced in the Midlands; however, existing surveillance provides early indications only, and data is still relatively limited.

The impact of climate change on pollens is likely to be mixed and vary considerably across the UK for different species and based on level of warming. In future decades, the first high pollen day is likely to occur earlier for alder, oak and grass pollen, while alder and birch pollen seasons are expected to continue to increase in severity in the Midlands and further north and west over the next 2 decades. In contrast, trees in the south and the east of the UK are likely to become stressed due to increased frequency and severity of heat and drought, which is expected to reduce pollen output and duration of the pollen season. Grass and nettle family pollen seasons are not expected to increase or decrease over time. It is likely that pollen potency will increase and this will enhance the season for hay fever sufferers in most years, although this may decline from the 2030s and with higher levels of warming.

The authors' assessment of trends in fungal spores found an earlier start of the season for all spores, partly associated with warmer temperatures in spring and summer coupled with higher precipitation. In a warmer and wetter future climate, there could be a further advance in the start of the season for many spores. Notably, the authors highlight the potential for interactions between pollutants and airborne fungal spores. Exposure to some urban air pollutants has been

shown to increase the allergenicity of some fungal spores. The authors suggest that there are likely to be health benefits for allergy suffers under decarbonisation scenarios involving electrification of transport and associated air pollutants, though there is limited evidence to quantify possible health co-benefits.

The results presented in this chapter highlight the relationship between aeroallergen species and climate, with several implications for public health. Firstly, earlier and prolonged pollen seasons may increase population exposure to airborne spores and extend the allergy season, meaning that hay fever and allergy sufferers may suffer symptoms earlier and for longer periods of the year. These trends will be highly variable by region and species; therefore, aeroallergen forecasting, preparedness, and response will need to be highly localised. For example, local health organisations should provide information in locally appropriate ways, outlining the risks, protective behaviours and support. Communication pathways should also exist to warn and inform residents, in addition to professionals. Secondly, it is possible that where temperatures reach levels high enough to cause pollen-producing species to wither or die, this will result in reduced aeroallergen exposure resulting in fewer hay fever and allergy symptoms. This is most likely in the south and west regions of England and at higher levels of warming.

The results in this chapter highlight several research gaps and priorities, including the need to:

- develop allergen-specific and highly localised public health forecasts, given that weather and climate impacts on aeroallergens range widely between species
- continue advancement of taxa-specific forecasts and research to support these as the climate changes will remain a priority
- build the evidence on how airborne fungal spores interact with air pollutants and how decarbonisation strategies could maximise health co-benefits associated with aeroallergens
- develop the evidence-base to inform urban planning and green infrastructure development on the implications of alternate designs for aeroallergen production, including potential health co-benefits and trade-offs

UKHSA is already contributing to research into aeroallergens working with NIHR Health Protection Research Units. UKHSA uses real-time syndromic surveillance to routinely monitor seasonal trends in allergenic rhinitis, primarily through consultations recorded in a GP network across England.

Contents

Chapter 6. Outdoor airborne allergenic pollen and fungal spores

Lead author

- Catherine H. Pashley – Department of Respiratory Sciences, University of Leicester

Contributing authors

- Carsten Skjøth – University of Worcester
- Debbie Hemming – Met Office; Birmingham Institute of Forest Research, Birmingham University
- Beverley Adams-Groom – University of Worcester
- Andrew Borman – National Mycology Reference Laboratory, UKHSA South West; Medical Research Council Centre for Medical Mycology, University of Exeter
- Elizabeth Johnson – National Mycology Reference Laboratory, UKHSA South West; Medical Research Council Centre for Medical Mycology, University of Exeter
- Samuel Anees-Hill – Centre for Environmental Health and Sustainability, University of Leicester; UK Toxicology, UKHSA
- Daniel Todkill – Real-time Syndromic Surveillance Team, UKHSA
- Alex Elliot – Real-time Syndromic Surveillance Team, UKHSA
- Holly Lam – Air Pollution Team, UKHSA
- Emma-Jane Goode – Toxicology, UKHSA

Acknowledgements

The authors wish to thank Letty de Weger and Bernard Clot for their valuable reviews of the chapter. The final chapter remains the responsibility of the authors.

1. Introduction

1.1 Summary of the past 3 reports

The first ‘Health Effects of Climate Change in the UK (HECC)’ report was published in 2002 (1). Pollen and fungal (mould) spores were listed as the main biological particles that comprise ambient pollutants of potential health significance within a chapter on air pollution and climate change; but there was no further information on either. There was no mention of either in the 2008 report; however, within the appendix, as a response to public comment on the report, was the statement: “we note a comment on the possible effects of climate change on ambient levels of allergens – caused by changes in the seasonal pollen abundance associated with the earlier onset of spring in Europe. We accept that this is an omission and recommend that it be rectified in any further reports in this area” (2). The rectification was a new chapter in the 2012 report titled ‘Effects of aeroallergens on human health under climate change’ (3). This chapter concluded that the main effects are likely to be on both the current allergic population and on the prevalence of allergic diseases within the population. The chapter summarised that climate effects on plant phenology, pollen production and plant distribution may result in an earlier seasonal appearance of respiratory symptoms, a longer duration of exposure to aeroallergens, and an increased risk of exposure to new (for the population) aeroallergens due to changes in plant distributions. However, uncertainties were emphasised, including the possibility of variations in the potency of the allergen carried, that is, how much allergen each pollen grain contained. Whilst there was less information on the effects of climate change on airborne fungal spores, there was a suggestion that climate change may result in an increase in ‘spore storms’, whereby large air masses travel long distances transporting high numbers of fungal spores. Climate changes may also result in increased spore production by many fungi and, as with pollen, could affect the potency of the allergenic fungal spores. The authors emphasised the research need for low-cost samplers for monitoring aeroallergens, a better understanding of the exposure-response relationship, and a better understanding of the possible effects of climate change on future trends of prevalence of allergic disorders and asthma.

1.2 What are aeroallergens?

Aeroallergen is a collective term used to describe airborne particles that can cause or exacerbate allergic disorders. In the outdoor environment, the 2 most common groups of biologically derived aeroallergens are pollen and fungal spores. Seasonal allergic rhinitis (more commonly referred to as hay fever) affects about 20% of people in the UK, with 10% to 15% of children and 26% of adults affected (4), and is an allergy to pollen from plants and spores from fungi (including moulds). Aeroallergens can also trigger asthma symptoms in sensitized individuals. There are 5.4 million people with asthma in the UK (approximately 11% of the population) and around 235 million people around the world. Asthma is the most prevalent chronic childhood disease, and can be caused by many factors, including the presence of highly allergenic aeroallergens. Over 80 million (more than 24%) adults living in Europe are believed to suffer from allergies, whilst the prevalence in children is 30% to 40% and increasing (5). Pollen allergy has been found in 80% to 90% of childhood asthmatics and 40% to 50% of adult-onset asthmatics. Despite the high prevalence of allergy in asthmatics, a causal relationship between the allergic response and asthma has not been clearly established. Fungal respiratory allergy affects up to 20% of atopic individuals. The major allergic manifestations induced by fungi are asthma, rhinitis, allergic bronchopulmonary mycoses, and hypersensitivity pneumonitis (6). There is a clear association between life-threatening asthma and sensitisation to fungal allergens, and several studies have correlated outdoor spore concentrations with asthma symptoms (7 to 10). Fungal sensitisation occurs in about 3% to 10% of the general population (11) and 7% to 20% of asthmatics. The prevalence is strikingly higher in people with severe asthma, with rates between 35% to 75% (12).

1.2.1 Allergenic pollen

Pollen is a highly specialized part of the male reproductive system from plants. Most pollen grains are 10 micrometres (μm) to 100μm in size, with the majority being 25μm to 50μm, and can be identified by examining them under a microscope at x400 magnification. Whilst pollen can rarely be used to identify a plant to its species using morphological identification, many can be identified to either genus (for example, birch) or families (for example, grasses). More accurate possibilities for identification to genus or species level can be achieved using molecular methods combined with DNA barcoding (13). In general, plants require an organism to transfer the pollen, such as an insect, bird or bat. The pollen grains tend to be large, heavy and sticky, and include projections to help them adhere to the transferring organism. Transfer is usually efficient, with little release into the air. These pollen rarely cause pollen allergy but may still contain allergenic material (allergens) but as exposure is limited, people in general do not become allergic unless they have higher levels of exposure (that is, through some occupations).

Less than 20% of flowering plants do not use other organisms to transfer their pollen. Of these, the vast majority use the wind to spread their pollen. This is particularly true of most grasses, almost all conifers, several weed species and some deciduous trees. These species can be recognized by their small, unscented flowers with dull colour. It is these wind-pollinated plants that are the most important in pollen allergy. These pollen grains tend to have characteristics which facilitate wind dispersal: they are usually dry, smooth, range between 20μm to 40μm in diameter, and some have buoyancy aids such as air sacs. Because wind pollination is less efficient than insect pollination, wind pollinating plants produce enormous numbers of pollen grains and therefore are the dominant pollen in the air (14). Levels of pollen in the air can change quickly over space and time. A single plant may pollinate for a few hours or days, mainly releasing pollen during the daytime, but the pollen can remain suspended for longer periods of time and cause allergy outbreaks away from their source at any time of the day (5).

Pollen grains are the primary carriers of pollen allergens, which explains why the symptoms typical of hay fever are located in the eyes, nose and nasopharynx. Intact pollen grains, which have the aerodynamic size of 15μm to 40μm, probably cannot enter the lower, thoracic regions of the respiratory tract; instead, they affect the nasal or nasopharyngeal mucous membrane.

Nonetheless, symptoms of the bronchial regions, such as coughing or wheezing, are seen in pollen-allergic patients. Among the various hypotheses put forward to account for the thoracic afflictions in hay fever is the existence of secondary pollen allergen-carrying particles of much smaller sizes, capable of penetrating the lower respiratory tract. Although it is plausible that, in spite of aerodynamic principles, a small number of pollen grains may penetrate into the lower respiratory tract, particularly by mouth breathing, there is now strong evidence for the atmospheric presence of pollen-allergen-carrying particles of sizes much smaller than intact pollen grains (15, 16). Allergenic particles can be as small as 0.1μm in diameter and may therefore penetrate deep into the lung. These small allergenic particles have been associated with several plant groups including ragweed, oak, grasses and birch. They can be detected before the pollen season and persist after pollen is no longer present in the air; however, they are much more abundant during the pollen seasons than in the rest of the year, suggesting the most important contribution comes from pollen grains (16, 17).

The 3 main types of allergenic pollen are grass, weed and tree pollen; however, not all species elicit strong allergenic effects (18). Furthermore, whilst these taxonomic groupings are widely used, from a human health perspective they may confuse rather than aid diagnoses as allergic reactions can be specific and may be masked by such artificial groupings. Pollen seasons (the period during which the pollen is being released from plants and therefore present in the air) vary greatly between regions because of differences in climate, topography and vegetation. These natural contrasts combined with variations in agricultural practices and land management procedures produce great variations in the abundance and combinations of airborne pollen types. As such, changes in climate will impact on what potential allergens people are exposed to and subsequently their health. Table 1 summarises the main pollen types found in the UK air, and their respective allergenicity. These pollen types can be split into 2 groups according to annual abundance, maximum daily concentration and the number of high-count days. Six taxa make up the abundant group: ash, birch, grass, oak, nettle-type and yew-type, representing approximately 90% of the total air spora, with grass being the most dominant (14).

Grass pollen is the main cause of pollen allergy in many parts of the world, including most of Europe and North America. The grass family (Poaceae) is extremely large, consisting of more than 10,000 species, but only a subset of grass species are recognised as native to the UK. Cross-reactivity (which occurs when proteins from one allergen are similar to the proteins in another) features between all members, but the more closely related they are, the stronger the cross-reactivity. Recently it was shown using DNA obtained from an environmental source (eDNA), in this case air, that the different grass species found most abundantly in the UK are unevenly distributed throughout Great Britain (19). Later, it was found by combining eDNA methods with health data that a small subset of UK grass species could be associated with the majority of hospital admissions (20).

In the UK, the birch family (*Betulaceae*) are considered the main cause of tree pollen allergy, with birch genera (*Betula*) being the most important. The family contains several known allergenic pollen-producing tree genera that are distributed across all northern temperate regions, including alder, birch, hazel and hornbeam. In northern and central Europe, it is estimated that between 10% to 20% of the population are allergic to birch pollen. The birch genera contain about 40 species, with downy birch and silver birch being the dominant species in the UK. These trees shed large amounts of wind-borne pollen between late March and May (21). Whilst the pollination periods for individual birch species tend to only last for a few weeks, the genera have a wide geographical range and individual species may have a succession of flowering across a region. Cross-reactions, both among birch species and with other tree pollen in particular of the Fagaceae family, which includes beeches, chestnuts and oaks, contribute to a prolonged season of symptoms for many allergic people (17).

Table 1. Pollen types identified at Leicester, UK, by morphological characteristics and their respective allergenicity

Allergenicity and cross reaction information taken from (22). (It is highly plausible that not all combinations of cross reactions have been tested.) The 12 taxa with an asterisk (*) are those counted by the UK pollen network. The majority are from wind-pollinated plants. However, those that are insect pollinated are identified with a hashtag (#) and those that are insect and wind pollinated are identified with a dagger symbol (†).

Common name	Latin name	Allergenicity	Cross reactions
Birch*	*Betula*	high	alder, hazel, hornbeam, beech, oak, sweet chestnut
Grass*	*Poaceae*	high	all grasses
Mugwort*	*Artemisia*	high	composites, especially ragweed
Ragweed*	*Ambrosia*	high	composites, especially mugwort
Alder*	*Alnus*	moderate to high	birch, hazel
Ash*	*Fraxinus*	moderate	olive, forsythia,
Hazel*	*Corylus*	moderate	birch, alder, hornbeam
Plantain	*Plantago*	moderate	none known
Goosefoot	Chenopodiaceae	low to moderate	none known
Oak*	*Quercus*	low to moderate	birch, alder, hazel, beech, sweet chestnut, hornbeam
Plane*	*Platanus*	low to moderate	birch, alder, hazel, hornbeam, oak, beech, sweet chestnut
Rape-type#	*Brassica*	low to moderate	none known
Yew-type	Taxaceae, Cupressaceae	low to moderate	Japanese cedar
Beech	*Fagus*	low	birch
Dock	*Rumex*	low	none known
Elder#	*Sambucus*	low	none known
Elm*	*Ulmus*	low	none known

Common name	Latin name	Allergenicity	Cross reactions
Hornbeam	*Carpinus*	low	birch, alder, hazel
Horse chestnut#	*Aesculus*	low	none known
Lime#	*Tilia*	low	none known
Nettle-type (including pellitory-of-the-wall) *	*Urtica* (*Parietaria judaica*)	low (moderate)	none known
Pine-type	Pinaceae	low	none known
Poplar	*Populus*	low	none known
Sweet chestnut†	*Castanea*	low	birch
Willow*#	Salix	low	poplar

1.2.2 Allergenic fungal spores

The fungal kingdom is highly diverse and includes taxa from numerous different ecological niches with varied life history strategies and morphologies, ranging from unicellular yeasts and microscopic moulds to large mushrooms. The number of currently accepted fungal species is over 120,000, with estimates of the true number of fungal species being between 2.2 million and 3.8 million (23). Fungi are ubiquitous and their spores are released into the air throughout the year, with most exhibiting seasonal periodicity. The spores vary greatly in size, morphology and method of release, with both passive and active spore liberation methods.

As with pollen allergy, where most allergenic pollen that dominate the air spora are from wind-pollinated plants, fungal sensitisation tends to be against commonly encountered fungal species. Some such as species from the genera *Candida*, *Malassezia,* and *Trichophyton* are human commensals or dermatophytes, but the majority have environmental sources and dominate the fungal air spora (11, 24). In many areas, including the UK, outdoor airborne fungal spores exceed pollen concentrations by 100- to 1,000-fold (11, 25). Fungal spore concentrations are highest outdoors, although they can penetrate indoor environments and are commonly found indoors, even in non-mould-complaint homes (26), where they are able to colonise indoor materials (27).

Of the literally thousands of species of fungal spores in outdoor air, only select species from about 80 genera have been investigated for their potential allergenicity (11). At most 2 or 3 are routinely included in the allergen work up of an asthmatic patient. The small number of fungi identified as allergenic are biased towards those that can be easily cultured. For example, there are estimated to be 20,000 to 25,000 basidiomycete species, and the basidiospores occur in the air in high concentrations, however, these are not readily identified by traditional culturing techniques. Of only 50 basidiomycete species tested for allergenicity, approximately 25 were determined to be allergenic, and at least 3 have been shown to cause hypersensitivity pneumonitis (11). A clearer understanding of airborne fungal biodiversity is required to help target future studies into fungal spore-related asthma.

There are currently 27 fungal species from 15 genera with allergens officially approved by the Nomenclature Subcommittee of the International Union of Immunological Societies (IUIS). The most important and most studied outdoor fungal aeroallergens in the UK are *Alternaria* and *Cladosporium;* the only fungal spores for which there are published allergenic thresholds, and *Aspergillus* which whilst lacking allergenic thresholds is arguably the most important fungal allergen in severe asthma due to the ability of some species to not only cause allergies but to colonise the human airways (28). In some countries, up to 78% of patients with allergic respiratory symptoms are sensitised to *Alternaria* (29). Thresholds of 3,000 spores per cubic metre of air for *Cladosporium* and 100 spores per cubic metre for *Alternaria* are expected to trigger symptoms of allergy in sensitised individuals (30). These values are easily exceeded on many days during the fungal spore season in the UK. Table 2 presents the taxonomy and phylogenetic relationships between confirmed and suspected fungal aeroallergens.

Table 2. Taxonomy and phylogenetic relationships between confirmed and suspected fungal aeroallergens
Those with a dagger symbol (†) are identified to genus or group of closely related genera within outdoor fungal spore counts in Leicester, UK. Those with an asterisk (*) have an ImmunoCap (Phadia) blood IgE assay available. The numbers in square brackets are the numbers of confirmed allergens within that genus in the World Health Organization and International Union of Immunological Societies (WHO/IUIS) allergen database.

Phylum	Subphylum	Class	Order	Family	Genus
Ascomycota	Pezizomycotina	Dothideomycetes	Pleosporales	Pleosporaceae	*Alternaria*†* [12] *Bipolaris* *Curvularia** [4] *Drechslera*† *Pleospora*† *Stemphylium*†*
Ascomycota	Pezizomycotina	Dothideomycetes	Pleosporales	Didymellaceae	*Epicoccum*†* [1] *Didymella*†
Ascomycota	Pezizomycotina	Dothideomycetes	Pleosporales	Astrosphaeriellaceae	*Pithomyces*†
Ascomycota	Pezizomycotina	Dothideomycetes	Pleosporales	Leptosphaeriaceae	*Leptosphaeria*†
Ascomycota	Pezizomycotina	Dothideomycetes	Pleosporales	Torulaceae	*Torula*†
Ascomycota	Pezizomycotina	Dothideomycetes	Capnodiales	Cladosporiaceae	*Cladosporium*†* [10] (10)
Ascomycota	Pezizomycotina	Eurotiomycetes	Eurotiales	Aspergillaceae	*Aspergillus*†* [31] *Penicillium*†* [17]
Ascomycota	Pezizomycotina	Leotiomycetes	Helotiales	Sclerotiniaceae	*Botrytis*†*
Ascomycota	Pezizomycotina	Sordariomycetes	Hypocreales	Nectriaceae	*Fusarium** [4]
Ascomycota	Pezizomycotina	Sordariomycetes	Hypocreales	Stachybotryaceae	*Stachybotrys* [1]

Phylum	Subphylum	Class	Order	Family	Genus
Mucoromycota	Mucoromycotina	Mucoromycetes	Mucorales	Mucoraceae	*Mucor**
Mucoromycota	Mucoromycotina	Mucoromycetes	Mucorales	Rhizopodaceae	*Rhizopus** [2]
Basidiomycota	Agaricomycotina	Agaricomycetes	Polyporales	Polyporaceae	*Ganoderma*†
Basidiomycota	Pucciniomycotina	Microbotryomycetes	Sporidiobolales	Sporidiobolaceae	*Sporobolomyces*†
Basidiomycota	Ustilaginomycotina	Exobasidiomycetes	Entylomatales	Entylomataceae	*Tilletiopsis*†
Basidiomycota	Ustilaginomycotina	Ustilaginomycete	Ustilaginales	Ustilaginaceae	*Ustilago*†

1.3 Chapter objective

Climate change is expected to increase the incidence of atopic disease (31). Current knowledge has linked aeroallergen exposure to incidences of asthma, allergic rhinitis, and other atopic conditions. In this chapter, the impact climate change will have on aeroallergens is addressed, covering changes in airborne aeroallergen concentrations and species composition, species allergenicity, phenology of the aeroallergen producing species, and changes in landcover, highlighting the implications for human health. We provide updated information since the 2012 report, including methods used to monitor aeroallergens, and highlight where gaps in knowledge still exist.

2. Methods for identification of airborne pollen and fungal spores

Reliable aeroallergen data is important both for individuals living within a particular area, and for allergic patients when they travel to other regions. From a clinical perspective, aerobiological data can be a useful aid in diagnosing the cause of an individual's allergies. For an individual allergic to a particular aeroallergen, the prediction of the start of that aeroallergen season can allow them to adjust their daily activities to avoid contact with the allergen or to begin taking medication. The traditional way to measure the presence and quantity of aeroallergen in the atmosphere is to assess the airborne pollen and fungal spore concentrations. With the demonstration of substantial quantities of airborne pollen allergen outside the pollen season (32 to 34), the question arises as to whether or not the traditional pollen count is a correct measurement of atmospheric pollen allergen. This point is still being debated because the conclusions drawn by different researchers are not in agreement (15).

Whilst there are several methods for collecting biological particles from the atmosphere, the technique used most frequently for monitoring airborne pollen and fungal spores is suction trapping. Air is sucked into a volumetric trap such as the Burkard trap at a rate of 10 litres per minute, through a narrow aperture of fixed size. The trap has a weathervane attached, so the aperture is always facing towards the direction of the prevailing wind. Traps are sited 10 to 12 meters above ground level, sampling air that has been thoroughly mixed by the turbulent boundary layer and representing a relatively large surrounding area in comparison to traps sited near ground level (35). The internal dimensions and plan of the trap provide a system that is aerodynamically efficient at capturing particles in the size range of pollen and many fungal spores. The pollen and fungal spores are deposited onto a sticky surface, and the distinctive features of different types of pollen and fungal spores can be identified morphologically by microscopy according to standards set out by the British Aerobiology Federation (36). Variations in the concentrations of airborne pollen and spores measured using the traditional approach can be determined to within one hour, although there is uncertainty regarding the absolute values (37). Counts are reported as the daily average number of grains of a particular pollen or fungal spore per cubic metre of air sampled over a 24-hour period using international agreed standard terminology (38). Counts are therefore a guide to conditions in the area and not specific to the level of exposure an individual may receive.

In most pollen-monitoring networks, sampling sites are located considerable distances apart. Pollen traps are usually situated on rooftops in exposed areas to sample from a mixed air flow away from local sources. It is well known that pollen concentrations can vary a lot over short distances, both vertically (39, 40) and horizontally (41). A study comparing 2 sites in the East Midlands situated 41km (25 miles) apart suggested that data from a single site was suitable for forecasting up to this distance (14). A similar study in Sydney, Australia, counted pollen from 3 sites in a 30km region, and concluded that, whilst for clinical trial purposes data collection must be local and applicable to the study population, the count from one trap is a reasonable estimation in a 30km region for informing the public about pollen counts (42). Dissecting this to key allergenic pollen, tree pollen are considered to be more homogeneously distributed in the air compared to grass pollen (43). This is likely because grass pollen are typically larger and heavier than most tree pollen, and tree pollen are released higher than grass pollen. High release levels enhance atmospheric dispersion, whilst higher weight increases gravitational fall-out. A consequence is that a pollen trap located 10m above the ground can be representative for larger areas than 30km for some tree pollen, while shorter distances may be relevant for grass pollen (44). Overall 30km is an accepted rule for all pollen types. The UK pollen monitoring network is administered by the UK Met (Meteorological) Office and comprises one site each in Scotland, Wales and Northern Ireland, and a further 8 in England. Most of the sites operate throughout the UK pollen season (mid-March to early September), but one operates only during the grass pollen season (mid-May to mid-August).

Whilst the pollen component of the air spora is well characterised, with the majority of the pollen load comprising 6 or 7 easily identifiable, well-characterised pollen (14), the airborne fungal load is less well defined. There is no UK spore monitoring network, with routine fungal spore counts only currently performed at Leicester, due in part to limitations of traditional identification methodologies. It is very labour intensive and requires skilled knowledge of fungal spore morphology. Many fungal spores are identified to either genera or groups of closely related genera, such as *Aspergillus/Penicillium* (*Asp/Pen*)-type spores (45). The remainder are placed into generalised groups with limited clinical utility. Combined, these unidentifiable 'others' can range from 8% to more than 80% of all spores in a day, with an average around 50% (25). DNA analysis can accurately identify airborne fungal spores to genera level (25), and recently high-throughput sequencing has been developed as an approach to identify airborne fungal spores (46).

2.1 Diagnosing allergy to aeroallergens

Diagnosis of allergy is based on patient history and in vivo and in vitro testing. The 2 most common tests used are skin prick tests (SPTs) and specific serum IgE tests. Measurement of specific IgE antibodies is more costly than SPTs. It has been suggested that both specific IgE measurement by the ImmunoCAP system and SPTs should be used in diagnoses of allergy due to discordance in test results; although of the 2, specific IgE testing is the more sensitive (47).

SPTs are widely used to demonstrate an immediate IgE-mediated allergic reaction and represent a major diagnostic tool in the field of allergy. If properly performed, they yield useful evidence for the diagnosis of specific allergy. SPTs represent the first diagnostic method in patients with a suggestive clinical history of allergic rhinitis (conjunctivitis) or asthma and can be used from infancy to old age. SPTs have a high specificity and sensitivity for the diagnosis of inhalant allergens. The quality of the allergen extract is of key importance as variations in the quality and/or potency of commercially available extracts exist. The Global Allergy and Asthma European Network suggest a panel of allergens for use in patients in Europe which includes: birch, cypress, grass, mugwort, olive or ash, *Parietaria*, plane and ragweed pollen and

Alternaria and *Cladosporium* fungal spores (48). There is no consensus regarding which fungi should be included in a fungal allergen panel. Based on aerobiological surveys conducted in different locations of the world and test availability, a recommendation for a skin test panel was *Alternaria*, *Aspergillus*, *Cladosporium*, *Epicoccum, Fusarium* and *Penicillium*. This list does not include any fungi from the Basidiomycota, even though they are important in terms of exposure and many have been shown to be allergenic, because suitable extracts are not often commercially available (11). The list also excludes species from the Mucorales, even though some are known opportunistic pathogens and allergens, and ubiquitously present in the environment.

Specific IgE levels in individuals sensitised to fungi often closely match the fungal phylogenetic relationships (Table 2). As such, this can be taken into consideration when deciding which allergens to test (24). Co-sensitisation between *Alternaria* and *Cladosporium* and between *Aspergillus* and *Penicillium* is common, with sensitisation to *Alternaria* and *Aspergillus* being the more common of the respective pairs in the UK. Given the important role of *Aspergillus* in asthma, a clinically relevant panel with respect to asthma should include *Alternaria* and *Aspergillus* (28).

More recently, allergen microarrays containing large numbers of different allergen molecules have been developed to allow simultaneous detection of IgE reactivities to a large number of allergen molecules with small serum volumes. These allergen microarrays are comprised of chips containing spotted allergens. An allergen microarray termed ImmunoCAP ISAC is available for chip-based allergy diagnosis. It tests against 51 allergen sources in a single step and includes grass, weed (including ragweed, mugwort, *Parietaria*) and tree pollen (birch, alder, cypress, olive and plane) and the fungal spores *Alternaria*, *Aspergillus* and *Cladosporium* in addition to other allergens (49).

3. Effect of climate change on pollen concentration and species composition

The UK is located in the temperate climatic zone and has a generally mild, breezy climate with cool and wet winters and warm and wet summers, although there is large variation on a daily, seasonal and yearly basis (50). As a result, UK pollen seasons are also very variable, both spatially and temporally. Climate and climate change generally impact pollen in the atmosphere by altering seasonality, concentrations, species composition and allergenic pollen potency. Changes to the climate have impacted pollen seasons, which has been documented through analysing airborne pollen counts across Europe (51, 52).

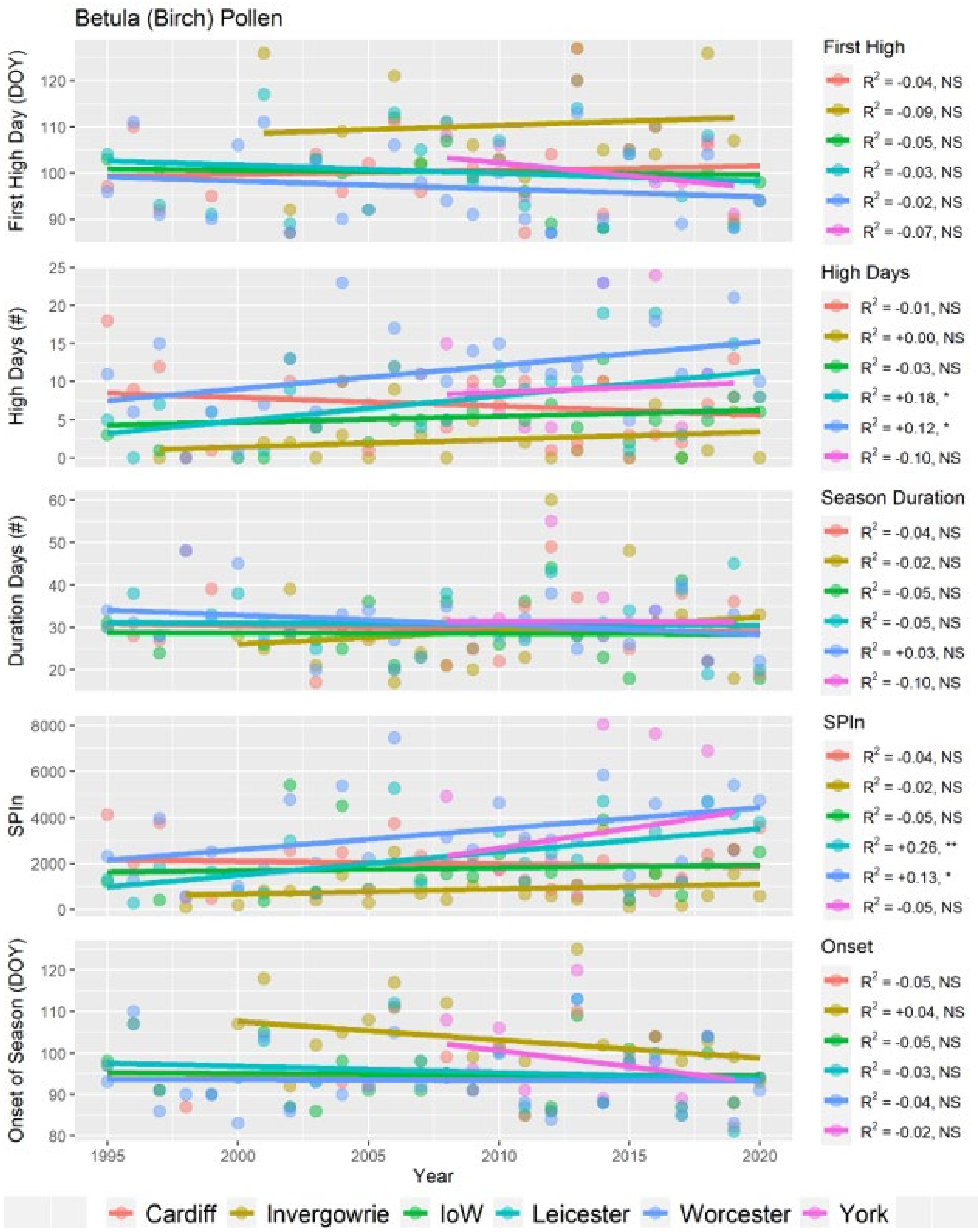
In the UK, pollen seasons start later at northern sites compared to southern sites (21), while much larger differences have been seen on the European scale (53). Climate and climate change also impact atmospheric transport of pollen grains. In spring, southern England can be impacted by atmospheric transport of allergenic pollen from the continent (54). Previously these events have been episodic and most often found for birch pollen early in the season (55). Recent research on pollen trends and climatic changes in the UK over the period 1995 to 2020 (56), and supplemented further in this chapter, has revealed a very mixed picture as described below. The way pollen seasons are likely to evolve under climate change depends on the interaction of various factors, particularly changes in the weather, the potential for extreme weather events, increasing CO_2, pollution levels, land-use changes and phenology. The picture is rather complex with some of these elements potentially causing increases in pollen concentrations and potency but others reducing or cancelling them out. Of all the factors acting on pollen seasons, weather and climate have the greatest impact.

3.1 Tree pollen

Birch seasons show no significant trends for onset, occurrence of the first high day (when hay fever sufferers are likely to be affected, with counts of 80 grains/m^3 air or higher) or duration (Figure 1). Since both February and March are key months for the pre-season weather influence on the onset of the birch season, a trend to earlier seasons would only be expected if these months had showed significant increase in temperature variables, which they did not. This finding is similar to that of the nearby countries of France, Belgium, the Netherlands, Luxembourg and Switzerland (57 to 61). However, there is a significant trend to more severe birch pollen seasons in the Midlands region, which is occurring due to increasing pollen production (Figure 1). This is being driven by warmer temperatures in the previous June when the pollen is set in the flowers. These findings are similar to trends recorded in recent studies from several countries across Europe and beyond (52, 57, 58, 60 to 66).

Research to investigate how birch Seasonal Pollen Integral (SPIn) (the sum of pollen concentrations obtained at a site during the grass pollen season) might change as climate change impacts take effect has been undertaken (65). Their modelling study for Bavaria, southern Germany, predicts that birch pollen will continue to increase as climate change progresses, up to the middle of this century. Trees at lower altitudes, however, will become stressed by excessive heat, emitting less pollen over time, while trees at higher altitudes and latitudes are expected to benefit from the warming and produce more pollen.

Figure 1. Time-series and linear regression trends for onset, Seasonal Pollen Integral (SPIn), duration, number of high days and first high day for Birch pollen seasons, 1995 to 2020, for 6 UK pollen stations (also included are the R^2 and p values (p<0.01; * p<0.05) (56))**



In contrast to birch pollen, oak (*Quercus* spp.) pollen seasons are starting earlier and lasting longer in some regions but not getting more severe (Figure 2). The trends to earlier onset and occurrence of the first high day (counts 50 grains/m^3 air or higher) were due to increasing temperature and sunshine totals in April. There were no significant climate drivers determined for the longer duration of the seasons. The lack of a general trend to increased oak pollen production found here is in contrast to the few studies in Sweden, Spain and Switzerland that include analysis on this genus (62, 64, 67, 68). In the UK, although a few of the weather variables affecting pollen production or oak pollen dispersal were found to be changing significantly, none of them were strong enough to be driving change in oak pollen severity during the study period.

In addition to the research conducted by Adams-Groom and others, alder (*Alnus* spp.) tree pollen has been analysed to broaden the picture of current trends (note that the trends have not yet been statistically tested for significance and only the Worcester pollen site has been studied; therefore, these trends should be seen as indications of possible trends only). Just like the other woody species discussed above, alder tree pollen is also showing a mixture of changes. Alder pollen is released in the winter (January to mid-March) (21). Currently, it is showing a trend to an earlier occurrence of the first high day (counts 80 grains/m^3 air or higher) in the Midlands (Figure 3a) and a limited trend in overall severity (Figure 3b). This pollen type has a very variable temporal pattern for SPIn, with occasional very severe years, often followed by one or 2 mild years, which makes trends difficult to discern. This variability has increased over the last few years, with alternate very mild and very severe seasons. Onset of the alder pollen season is affected by the previous October temperatures (positively), December temperatures (negatively) and January temperatures (negatively) (69). The temperature trends for October and January are not significant but December temperatures are strongly and significantly on the rise (56) and could therefore drive a trend to an earlier occurrence of the first high day that is suggested in Figure 3a.

In general, tree pollen seasons in the UK are subject to great interannual variation and this is expected to continue over the next 2 decades for all tree pollen types. For birch pollen, the onset of the season and the first high day are unlikely to start trending significantly earlier because the weather trends are unfavourable for this to happen, whereas they are favourable for alder and oak, which have different emission times.

The trend to more severe birch pollen seasons is expected to continue, due to increasing temperatures enhancing pollen production in June and increasing April sunshine aiding dispersal. The trend is currently only significant in the Midlands but is likely to become more significant in the north and western regions of the UK over the next 2 decades, where the trees are likely to benefit from warming and produce more pollen. Trees in the south and east of the UK are expected to become stressed through heat and drought more frequently, which will reduce their pollen output and result in short seasons. Birch pollen seasons have a biennial pattern of pollen production, therefore alternate years will have an increasing potential to be severe. For instance, 2022 was a mild year, so the next potentially severe year will be 2023. Even mild years are likely to worsen. Alder pollen seasons are likely to continue to be very variable in severity, but severe years will probably occur with more frequency. Oak pollen seasons are not expected to become more severe. Overall, because the pollen production time period is not getting sufficiently warmer, tree pollen season duration is expected to remain very variable, although there is a trend for oak pollen seasons to lengthen in the north and west.

Figure 2. Time-series and linear regression trends for onset, Seasonal Pollen Integral (SPIn), duration, number of high days and first high day for Oak pollen seasons, 1995 to 2020, for 6 UK pollen stations

Also included are the R2 and p values (*** p<0.001; ** p<0.01; * p<0.05) (56). Note that the increases in SPIn and NH at Leicester are attributed to the maturing of a planting scheme of oak trees in a nearby park.

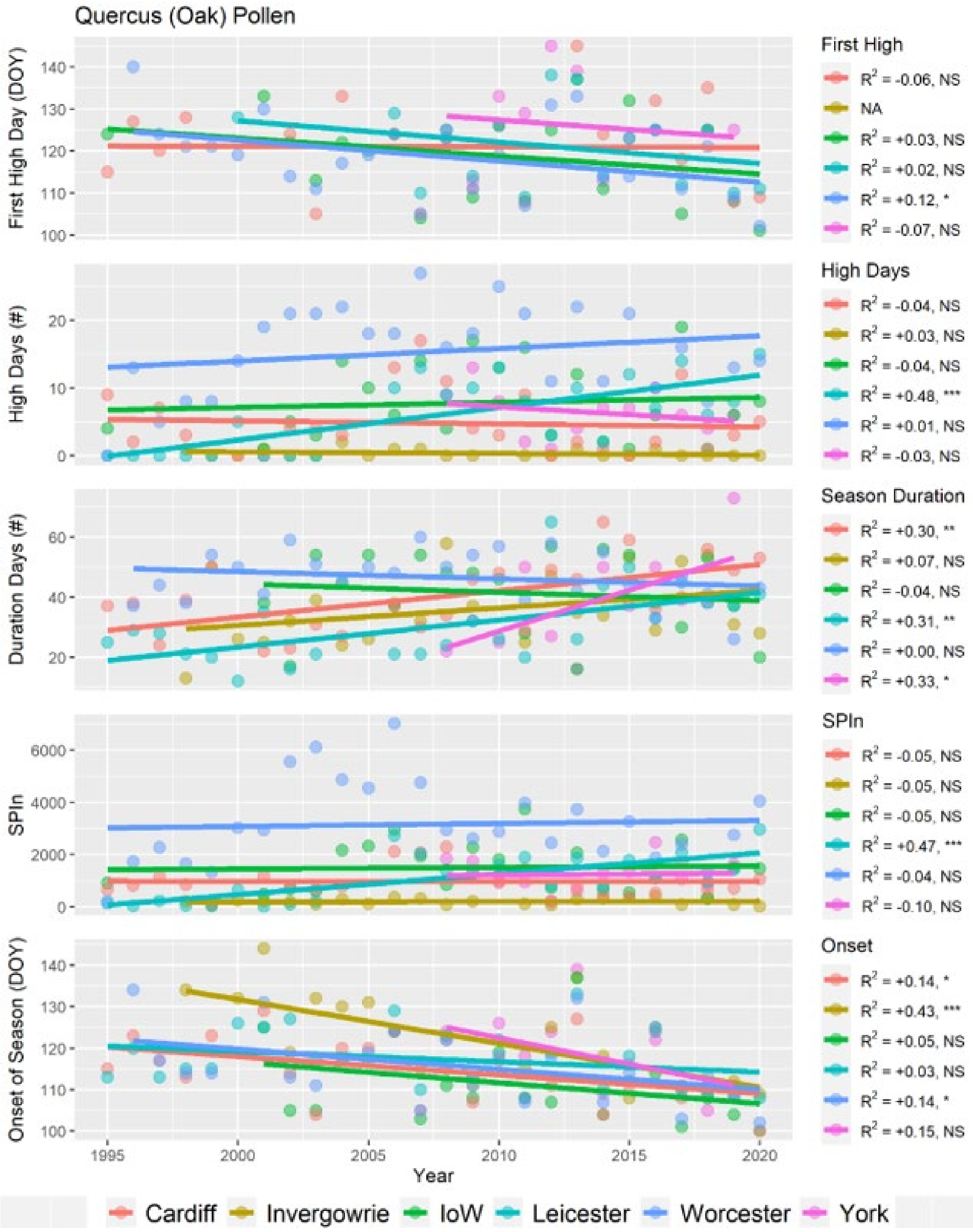
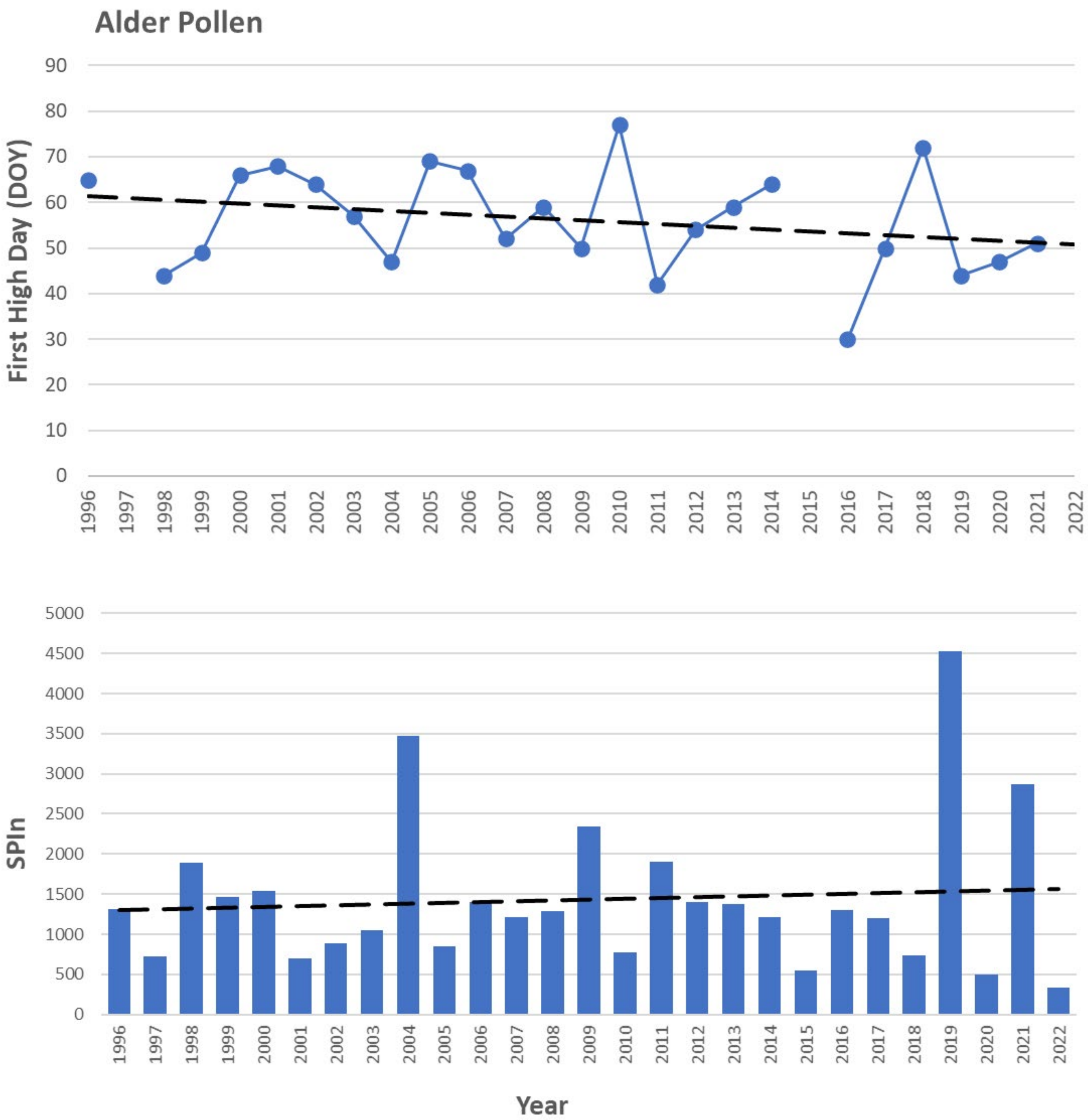


Figure 3. Alder pollen seasons: (top) Occurrence of the first high day (day of year); (bottom) SPIn (total grains per cubic metre of air) at Worcester in the Midlands, 1995 to 2022 (unpublished data from the University of Worcester standard pollen monitoring trap). Note that not all years have high count days in them.



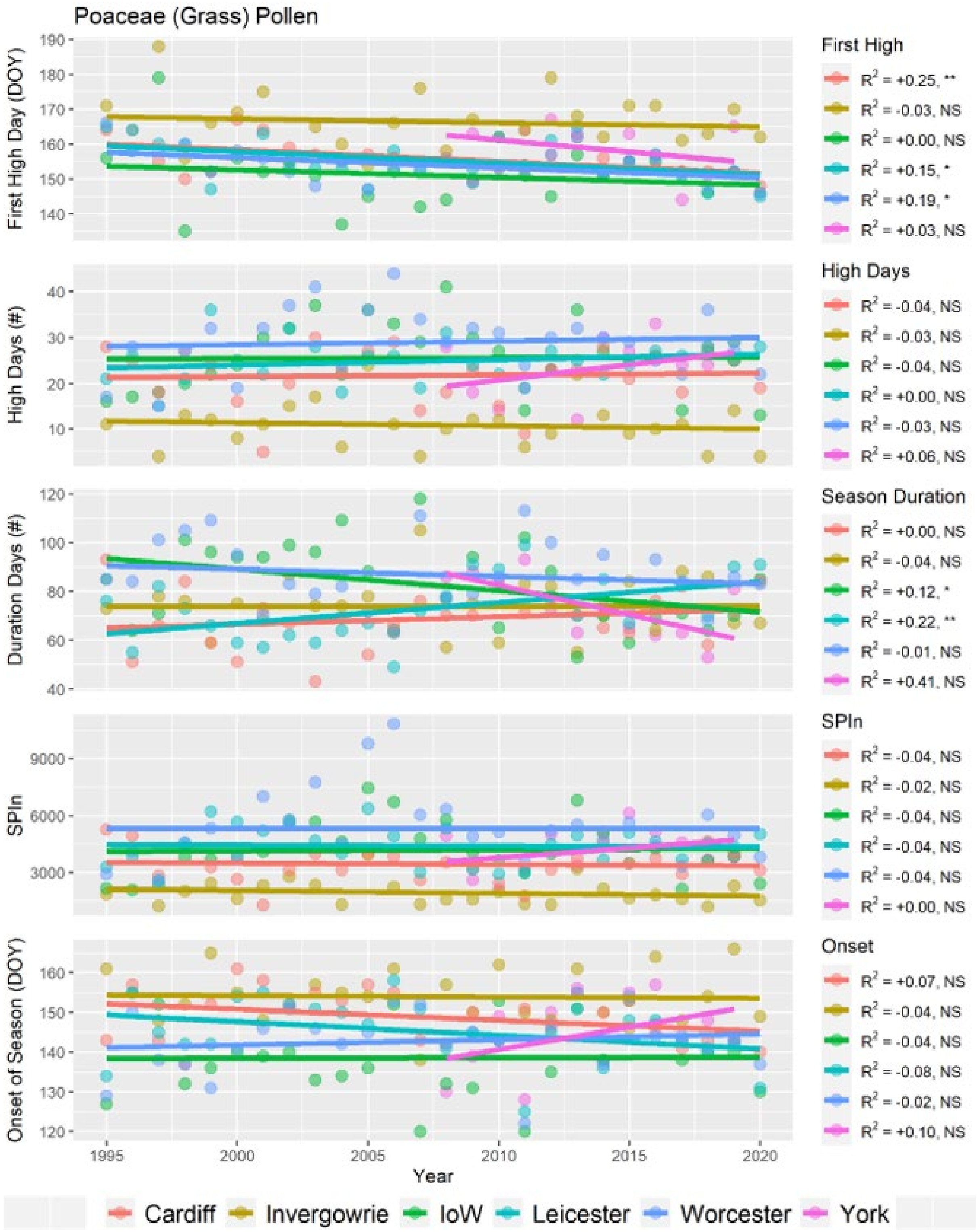
3.2 Grass and weed pollen

The first high day (counts 50 grains/m^3 air or more) of the grass pollen season is occurring earlier in central regions of the UK, due to an increasing trend in all temperature variables in the previous December, January, April, May and June (56). However, severity and duration of the grass pollen seasons show no significant trends and remain spatially and temporally variable across the UK (Figure 4). Warm cumulative mean temperature above 5.5°C in January is associated with increased grass pollen production, but this weather variable showed no significant climatic trend and may partly explain why the grass SPIn trend remained flat. Grass growth and pollen production mostly occur in April, May and early June in the UK, and SPIn is significantly increased when some or all of these months are warm. Pollen production can also be increased by enhanced levels of CO_2, which encourages good plant growth and pollen production (70). However, despite an increase in the temperature trends of these months, plus increasing levels of CO_2 in the atmosphere, grass pollen seasons are not getting more severe in terms of pollen production or SPIn. In-season pollen dispersal is aided by higher temperatures between May and August, causing greater season severity, while windy weather during May to August leads to a reduction. Although the temperature trends showed an increase in some of these months, the wind speeds showed a decrease, producing an overall flat trend in the pollen levels. These trends are consistent with studies from nearby countries in Europe. The number of high days (NH) in Belgium was in decline and severity decreasing; of 6 sites studied in Switzerland, half of them had decreased SPIn, one was flat and only 2 showed any increase; while a flat trend was shown in Sweden and Switzerland, similar to this study (57, 59, 62, 68).

There is already the tendency under climate change for more extreme but relatively short-term temperature and rainfall events (71 to 73). Such events at key points in the development of plants can lead to reduced growth and pollen production, although the tolerance ranges vary between plant species (74). Grass pollen seasons will be particularly impacted by future extreme heat events (heatwaves). Grass species in the UK are adapted to cool, moist, temperate conditions and require warmth and rain to grow successfully and produce lots of pollen. Indeed, there were 4 severe years in the early 2000s where such conditions were met and when suitable weather for pollen dispersal occurred during the peak season period (Figure 5). Conversely, if a drought occurs during the growth and pollen production period for grasses, they will not grow particularly well and produce little pollen (75). This occurred in parts of the UK during the spring of 2020, when almost no rain fell in May and temperatures were well above average. Many of the grasses failed to start growing until rain eventually arrived in late May and early June. As a result, the main grass pollen season was delayed, and SPIn was milder than average. Although much of England and Wales were similarly affected, SPIn in Worcester during 2020 was 3,794 (Figure 5) compared to a 27 year mean of 5,314, and there were only 16 high count days compared to the mean of 29 days (56).

Optimum temperatures for the release of grass pollen are between 17°C and 28°C in the UK, according to observations by UK pollen forecasters. The warmer days within this range result in the highest daily pollen counts, as was seen quite recently in 2018 (Figure 5). However, when the top threshold temperature is breached the grasses may close their flowers or, if there are several hot days together, they quickly desiccate and die. This effect both reduces the release of pollen and shortens the pollen season (75). With heatwaves predicted to occur more often and to increase in intensity, duration and peak temperature (76, 77), it is likely that during the next few decades, grass pollen production and dispersal will be adversely affected more frequently.

Figure 4. Time-series and linear regression trends for onset, Seasonal Pollen Integral (SPIn), duration, number of high days and first high day for grass pollen seasons, 1995 to 2020, for 6 UK pollen stations (also included are the R2 and p values (p<0.01; * p<0.05) (56))**



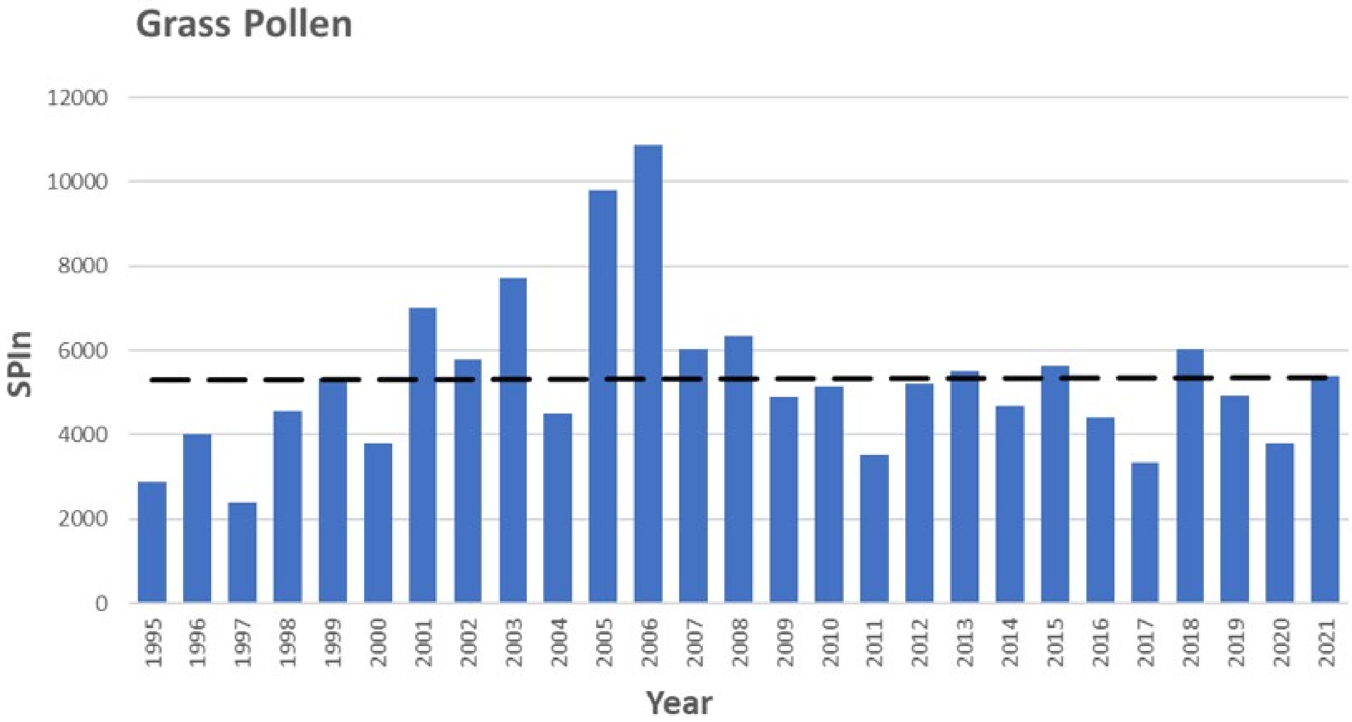
A large-scale study using the vegetation model JULES on grass pollen productivity study covering the UK and countries around the North Sea showed that climate change will induce large increases in pollen productivity (70), similar to the increases seen in the Chamber experiments. The same study also analysed long-term time series of grass pollen concentration using the annual pollen integrals from 34 stations and time series covering up to 30 years each. It found limited connection between nearby sites despite similar climatological regions and therefore concluded that interannual variations in pollen integrals must be explained by local meteorological conditions, local changes in grassland cover and other local environmental variables, thereby confirming that management, such as frequency of grass cutting, may impact pollen concentrations locally (43).

Considering the next 2 decades for grass pollen, season analysis for SPIn suggests that the total number of pollen grains in the air each year will stay around the average, with year-to-year variability consisting of milder or somewhat more severe years. Although increasing temperatures and CO_2 will tend to allow enhanced pollen and allergen production more often, extreme weather events such as heatwaves or heavy rainfall, coupled with continued loss of grassland to urbanisation and woodland, are likely to counteract it and continue the overall flat trend. However, it is likely that in the short-term, the pollen potency of the pollen grains will be increased by a combination of the effects of generally warmer temperatures and interaction with pollutants from fossil fuel emissions. Therefore, high levels of seasonal respiratory allergies are expected to continue over the next decade or 2, with occasional milder seasons occurring when the pollen or allergen production is adversely affected. The effect of pollutants on seasonal allergy is likely to start waning from around 2030 onwards as fossil fuel vehicle emissions reduce due to the uptake of electric vehicles and other actions taken to mitigate the effects of climate change. However, it isn’t possible to predict the extent or speed of this reduction.

The onset of the grass pollen season is unlikely to start earlier in the future since the trend is flat. The tendency of an earlier first high day over time is likely to continue in the central areas of the UK and spread to more northern regions. The current trend sits at one to 2 days earlier than the average. Potentially, this could increase to 3 to 4 days but could also be cancelled out by climate change effects which can delay the season.

There is no clear picture on grass pollen season duration for the UK, due to the high number of variables that affect the seasons. Great seasonal variability is expected to continue but heatwaves will tend to shorten the seasons more frequently over time.

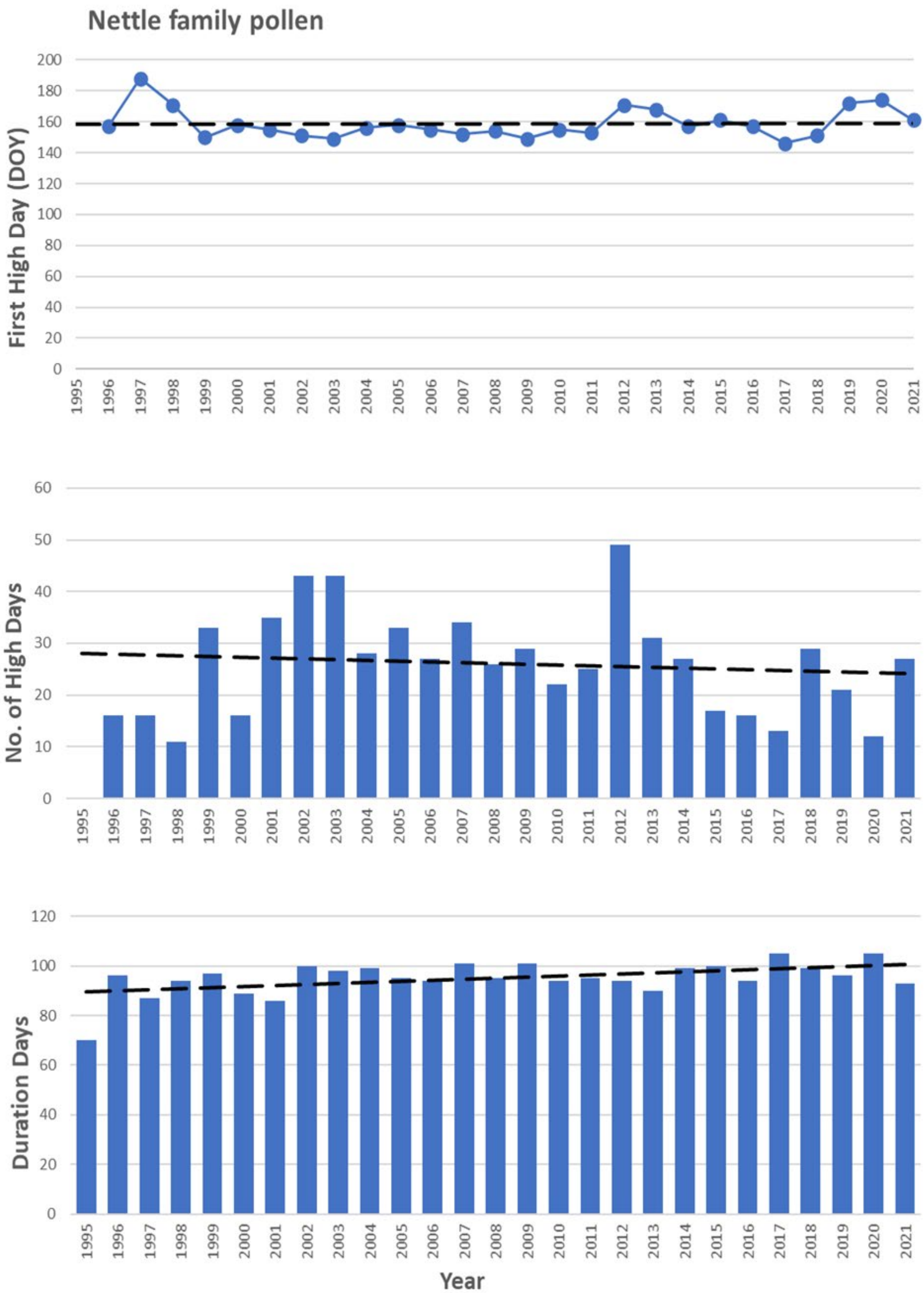
Figure 5. Grass pollen Seasonal Pollen Integral (SPIn) (total grains per cubic metre of air) at Worcester, in the Midlands, 1995 to 2021



According to research from Spain (64) and Poland (78) warming trends may be adversely affecting pollen production in a range of herbaceous pollen types, such as the nettle family (Urticaceae). The nettle family includes *Parietaria judaica*, a known allergen in the UK (79), as well as in the Mediterranean (15). *Parietaria judaica* pollen is difficult to separate morphologically from other members of the family using microscopy but it is a widespread plant in lowland areas of the UK (80). Nettle family pollen is very common in the UK airstream (21) and, as such, may be another useful indicator of climate change impacts on airborne pollen. As with alder, and with the same caveats, nettle family pollen at Worcester has been analysed to further the study conducted by Adams-Groom and colleagues (56). Nettle family pollen trends for the period 1995 to 2021 suggest that there is no change in the occurrence of the first high day (counts 80 grains/m^3 air or more) (Figure 6a), the number of high days (Figure 6b) may be declining but the seasons could be getting longer (Figure 6c). However, in Switzerland, nettle pollen seasons were starting significantly earlier and the season severity had increased, as well as the occurrence of longer seasons (61).

Weed pollen (AKA allergenic herbaceous pollen types) are likely to be similarly affected to grass pollen. Nettle family pollen seasons tend to operate in tandem with grass pollen seasons, except that there is a second peak period in mid to late August in some years. It should be noted that mugwort (*Artemisia* sp.) and ragweed (*Ambrosia* spp.) occur in concentrations too low for analysis in the UK.

Figure 6. Nettle family pollen seasons: (top) occurrence of the first high day (day of year); (middle) number of high days; bottom) duration (number of days), at Worcester in the Midlands, 1995 to 2021 (unpublished data from the University of Worcester standard pollen monitoring trap). Note that not all years have high count days in them.



4. Effect of climate change on fungal spore concentrations and species composition

4.1 Effect on changing prevalence of various fungal species

As alluded to above (section 1.2.2), several studies have found significant correlations between asthma-related hospital admissions and increased airborne fungal spore concentrations (81, 82). As it can be anticipated that climate change will directly impact the types and numbers of airborne fungal spores in a variety of ways, global warming and increased extreme weather events associated with climate change are likely to have important effects on fungal sensitisation (83). Indeed, changes in weather have been shown to explain a significant proportion of measured differences in airborne fungal spore counts (84). The most compelling evidence for a role of global warming on fungal prevalence stems from studies on human and plant fungal pathogens, which have received much more attention for their infection-causing potential than for their roles as allergens (although many are indeed capable of both). In many cases, increased temperatures have been directly linked with or proposed to be responsible for expanded geographic niches and selection due to temperature-adaptation (85 to 88) and will certainly influence seasonality of fungi and their periods of sporulation, especially in the case of the basidiomycetes. Moreover, increased adaptation to host body temperature, as a result of exposure to higher environmental temperatures, will likely result in increased pathogenic potential and greater propensity to cause respiratory disease (88 to 90). Similar predictions have been made for fungal contamination of foods with increased global warming, with thermophilic fungi predicted to dominate mycotoxigenic species due to environmental thermal selection (91).

There are also the other, less direct effects of global warming on fungal proliferation and airborne fungal spore concentrations. Changes in climate, and in particular global warming, increase the frequency of a range of extreme weather events including droughts, thunderstorms, floods and hurricanes (92). Abundance of the key fungal allergen *Alternaria* has been found to be particular sensitive to droughts as it is mainly hosted by crops (93, 94), and the host environment has been found to be negatively impacted by droughts (95). The numbers of airborne spores of key fungal allergens, in particular *Alternaria* and *Cladosporium*, have been shown to increase significantly in parallel with the air temperature and ozone increases that directly precede thunderstorms (96) with fungal spore count increases mirroring asthma admissions in the UK following thunderstorms (97). Moreover, damaged *Alternaria* spores, which are associated with increased asthma severity, have been detected during thunderstorms (98, 99). Storms that result in extensive flooding have increased indoor fungal spore burdens due to fungal contamination or colonisation of living spaces (83, 100), changes in the composition of fungal populations in flood-affected homes (101) and increased outdoor fungal proliferation due to residual elevated humidity. Additionally, *Alternaria, Cladosporiu*m and

Aspergillus spp. produce higher quantities of allergens when their spores germinate under increased humidity (102).

Elevated atmospheric CO_2 concentrations, which are associated with climate change, have been shown to increase both spore production and the allergenic protein content of liberated spores in *Alternaria* spp. (103). The spores of *Aspergillus fumigatus* cultured in pre-industrial period levels of CO_2 were significantly less allergenic than those produced under present-day atmospheric CO_2 conditions (104). Protracted periods of drought are likely to also alter outdoor fungal population structure by selecting the most stress-resistant spores which will then germinate and proliferate when humidity levels return to normal (105), with weather conditions propitious to the growth and dispersal of spores (prior precipitation and increased wind speeds). This is directly linked to seasonal changes in the incidence of pulmonary infections in areas where the dimorphic human fungal pathogen *Coccidioides* is endemic (106). For *Alternaria* spp., the most allergenic spores were those collected during the driest seasons, suggesting that drought or spore desiccation might also directly influence allergenicity (107). Elevated UV indices that occur with global warming are likely to further select for certain groups or genera of allergenic fungi (*Alternaria, Cladosporium*, *Aspergillus* spp.) (108) possibly due to the increased concentrations of protective melanin present in their fungal cell walls that permit their extended survival.

4.2 Effect on airborne fungal spores at the European scale

The impact of climate change on airborne fungal spore seasonality is comparatively less understood compared to pollen. A European study on *Alternaria* spores suggested a consistent seasonal pattern year-to-year, with a degree of annual variation driven by factors including land-use and meteorological conditions (109). Analysis of long-term aeroallergen trends rely upon continuous sampling and the subsequent calculation of annual seasonal markers (season length, start and end dates), peak concentrations, and total annual counts. This requires a sufficient period of study to overcome a pattern of undulating variations that typically occur across time. A recent systematic review focused on fungal spore seasonality across Europe, with a specific examination of studies sampling outdoor air across multiple seasons (110). The studies included in this review covered samples from most areas of Europe, spanning multiple climatic types, geographical topographies and land-uses (collectively characterised as biogeographical regions). Most studies focussed upon fungal spores from the taxonomic genera of *Alternaria* and *Cladosporium*, as these are readily identifiable via microscopy and of confirmed clinical importance. For these 2 genera, enough evidence was available to perform further meta-analyses of season length versus the latitudinal and longitudinal coordinates of the samplers. This revealed a statistically significant trend of longer season lengths for these 2 genera in south-westerly versus north-easterly regions of Europe. These findings corroborate with correlations typically drawn for airborne concentrations of these 2 genera, with both positively and strongly influenced by higher air temperatures.

Studies involving the long-term sampling of fungi are few, due in part to the technical challenges associated with identifying fungal spores via microscopy as mentioned in section 2. From the same review (110), only 6 of 74 studies included analyses of long-term trends (defined here as 10 years or more). Trends for the limited groups of fungi analysed included longer seasons over time for *Alternaria* and the genera of *Stemphylium* (111). Less consistent across locations were trends for annual peak concentrations and seasonal spore integrals (SSIn), which were seen to increase for the *Aspergillus*/*Penicillium* (112), but decrease for *Alternaria* and *Cladosporium* in multiple locations (113 to 116). Such analyses may be impacted by the confounding influence of land-use due to changing agricultural practice, deforestation or tree-planting, and urbanisation across time.

With the forecasted impact of climate change including hotter and wetter conditions in the UK (71), a possible implication may be prolonged fungal season lengths similar to those in Mediterranean Europe, with longer annual periods of exposure to allergenic fungal spores as a consequence. There is some uncertainty with this however, as only fungal growth, rather than sporulation, could increase, dependent upon species (117). Climate change also impacts upon tertiary factors including host species availability (confounded by increasing atmospheric CO_2 concentrations) and the incidence of extreme weather events, all of which may have uncertain knock-on effects for fungal sporulation patterns (118, 119). Understanding the complex interplay between these factors requires further studies that utilise long-term data sets of fungal spore counts and utilises local meteorological measurements including the incidence of specific weather events, and land-use patterns across time.

4.2.1 Long-term trends in airborne concentrations of key allergenic fungal spores in the UK

To examine the long-term trend of spore concentrations and the start of spore season, and to investigate their association with ambient temperature, we conducted a time-series analysis with the use of a 52-year data set (1970 to 2021) with daily fungal spores measured in Derby and Leicester. Due to substantial missing data outside of the main fungal spore season from 1970 to 1990, we limited the analysis to data collected between April and September. We considered 2 indices, the seasonal spore integral (sum of concentration in spore/m^3 between April and September) and start of season (in day-of-year, using the 2.5% method (21) and focus on 2 dry-weather fungal spores, *Cladosporium* and *Alternaria*, and 2 wet-weather fungal spores, *Sporobolomyces* and *Tilletiopsis*, that are known fungal aeroallergens (section 1.2.2).

Maximum and minimum daily temperature and precipitation within 30km of the pollen traps were collected and averaged in the study periods for the calculation of the seasonal meteorological variables. The spore concentrations were highest from May to September, so February to April was defined as pre-season, and May to September as in-season. In-season and pre-season mean temperature and mean precipitation were calculated for each year.

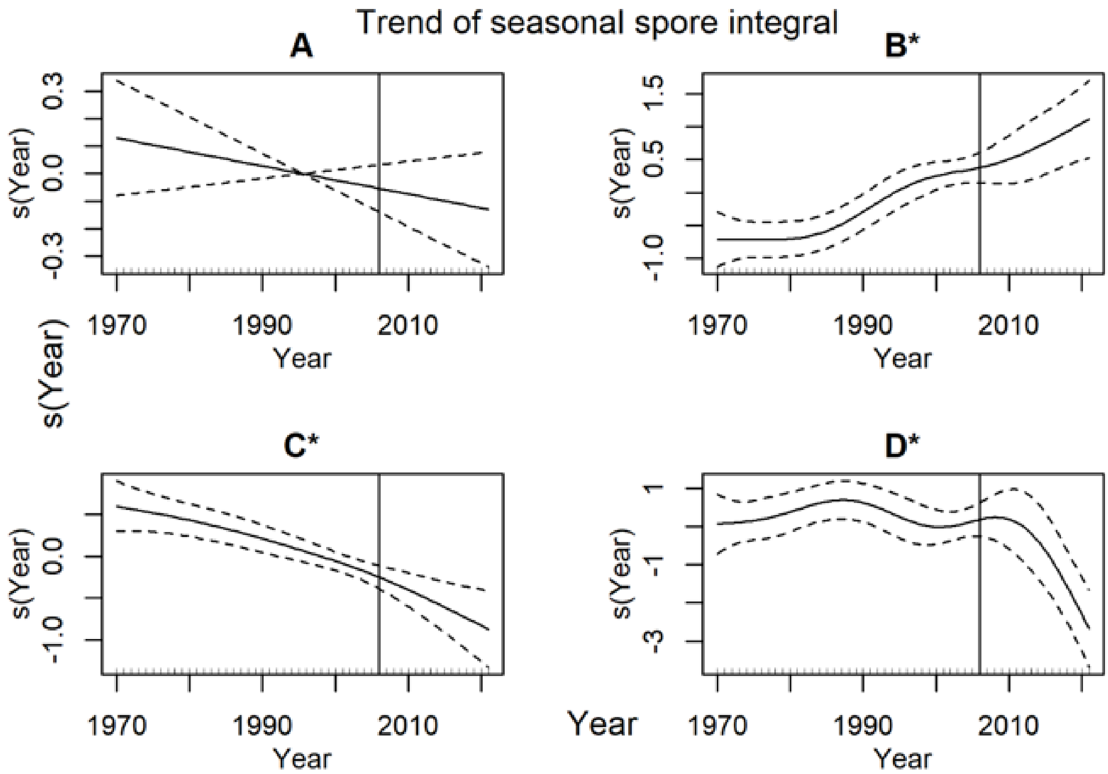
The long-term trend of the 2 spore indices were examined by using a generalized additive model (GAM) for time series (120). The model allows the assessment of the potential non-linear yearly trend of spore indices with the adjustment of location. Gamma distribution was adopted for the positively skewed spore indices. To observe if there are any overall upward or downward going trend of the spore indices, we regressed the indices against year using a smooth function (splines) with maximum one degree of freedom for each 10 years. The best degree of freedom was then determined through considering the general cross validation (GCV) score.

To evaluate the association between seasonal temperatures and the spore indices, we again applied the Gamma GAM and regressed the spore indices against a smooth function of each temperature variables. Seasonal integral was linked to in-season temperature, while the start of season was linked to pre-season temperature. All models were adjusted for decade, defined as every 10 years since 1970 and with 2020 and 2021 included in decade 5, to account for other unmeasured long-term factors such as change of plant composition. The intercorrelation within region was also adjusted using a random slope. In-season precipitation (later with pre-season precipitation) were further adjusted for in the seasonal integral analysis as literature suggested both pre- and in-season precipitation was associated with spore concentrations (31). Plots were created to visualize the estimated trends and associations.

Since the counts began in 1970 there has been an increasing trend for the seasonal integral for *Alternaria* and a decreasing trend for *Sporobolomyces* (Figure 7). We also see a decreasing trend for *Tilletiopsis* from 2010, but no significant trend for *Cladosporium*. In terms of the start of season, we observed a consistent trend of earlier start of season for 3 out of 4 genera between 1970 and the 2000s, except for *Alternaria* (Figure 8). The trends then attenuated and become unclear (indicated by the wide confidence intervals) which coincided with the movement of the spore traps from Derby to Leicester in 2006.

Figure 7. Trend of seasonal spore integral for A) *Cladosporium*, B) *Alternaria*, C) *Sporobolomyces* and D) *Tilletiopsis*

The y-axis shows the smooth function of the year term (that is, the contribution of year on log-transformed expected seasonal integral). The solid line shows the estimated trend. The dotted lines show the 95% confidence interval of the estimations. The vertical lines indicate the year 2006, when the spore traps were moved from Derby to Leicester. Significant trend (p<0.05) is marked with an asterisk (*).



The association between seasonal integral and in-season temperature appears to be opposite between dry-weather and wet-weather spores (Figure 9). Higher in-season temperatures were associated with higher concentration for *Cladosporium* and *Alternaria* but were associated with lower concentration for *Sporobolomyces* and *Tilletiopsis*. Warmer pre-season temperatures seem to have similar effects on the start of season for *Cladosporium*, *Alternaria* and *Sporobolomyces*, with an earlier start associated with warmer temperature (although on the negative association was only statistically significant for *Cladosporium*) (Figure 10). A non-significant positive trend was seen for *Tilletiopsis*.

Our analysis supports a positive association between in-season temperature and seasonal integral for the dry-weather fungal spores, *Cladosporium* and *Alternaria*. The warmer summer temperature in Derby and Leicester seems to be supporting the observed up-going trend of the seasonal integral for *Alternaria* in the past 5 decades. The increasing mean temperature in English summers caused by climate change will likely contribute to higher concentration of *Alternaria* spores in the summer, with the caveat that this would only occur until the increasing temperatures had a negative effect on the health of the plant-host for this pathogenic fungus. The effect of warming summers on *Cladosporium,* however, appears to be less certain. We did not see a convincing up-going trend for seasonal integral for *Cladosporium* in the past 5 decades despite its positive association with temperature. As mentioned in the previous section, the concentration of spores is known to be a mixed effect of different factors, including humidity. Our analysis indicates a negative association between in-season precipitation and concentration for *Cladosporium*. Thus, it's possible that the increasing annual precipitation in the past few decades might have cancelled out the positive effect of the rising summer temperature on *Cladosporium* concentration. A warmer and wetter climate in England will therefore have a mixed effect on *Cladosporium*. On the other hand, concentration integral for the 2 wet-weather spores had been decreasing and these are supported by their negative association with in-season temperature. Hotter summers in the future will likely have a negative effect of the concentration for the wet-weather spores *Sporoboloymces* and *Tilletiposis*.

Figure 8. Trend of start of season (in day-of-year) for A) *Cladosporium*, B) *Alternaria*, C) *Sporobolomyces* and D) *Tilletiopsis*

The y-axis shows the smooth function of the year-term (that is, the contribution of year on log-transformed expected start day of the season. Lower values indicate earlier starts). The solid curves show the estimated trend. The dotted curves show the 95% confidence interval of the estimations. The vertical lines indicate the year 2006, when the spore traps were moved from Derby to Leicester. Significant trends (p<0.05) are marked with an asterisk (*).

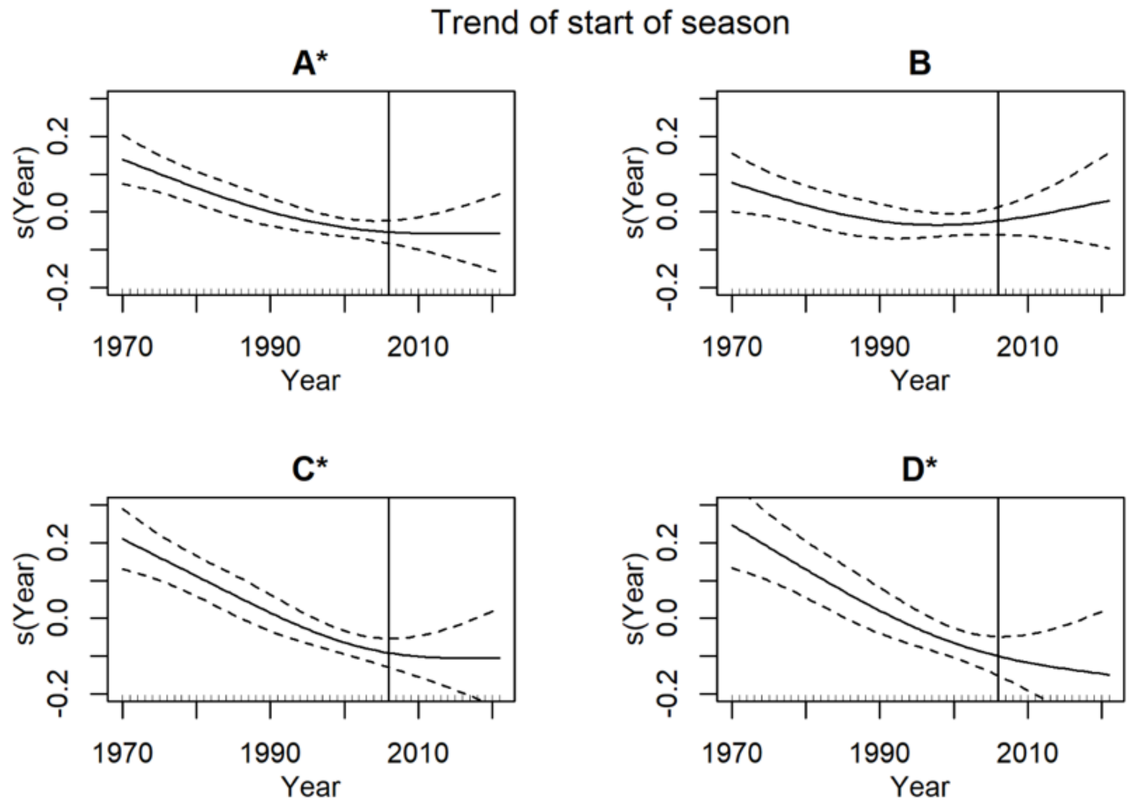
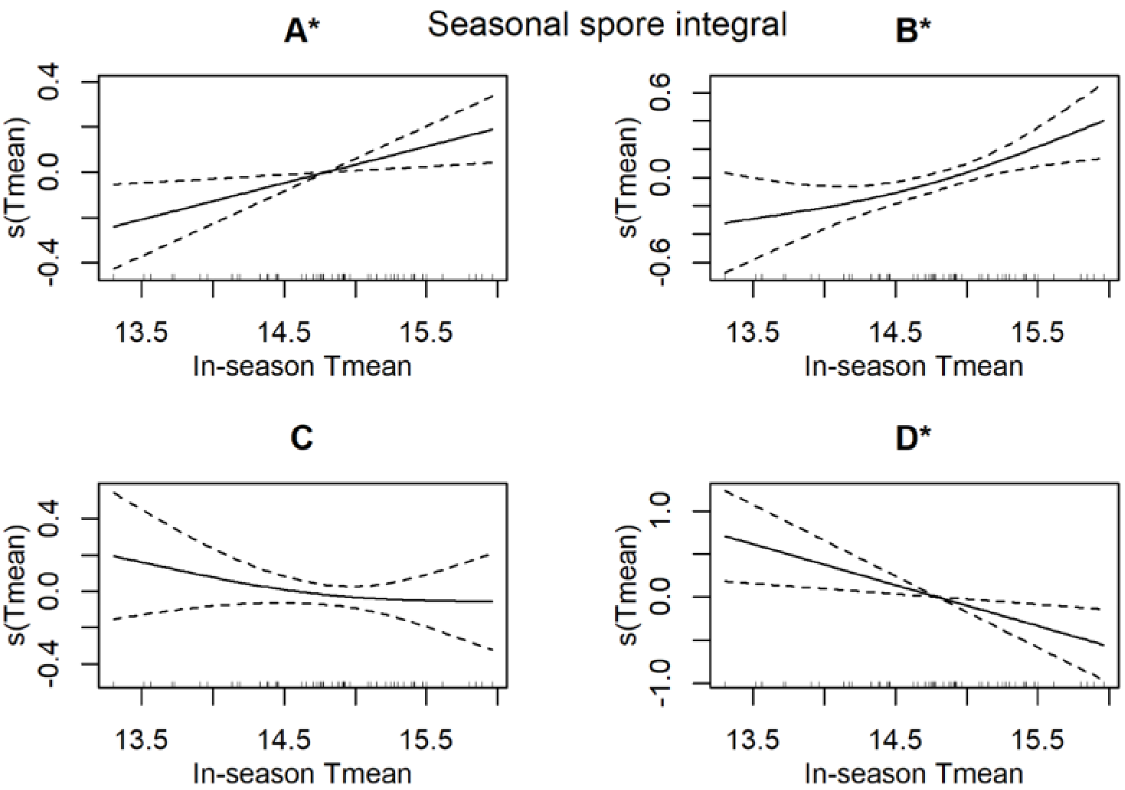


Figure 9. Association between in-season mean temperature and seasonal spore integral for A) *Cladosporium*, B*) Alternaria*, C) *Sporobolomyces* and D) *Tilletiopsis*

Models were adjusted for decade, location and in-season precipitation. The y-axis shows the smooth function of the corresponding temperature variable (that is, the contribution of temperature on the log-transformed expected seasonal integral when other variables in the model remained unchanged). The solid line shows the estimated association. The dotted lines show the 95% confidence interval of the estimations. The short vertical lines on x-axis show the distribution of the observations. Significant trend (p<0.05) is marked with an asterisk (*).

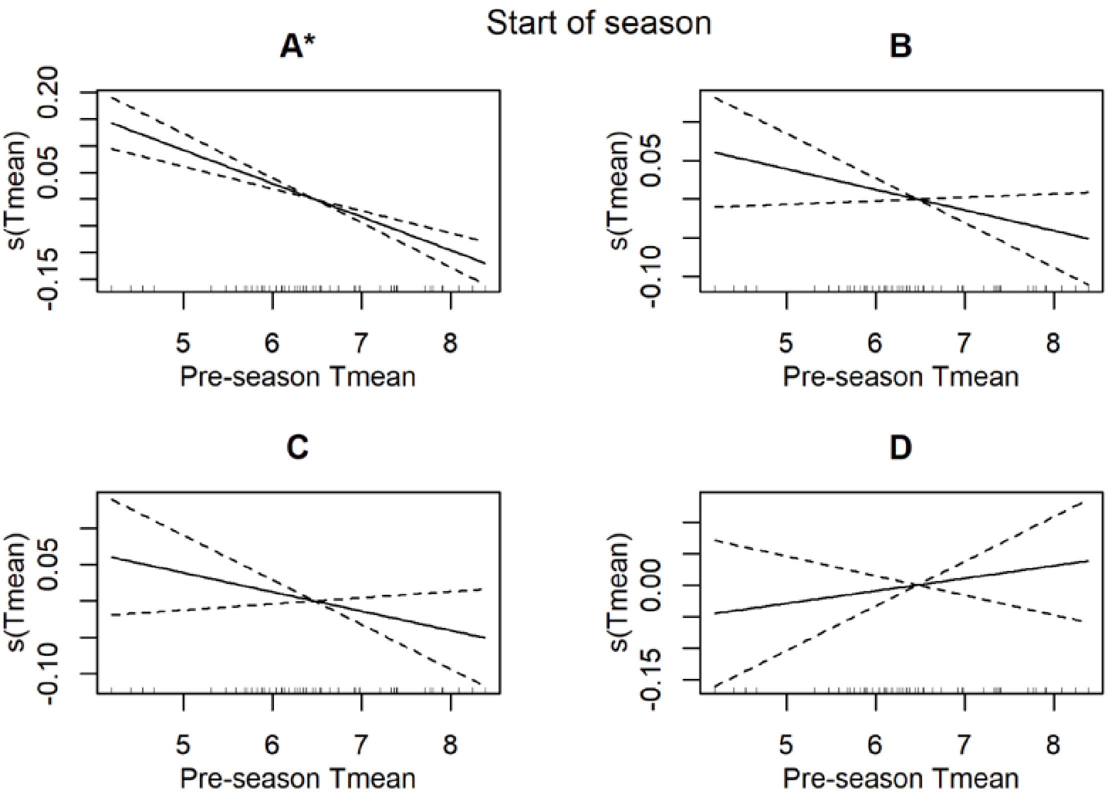


Cladosporium, *Alternaria* and *Sporobolomyces* had been having earlier starts of spore season from 1970 until the 2000s. This seems to be supported by their negative associations with temperature observed in this analysis (the warmer the pre-season temperature, the earlier start of season) and the warming temperature in February to April in the corresponding period. The relatively stable start of season observed in the recent 2 decades could be similar to that observed for the birch season, section 3.1 (56), related to the stable mean temperature between February and April in the study sites since 2000s. The *Tilletiopsis* season was also beginning earlier, however it appears to be less sensitive to pre-season temperature and, instead, showed a positive association with pre-season precipitation in our post hoc analysis. Nonetheless, if climate change is bringing a warmer and wetter climate to all seasons in England, we expect to see an earlier season for all these fungal spores.

This analysis benefited from a long-term data set, one of the longest ever published for fungal spores, and certainly the longest within the UK; yet it was not without limitations. We excluded the spore data from October to March, therefore, we only referred the start of season in relation to the concentration within April to September. There was a higher proportion of missing data in 2006 so we had to input the missing data by considering data from the same periods in other years, potentially compromising the accuracy of the trend estimations. In the same year, the spore trap sites were moved from Derby to Leicester. The 2 sites were found to be comparable for pollen data forecasting (14), however, this might further compromise the trends estimated around 2006, even though locations were adjusted for statistically. Estimation of trends near 2006 should thus be interpreted with caution. The yearly based analysis limited the statistical power and might not be able to capture weaker associations. We did not adjust for other known factors of fungal spore concentrations and season, such as CO_2, sunshine duration and land-use, due to the lack of information in this temporal scale. Factors that were not correlated with temperature (for example, CO_2) should have limited effect on our estimations. However, we failed to adjust for confounders of temperature and spore indices, for example, sunshine duration might cause overestimations of the associations with temperature. Finally, this analysis was limited to the East Midlands region in England and the results may not be generalized to wider regions, although experience from pollen would suggest that trends are similar across regions, albeit with variable timings and absolute values.

Figure 10. Association between pre-season mean temperature and start of season (in day-of-year) for A) *Cladosporium*, B) *Alternaria*, C) *Sporobolomyces* and D) *Tilletiopsis*

Models were adjusted for decade and location. The y-axis representing the smooth function of the year-term (that is, the contribution of temperature on the log-transformed expected start day of season when other variables remained unchanged. Lower values indicate earlier starts). The solid line shows the estimated association. The dotted lines show the 95% confidence interval of the estimations. The short vertical lines on x-axis show the distribution of the observations. Significant trend ($p<0.05$) is marked with an asterisk (*).



4.3 Aeroallergen potency and the interaction of pollution

Pollen grains contain proteins, which are the allergen particles that trigger the respiratory symptoms of hay fever and asthma. The allergen particles available for release are often referred to as the 'pollen potency', which can vary both temporally and spatially depending on a number of environmental factors (33, 92, 111, 121). In the few days before pollen is released, the allergens develop on the pollen grains. If particularly warm temperatures force the flowers to release pollen early, then less ripe and therefore less potent pollen will be dispersed and vice versa with a delayed onset (121).

Pollen potency is not something that is currently measured in the UK due to the complicated techniques involved. However, the European-wide HIALINE study (33, 122) demonstrated that the number of pollen grains and the amount of allergen in the atmosphere can differ from one another, both in the UK and in other countries.

Pollutants in the air, such as diesel exhaust particles (DEP), ozone (O_3) and carbon monoxide (CO), mainly from fossil fuel vehicle emissions, can increase pollen potency (111), particularly in urban areas. Moreover, pollutants can stress plants, causing a reduction in flowering but an increase in the pollen potency, which has been suggested as a plant strategy to ensure pollination efficiency (123). Pollutants also reduce the threshold of response to allergens in the respiratory system, particularly DEP and O_3, which cause increased airway reactivity and inflammation (124). Nitrogen dioxide (NO_2), O_3 and DEP have all been demonstrated to induce permeability of human bronchial epithelial cells while inhibiting ciliary beat frequency, which in turn may delay clearance of inhaled allergens and irritants (123). This means that people can suffer allergic disease at lower pollen concentrations than normal when DEP and O_3 levels are elevated, particularly if they live in areas with heavily polluted air, such as near busy roads. Symptoms of asthma were aggravated by O_3 and NO_2 (from vehicle exhaust) and SO_2 (from burning of sulphur-containing fossil fuels) interacting with allergenic pollen in the ambient air (125). Therefore, a combination of factors, such as warm temperatures with high pollution, can allow increased allergen load in the atmosphere. This allergen load may not correspond particularly well with the absolute pollen concentrations (111), so pollen counts can be indicative of allergen load but won't necessarily expose the full extent of it.

Most work has focused on pollen, whilst little is known about the interactions between pollutants and airborne fungal spores. Exposure to atmospheric CO_2 and gaseous urban air pollution (NO_2 and O_3) has been shown to increase the allergenicity of the fungus *A. fumigatus* (104, 126)*;* increased *Alternaria* spore allergenicity has been linked to higher seasonal pollution (elevated O_3, sulphur dioxide and other particulates (107)); and exposure to organic pollutants have been shown to favour the development of pathogenic trade-offs in plant pathogenic fungi (127).

According to the Office for Budget Responsibility, the projection for electric vehicles registered for use on UK roads by 2025 to 2026 is estimated at approximately 10% and rising on an exponential trend (128). From 2035, the sale of fossil fuel vehicles and hybrid vehicles will be banned. Thus, the sale of electric vehicles is already accelerating, and their share of the total registered road vehicles will exponentially rise over the next decade. As a result, the emission of pollutants that interact with allergens and allergy will also reduce. Currently, however, there is little quantification on the estimates for the reduction in allergy-related pollutants from vehicles in the UK. It can only be assumed that there will be health benefits for allergy sufferers once the proportion of fossil fuel vehicles on the UK roads drops down sufficiently.

4.4 Recent changes in UK plant phenology and relevance for allergenic pollen

Phenology is the study of recurring events in nature and their relationships with climate (meteorological events and variations including hourly to multi-decadal timescales) (129). For plants, the timing and magnitude of phenological events, such as budburst, leaf-out, flowering or senescence, are strongly influenced by climate variability, with different species and events responding to different climate drivers, such as temperature (warming and chilling), photoperiod and moisture availability (130 to 132). Multiple phenological records have shown that recent climate warming trends are associated with earlier spring, later autumn and longer growing season events for many plant species, particularly across temperate and boreal zones where the seasonality of vegetation and climate are closely related (133 to 135).

Pollen concentrations within a geographical region are mainly governed by the distribution of pollen producing vegetation (136). Over large geographical regions it has been shown that the abundance of ragweed plants correlates highly and statistically significantly with long term indices for pollen productivity such as the pollen integral (137). Current knowledge suggests that this principle may be applied to all pollen producing plants. Changes in plant species composition within a region can have a considerable impact on pollen concentrations both locally and remotely. A good example is ragweed, where its invasion of new areas in France has significantly increased pollen concentration (138). As the climate changes, non-native plants can invade an area, as seems to be occurring in central and northern France for ragweed and is predicted for the UK by 2050 (139).

In the UK, many thousands of observations from the citizen science phenology network, Nature’s Calendar, demonstrate strong sensitivities between spring climate and the timing of phenological events for a wide range of plant species (140). For example, the timing of budburst for 10 common tree species is significantly related to March or April temperature across the UK, with a 1°C lower (or higher) average temperature in these months associated with up to 6 days later (or earlier) average budburst (141). Similarly, the average date of first flowering for 406 plant species in the UK has become earlier by an average of 5.4 days per decade between 1952 and 2019, and this is significantly correlated with warmer temperatures during spring (142). The largest shifts occurred in herb species (less than 20cm tall, including grasses) probably because they are characterised by fast turnover rates and rapid responses to environmental change (142).

Human allergic reactions to pollen are triggered by changes in the concentration and/or type of allergenic pollen grains in the lower atmosphere (see section 1.2.1). These changes are strongly influenced by the location and phenology of allergenic plant types (species or broader groupings) and the mechanisms by which their pollen grains are emitted and dispersed in the atmosphere (124, 143 to 145). Climate variations and thresholds regulate many of the processes that determine the location, timing and concentration of pollen in the air, including:

- distribution and productivity of plant species (146)
- development of pollen grains (147)
- timing of flowering (142, 148)
- timing and amount of pollen emissions into the atmosphere (52, 149)
- dispersion of pollen grains within the atmosphere (150)

Despite the multiple processes involved, clear relationships have been noted between the seasonal timing and magnitude of airborne pollen concentrations for different plant types and the observed climate conditions, particularly temperature (53, 63). In the UK, the recent shift to earlier and prolonged flowering periods (142) would have increased the exposure of the population to airborne pollen spores and extended the pollen and spore allergy seasons for some types (75, 151), likely providing a major driver for recent increases in hospital admissions (152, 153). Future projected changes in climate, atmospheric CO_2 concentration, land use and other environmental factors are expected to further increase seasonal pollen and spore production for certain types and the health burden of seasonal allergies (145).

4.5 Effect of land-use changes on pollen seasons

Besides climate change effects, it is likely that changes in land-use are also affecting the pollen and fungal-spore seasons. Changes in woodland and grassland area are likely to be impacting on both grass and tree SPIns and on any fungal pathogens that utilise these as hosts. A recent study reported that almost 2 million hectares of UK grassland were lost to both urbanisation and woodland between 1990 and 2015 (154) and research has shown that loss of grassland leads locally to reduced grass SPIn (155). It can be assumed that the increase in woodland, which is likely to continue, will contribute to the pollen levels from trees such as birch, alder and eventually oak (the latter taking decades to reach flowering maturity). However, the pattern of these changes across the UK is likely to be uneven and may not have any impact on seasonal respiratory allergy in any areas where changes are negligible. Ash (*Fraxinus* spp.) pollen is likely to see a sharp decline as the effects of ash die-back disease take hold. Approximately 80% of ash trees are expected to die in the UK (156).

The UK government currently has a tree planting scheme in place entitled the ‘Urban Tree Challenge Fund’ (157), aimed at helping the UK meet the 2050 net zero target on carbon emissions. The guide associated with this project, the ‘Urban Tree Manual’, gives only very limited advice on how to avoid planting highly allergenic trees (157). It is recommended that the government enhance the information on the Urban Tree Challenge Fund website to avoid unnecessary increases in tree pollen concentrations in urban areas.

4.6 Health effects of airborne allergens

We know climate change is expected to increase the incidence of atopic disease (31). Whilst there are links between aeroallergen exposure and incidences of asthma, allergic rhinitis, and other atopic conditions, few longitudinal cohort studies can demonstrate these effects sufficiently in a population.

Allergic rhinitis (AR) is a global health problem affecting an estimated 500 million people worldwide (158). Rhinitis is an inflammation of the lining of the nose characterised by nasal symptoms such as anterior or posterior rhinorrhoea, nasal blockage, sneezing and itching of the nose, and occurring during 2 or more consecutive days for more than one hour on most days. The symptoms can negatively affect individuals' sleep (159), performance at school (160) and work (161). In addition, AR has substantial financial costs to society; in Sweden, it is estimated to cost the economy approximately €2.7 billion annually (162). The prevalence of AR is increasing worldwide, with some countries describing over 50% of adolescents self-reporting compatible symptoms (163). In the UK, prevalence among adults has been estimated at 26% (95% CI 20.3% to 30.7%) (164).

Routinely, the UKHSA real-time syndromic surveillance service monitors seasonal trends in AR. This is primarily through AR consultations recorded in a network of general practitioners (GP) across England. Surveillance is undertaken throughout the year; however, seasonal trends in AR follow distinct patterns with an initial increase in April to May followed by a second larger peak in June. Collecting and monitoring GP consultations provides a further opportunity to study and understand AR presentations in the community.

A retrospective, time series analysis of GP consultations for AR using data between 3 April 2012 and 11 August 2014 looked at how changes in pollen counts, temperature and pollutants were associated with presentations for AR (165). High grass and nettle pollen counts (combined) were associated with the highest increases in consultations (for the category 216 to 270 grains/m^3, relative risk (RR) 3.33, 95% CI: 2.69 to 4.12) followed by high tree (oak, birch and plane combined) pollen counts (for the category 260 to 325 grains/m^3, RR 1.69, 95% CI: 1.32 to 2.15) and average daily temperatures between 15°C and 20°C (RR 1.47, 95% CI: 1.20 to 1.81) (165). Higher levels of NO_2 were associated with increased consultations (for the category 70 to 85μg/m^3, RR 1.33, 95% CI: 1.03 to 1.71), but no significant effect was found with O_3. Higher daily rainfall was associated with fewer consultations (15mm to 20mm/day; RR 0.812, 95% CI: 0.674 to 0.980). Changes in grass, nettle or tree pollen counts, temperatures between 15°C and 20°C, and (to a lesser extent) NO_2 concentrations were found to be associated with increased consultations for AR. In the context of climate change and continued exposures to environmental air pollution, intelligent use of this data will aid targeting public health messages and plan healthcare demand (165).

With regards to fungal spore exposures, evidence is particularly lacking, including a limited knowledge of the deeper taxonomic groups that may be involved with allergic sensitisation but cannot be distinguished via microscopy. Further research can address this gap via the use of molecular methods, such as high-throughput sequencing (HTS), to better characterise the composition of fungal spores in the air. Public health records, such as syndromic based counts, can act as effective proxies to episodic incidences of atopic illnesses including asthma. In analyses involving both allergen exposure and health outcomes, long-term, consistent records are required to overcome regular seasonal patterns, and to achieve the statistical power required to detect the small but important effects of aeroallergens amongst other relevant factors, including air pollution and respiratory viral infections.

4.7 Improved methods for monitoring airborne allergens

Whilst the impact of bioaerosols is a source of public concern, there is scientific uncertainty and lack of data regarding exposure levels and geographic variability, particularly for fungal spores. To fill this evidence gap, there is a need for robust approaches that can generate real-time measurements capable of identification and quantification of bioaerosols, and there is a need for methodology that can be routinely used by non-specialists. In recent years, the detection of bioaerosols has been revolutionised by the introduction of samplers capable of autonomous and continuous real-time (RT) or near-RT analysis (166). Three commercial devices are available for the automated real-time analysis of bioaerosols. The BAA500 was one of the earlier devices and is used in the ePIN pollen monitoring network established in Bavaria, Germany (167). The device is inspired by the manual pollen monitoring methodology, with samples collected and fed through a microscope system. The scope of the device is restricted to particles greater than 10μm, which are mostly pollen and some larger fungal spores. As such it is unsuitable for the identification of most airborne fungal spores. The Swisens-Poleno and Rapid-E (Plair) both use laser-induced fluorescence (LIF) technology to discriminate between biological particles and use multiple excitation wavelengths to improve discrimination and reduce false positives. The optical data is continuously downloaded and accessible in real time. The Swisens-Poleno also uses digital holography to reconstruct images of airborne particles, providing the possibility for external verification of analyses. It was selected as the sampler for a network of samplers in Switzerland focused on pollen identification. The UV-LIV measurements of the Swisens-Poleno have been shown to be useful for the automatic discrimination of fungal spores in addition to pollen (168). In the UK, the University of Worcester own a Rapid-E, and the University of Manchester a Swisens-Poleno. These types of instruments have shown good performance for a number of key pollen types, but there continue to be challenges in the separation of specific key pollen allergens demonstrated for grass under laboratory conditions (169). Larger studies covering common aeroallergens detected at traditional monitoring sites are scarce. Evidence on their capability to fully quantify the spore community has not yet been produced, although preliminary data from the Swisens-Poleno shows promise. The full capability of these real-time instruments has not yet been fully explored for pollen or fungal spores, and the underlying technology, potentially both hardware and software, may need to be developed to robustly quantify aeroallergens.

With the demonstration of substantial quantities of airborne pollen allergen outside the pollen season, the question arises as to whether the traditional pollen and fungal spore count is a correct measurement of aeroallergens. This point is still being debated as researchers are not in agreement (15).

5. Policy review

Given that airborne pollen and fungal spores are a ubiquitous part of our ecosystem, with levels intricately dictated by natural phenomenon, it is hard to produce effective policy to control levels. The lack of clinically defined thresholds for most pollen and fungal spores further complicates the matter. Nevertheless, there are actions which can alleviate the health burden caused by aeroallergens; for example, imposing distance regulations and emission levels on businesses such as industrial composting sites that produce known aeroallergens (170). Furthermore, there are policies relating to reducing the effects of climate change, detailed below, which could have a negative effect on human health due to their impact on aeroallergens unless urgent care is taken.

Trees are amazing at carbon capture and storage. Woods and forests absorb atmospheric carbon and as such have become our allies in the fight against climate change (171). Unsurprisingly, there are numerous drives to plant more trees, and tree planting is a key part of the UK government's plan to combat climate change. They have committed to increasing tree-planting rates to 30,000 hectares per year by March 2025, which equates to 90 million to 120 million trees planted each year (172). The UK National Health Service also has a tree-planting scheme in operation (173).

Some say the best trees to combat climate changes are broadleaved species such as oak, beech and maple, which have a larger surface area of leaves (174). Silver birch, yew, plane and elder have been shown to be highly effective at capturing air pollution particles due to the hairs of their leaves (175), whilst others say conifers offer the best particulate matter (a major source of air pollution) reduction because they are evergreen (176). All of the trees mentioned above are known to produce allergenic pollen. Silver birch in particular is used as a street tree in part due to a study recommending it as a biofilter (177). However, birch pollen is the major pollen-allergen-producing tree in northern Europe (15), and the second most common pollen allergen in the UK after grass.

There are actions that can be taken to reduce the allergenic burden that some wind-pollinated trees create. Some cities have banned the planting of specific trees that produce highly allergenic pollen: olive trees in Pima County, Arizona, US (178) and Oujda, Morocco, North Africa (179), birch trees in Aarhus, Denmark (180), and cypress and mulberry in Albuquerque, New Mexico, US (181) are all banned. In Marydale Park, Canada, a low allergen forest has been planted (182). Other places have allergen information available in tree selections tools such as Citree website used in Dresden, Germany (183) or Queux's Allergy Friendly plants website in Guernsey, UK (184). There are trees available that produce less or no pollen or trees that produce heavier pollen that is less likely to drift on the wind and cause allergy symptoms. In the interests of public health and reducing the burden of disease from aeroallergens, consideration of tree diversity and the type of pollen produced by trees, will be important for future tree planting schemes.

6. Summary and research priorities

Recent research on pollen trends and climatic changes in the UK has revealed a very mixed picture as detailed in this chapter. The pollen trends available to date for the UK (56) provide a starting point on which to build the estimates of potential for future pollen seasons. In a dynamic climate such as in the UK, high temporal and spatial variation in pollen seasons is likely to continue. Climate projections suggest that more extreme weather events of heat and rainfall and a general increase in temperatures and rainfall, will impact on the seasons in the decades to come both positively and negatively. Alder and birch pollen seasons are expected to continue to increase in severity in the Midlands and further north and west during the next 2 decades. Grass and nettle family pollen seasons are expected to maintain an overall flat trend for the total yearly pollen catch. However, an increase in pollen potency, which may start declining from the 2030s, is likely to enhance the season for hay fever sufferers in most years. The first occurrence of a high day is likely to trend earlier for alder, oak and grass pollen. Pollen season duration will remain very variable overall. Regular research will be required to keep abreast of the changing trends and to update the public and organisations who are affected by seasonal respiratory allergy, and the development of taxa-specific forecasts for key aeroallergens would help with allergy management.

It is likely that the variability of the UK weather partly explains why there were several flat trends revealed in the pollen trends research by Adams-Groom and colleagues (56) and the additional data presented here. Some of the key monthly meteorological variables that are known to drive the variation in the seasons do not yet show significant trends, although this may change in the future as climate change progresses. Moreover, the impact of one weather variable on pollen seasons can be counteracted or cancelled out by another one. For example, higher temperatures between May and August caused greater grass pollen season severity, while windy weather during May to August led to a reduction. Although the temperature trends acted positively in some of these months, the wind speeds acted negatively, with an overall flat trend in the pollen levels (56).

Our 52-year time-series analysis of airborne fungal spores in the East Midlands region of the UK observed an increasing trend of spore count integral for *Alternaria* and decreasing trends for *Sporobolomyces* and *Tilletiopsis*. We also saw a trend of advancing the start of season for all considered spores between 1970 and the 2000s. Our analysis suggested that these trends were partly associated with the warmer seasonal temperatures (mainly in spring and summer) and/or higher seasonal precipitation in the corresponding periods. Climate change is likely to bring warmer and wetter weather in England (71), meaning that without adaptation, a higher count integral for *Alternaria*, reduced count integral for *Sporobolomyces* and *Tilletiopsis*, and an earlier start of season for all spores considered including *Cladosporium* could be seen. Further analyses of this data are required to fully understand the relationship between climate and airborne fungal spores, as well as studies to investigate how the seasons change in differing regions across the UK. Given the dearth of historical morphological spore data from other regions, and the difficulties in counting fungal spores manually, this would best be generated prospectively using alternative methods such as the use of real-time monitoring or DNA-based technologies.

Research priorities (185, 186) to provide further evidence of the effects of climate change on aeroallergens include:

- evidence-based, allergy-specific research to inform urban planning and green infrastructure development
- continued long-term monitoring of pollen across the UK, including new sites where applicable, in Scotland, Wales and Northern Ireland
- development of a long-term fungal spore monitoring system similar to that of the UK pollen network
- development of taxa-specific forecasts for key aeroallergens to help with allergy management
- robust approaches that can generate real-time measurements capable of identification and quantification of bioaerosols
- a clearer understanding of airborne fungal biodiversity potentially aided by further use of high-throughput sequencing methods to better characterise composition of fungal spores in the air
- understanding the complex interplay between climate change, host species availability, incidence of extreme weather events, land-use patterns and fungal sporulation patterns using long-term data sets
- further research on the potential reduction in allergy-related pollutants from vehicles in the UK as electric vehicles become more prevalent and the potential effects on human allergy

Acronyms and abbreviations

Abbreviation	Meaning
AR	allergic rhinitis
DEP	diesel exhaust particles
GAM	general additive model
HECC	Health Effects of Climate Change in the UK report
eDNA	DNA obtained from an environmental source
IUIS	International Union of Immunological Societies
NH	number of high pollen days
NO_2	nitrogen dioxide
O_3	ozone
RR	relative risk
RT	real-time
SO_2	sulphur dioxide
SPIn	seasonal pollen integral
SSIn	seasonal spore integrals
spp.	species (plural)
SPTs	skin prick tests

References

1. Department of Health (2002). 'Health Effects of Climate Change in the UK'
2. Health Protection Agency (HPA) (2008). 'Health Effects of Climate Change in the UK 2008: an update of the Department of Health report 2001 to 2002' Kovats S, editor
3. HPA (2012). 'Health Effects of Climate Change in the UK 2012' Vardoulakis S, Heaviside C, editors
4. Scadding GK, Kariyawasam HH, Scadding G, Mirakian R, Buckley RJ, Dixon T, and others (2017). 'BSACI guideline for the diagnosis and management of allergic and non-allergic rhinitis (Revised Edition 2017; First edition 2007)' Clinical and Experimental Allergy: volume 47, pages 856 to 889
5. World Health Organization (WHO) (2012). 'Atlas of Health and Climate' World Meteorological Organization, editors
6. Kurup VP, Shen HD, Banerjee B (2000). 'Respiratory fungal allergy' Microbes and Infection: volume 2, pages 1101 to 1110
7. Targonski P V, Persky VW, Ramekrishnan V (1995). 'Effect of environmental moulds on risk of death from asthma during the pollen season' Journal of Allergy and Clinical Immunology: volume 95, pages 955 to 961
8. Delfino RJ, Zeiger RS, Seltzer JM, Street DH, Matteucci RM, Anderson PR, and others (1997). 'The effect of outdoor fungal spore concentrations on daily asthma severity' Environmental Health Perspectives: volume 105, pages 622 to 635
9. Black PN, Udy AA, Brodie SM (2000). 'Sensitivity to fungal allergens is a risk factor for life-threatening asthma' Allergy: volume 55, pages 501 to 504
10. Zureik M, Neukirch C, Leynaert B, Liard R, Bousquet J, Neukirch F (2002). 'Sensitisation to airborne moulds and severity of asthma: cross sectional study from European Community respiratory health survey' BMJ: .volume 325, pages 411 to 414
11. Horner WE, Helbling A, Salvaggio JE, Lehrer SB (1995). 'Fungal allergens' Clinical Microbiology Reviews: volume 8, pages 161 to 179
12. Del Giacco SR, Bakirtas A, Bel E, Custovic A, Diamant Z, Hamelmann E, and others (2017). 'Allergy in severe asthma' Allergy: volume 72, pages 207 to 220
13. de Vere N, Rich TC, Ford CR, Trinder SA, Long C, Moore CW, and others (2012). 'DNA barcoding the native flowering plants and conifers of Wales' PLoS ONE: volume 7, page e37945
14. Pashley CH, Fairs A, Edwards RE, Bailey JP, Corden JM, Wardlaw AJ (2009). 'Reproducibility between counts of airborne allergenic pollen from 2 cities in the East Midlands, UK' Aerobiologia: volume 25, pages 249 to 263
15. D’Amato G, Cecchi L, Bonini S, Nunes C, Annesi-Maesano I, Behrendt H, and others (2007). 'Allergenic pollen and pollen allergy in Europe' Allergy: volume 62, pages 976 to 990
16. Oh JW (2022). 'Pollen allergy in a changing planetary environment' Allergy, Asthma and Immunology Research: volume 14, pages 168 to 181
17. Emberlin J, Mullins J, Corden J, Millington W, Brooke M, Savage M, and others (1997).

'The trend to earlier birch pollen seasons in the U.K.: a biotic response to changes in weather conditions?' Grana: volume 36, pages 29 to 33
18. Knox B, Suphioglu C (1996). 'Environmental and molecular biology of pollen allergens' Trends in Plant Science: volume 1, pages 156 to 164
19. Brennan GL, Potter C, de Vere N, Griffith GW, Skjøth CA, Osborne NJ, and others (2019). 'Temperate airborne grass pollen defined by spatio-temporal shifts in community composition' Nature Ecology and Evolution: volume 3, pages 750 to 754
20. Rowney FM, Brennan GL, Skjøth CA, Griffith GW, McInnes RN, Clewlow Y, and others (2021). 'Environmental DNA reveals links between abundance and composition of airborne grass pollen and respiratory health' Current Biology: volume 31, pages 1995 to 2003
21. Adams-Groom B, Ambelas Skjøth C, Selby K, Pashley C, Satchwell J, Head K, and others (2020). 'Regional calendars and seasonal statistics for the United Kingdom's main pollen allergens' Allergy: volume 75, pages 1492 to 1494
22. Bucher E, Kofler V (2022). 'Pollen atlas'
23. Hawksworth DL, Lücking R (2017). 'Fungal diversity revisited: 2.2 to 3.8 million species' Microbiology Spectrum: volume 5, page 5.4.10
24. Levetin E, Horner WE, Scott JA (2016). 'Taxonomy of allergenic fungi' Journal of Allergy and Clinical Immunology: volume 4, pages 375 to 385.e1
25. Pashley CH, Fairs A, Free RC, Wardlaw AJ (2012). 'DNA analysis of outdoor air reveals a high degree of fungal diversity, temporal variability, and genera not seen by spore morphology' Fungal Biology: volume 116, pages 214 to 224
26. Fairs A, Wardlaw AJ, Thompson JR, Pashley CH (2010). 'Guidelines on ambient intramural airborne fungal spores' Journal of Investigational Allergology and Clinical Immunology: volume 20, pages 490 to 498
27. Burge HA (2002). 'An update on pollen and fungal spore aerobiology' Journal of Allergy and Clinical Immunology: volume 110, pages 544 to 552
28. Pashley CH, Wardlaw AJ (2021). 'Allergic fungal airways disease (AFAD): an under-recognised asthma endotype' Mycopathologia: volume 186, pages 609 to 622
29. Knutsen AP, Bush RK, Demain JG, Denning DW, Dixit A, Fairs A, and others (2012). 'Fungi and allergic lower respiratory tract diseases' Journal of Allergy and Clinical Immunology: volume 129, pages 280 to 283
30. Gravesen S (1979). 'Fungi as a cause of allergic disease' Allergy: volume 34, pages 135 to 154
31. Paudel B, Chu T, Chen M, Sampath V, Prunicki M, Nadeau KC (2021). 'Increased duration of pollen and mould exposure are linked to climate change' Scientific Reports: volume 11, page 12816
32. Galan C, Antunes C, Brandao R, Torres C, Garcia-Mozo H, Caeiro E, and others (2013). 'Airborne olive pollen counts are not representative of exposure to the major olive allergen Ole e 1' Allergy: European Journal of Allergy and Clinical Immunology: volume 68, pages 809 to 812
33. Buters J, Prank M, Sofiev M, Pusch G, Albertini R, Annesi-Maesano I, and others (2015). 'Variation of the group 5 grass pollen allergen content of airborne pollen in relation to

geographic location and time in season' Journal of Allergy and Clinical Immunology: volume 136, pages 87 to 95.e6
34. Maya-Manzano JM, Oteros J, Rojo J, Traidl-Hoffmann C, Schmidt-Weber C, Buters J (2022). 'Drivers of the release of the allergens Bet v 1 and Phl p 5 from birch and grass pollen' Environmental Research: volume 214, page 113987
35. Lacey ME, West JS (2006). 'The air spora - a manual for catching and identifying airborne biological particles' Dordrecht: Springer, page 156
36. British Aerobiology Federation (1995). 'Airborne pollens and spores: a guide to trapping and counting'
37. Adamov S, Lemonis N, Clot B, Crouzy B, Gehrig R, Graber MJ, and others (2021). 'On the measurement uncertainty of Hirst-type volumetric pollen and spore samplers' Aerobiologia: volume special issue
38. Galan C, Ariatti A, Bonini M, Clot B, Crouzy B, Dahl A, and others (2017). 'Recommended terminology for aerobiological studies' Aerobiologia: volume 33, pages 293 to 295
39. Hart ML, Wentworth JE, Bailey JP (1994). 'The effects of trap height and weather variables on recorded pollen concentration at Leicester' Grana: volume 33, pages 100 to 103
40. Rojo J, Oteros J, Pérez-Badia R, Cervigón P, Ferencova Z, Gutiérrez-Bustillo AM, and others (2019). 'Near-ground effect of height on pollen exposure' Environmental Research: volume 174, pages 160 to 169
41. de Weger LA, Molster F, de Raat K, den Haan J, Romein J, van Leeuwen W, and others (2020). 'A new portable sampler to monitor pollen at street level in the environment of patients' Science of The Total Environment: volume 741, page 140404
42. Katelaris CH, Burke T V, Byth K (2004). 'Spatial variability in the pollen count in Sydney, Australia: can one sampling site accurately reflect the pollen count for a region?' Annals of Allergy, Asthma and Immunology: volume 93, pages 131 to 136
43. Skjøth CA, Ørby P V, Becker T, Geels C, Schlünssen V, Sigsgaard T, and others (2013). 'Identifying urban sources as cause of elevated grass pollen concentrations using GIS and remote sensing' Biogeosciences: volume 10, pages 541 to 554
44. Frisk CA, Apangu GP, Petch GM, Adams-Groom B, Skjøth CA (2022). 'Atmospheric transport reveals grass pollen dispersion distances' Science of The Total Environment: volume 814, page 152806
45. Sadyś M, Adams-Groom B, Herbert RJ, Kennedy R (2016). 'Comparisons of fungal spore distributions using air sampling at Worcester, England (2006 to 2010)' Aerobiologia: volume 32, pages 619 to 634
46. Rick EM, Woolnough KF, Seear PJ, Fairs A, Satchwell J, Richardson M, and others (2020). 'The airway fungal microbiome in asthma' Clinical and Experimental Allergy: volume 50, pages 1325 to 1341
47. Pashley CH (2014). 'Fungal culture and sensitisation in asthma, cystic fibrosis and chronic obstructive pulmonary disorder: what does it tell us?' Mycopathologia: volume 178, pages 457 to 463
48. Bousquet J, Heinzerling L, Bachert C, Papadopoulos NG, Bousquet PJ, Burney PG, and others (2012). 'Practical guide to skin prick tests in allergy to aeroallergens' Allergy:

volume 67, pages 18 to 24
49. Lupinek C, Wollmann E, Baar A, Banerjee S, Breiteneder H, Broecker BM, and others (2014). 'Advances in allergen-microarray technology for diagnosis and monitoring of allergy: the MeDALL allergen-chip' Methods: volume 66, pages 106 to 119
50. Met Office (2021). 'UK regional climates'
51. Ziello C, Sparks TH, Estrella N, Belmonte J, Bergmann KC, Bucher E, and others (2012). 'Changes to airborne pollen counts across Europe' PLoS ONE: volume 7, page e34076
52. Ziska LH, Makra L, Harry SK, Bruffaerts N, Hendrickx M, Coates F, and others (2019). 'Temperature-related changes in airborne allergenic pollen abundance and seasonality across the northern hemisphere: a retrospective data analysis' Lancet Planet Health: volume 3, pages e124 to e131
53. Emberlin J, Detandt M, Gehrig R, Jaeger S, Nolard N, Rantio-Lehtimäki A (2002). 'Responses in the start of *Betula* (birch) pollen seasons to recent changes in spring temperatures across Europe' International Journal of Biometeorology: volume 46, pages 159 to 170
54. Skjøth CA, Kurganskiy A, Grundstrom M, Werner M, Adams-Groom B (2021). 'Air pollution affecting pollen concentrations through radiative feedback in the atmosphere' Atmosphere: volume 12, page 1376
55. Skjøth CA, Smith M, Brandt J, Emberlin J (2009). 'Are the birch trees in Southern England a source of *Betula* pollen for North London?' International Journal of Biometeorology: volume 53, pages 75 to 86
56. Adams-Groom B, Selby K, Derrett S, Frisk CA, Pashley CH, Satchwell J, and others (2022). 'Pollen season trends as markers of climate change impact: *Betula*, *Quercus* and *Poaceae*' Science of the Total Environment: volume 831, page 154882
57. Hoebeke L, Bruffaerts N, Verstraeten C, Delcloo A, De Smedt T, Packeu A, and others (2018). 'Thirty-four years of pollen monitoring: an evaluation of the temporal variation of pollen seasons in Belgium' Aerobiologia: volume 34, pages 139 to 155
58. Besancenot JP, Sindt C, Thibaudon M (2019). 'Pollen et changement climatique. Bouleau et graminées en France métropolitaine' Revue Française d'Allergologie: volume 59, pages 563 to 575
59. Jochner-Oette S, Menzel A, Gehrig R, Clot B (2019). 'Decrease or increase? Temporal changes in pollen concentrations assessed by Bayesian statistics' Aerobiologia: volume 35, pages 153 to 163
60. de Weger LA, Bruffaerts N, Koenders MMJF, Verstraeten WW, Delcloo AW, Hentges P, and others (2021). 'Long-term pollen monitoring in the Benelux: evaluation of allergenic pollen levels and temporal variations of pollen seasons' Frontiers in Allergy: volume 2, page 676176
61. Glick S, Gehrig R, Eeftens M (2021). 'Multi-decade changes in pollen season onset, duration, and intensity: a concern for public health?' Science of The Total Environment: volume 781, page 146382
62. Lind T, Ekebom A, Alm Kübler K, Östensson P, Bellander T, Lõhmus M (2016). 'Pollen season trends (1973 to 2013) in Stockholm area, Sweden' PLoS One: volume 11, page e0166887

63. Bruffaerts N, De Smedt T, Delcloo A, Simons K, Hoebeke L, Verstraeten C, and others (2018). 'Comparative long-term trend analysis of daily weather conditions with daily pollen concentrations in Brussels, Belgium' International Journal of Biometeorology: volume 62, pages 483 to 491
64. Ruiz-Valenzuela L, Aguilera F (2018). 'Trends in airborne pollen and pollen-season-related features of anemophilous species in Jaen (south Spain): a 23-year perspective' Atmospheric Environment: volume 180, pages 234 to 243
65. Rojo J, Oteros J, Picornell A, Maya-Manzano JM, Damialis A, Zink K, and others (2021). 'Effects of future climate change on birch abundance and their pollen load' Global Change Biology: volume 27, pages 5934 to 5949
66. Rojo J, Picornell A, Oteros J, Werchan M, Werchan B, Bergmann KC, and others (2021). 'Consequences of climate change on airborne pollen in Bavaria, Central Europe' Regional Environmental Change: volume 21, page 9
67. Recio M, Picornell A, Trigo MM, Gharbi D, García-Sánchez J, Cabezudo B (2018). 'Intensity and temporality of airborne *Quercus* pollen in the southwest Mediterranean area: correlation with meteorological and phenoclimatic variables, trends and possible adaptation to climate change' Agricultural and Forest Meteorology: volume 250–251, pages 308–18
68. Gehrig R, Clot B (2021). '50 years of pollen monitoring in Basel (Switzerland) demonstrate the influence of climate change on airborne pollen' Frontiers in Allergy: volume 2, page 677159
69. Emberlin J, Smith M, Close R, Adams-Groom B (2007). 'Changes in the pollen seasons of the early flowering trees *Alnus* spp. and *Corylus* spp. in Worcester, United Kingdom, 1996 to 2005' International Journal of Biometeorology: volume 51, pages 181 to 191
70. Kurganskiy A, Creer S, de Vere N, Griffith GW, Osborne NJ, Wheeler BW, and others (2021). 'Predicting the severity of the grass pollen season and the effect of climate change in Northwest Europe' Science Advances: volume 7, page eabd7658
71. Kendon M, McCarthy M, Jevrejeva S, Matthews A, Sparks T, Garforth J (2021). 'State of the UK Climate 2020' International Journal of Climatology: volume 41, pages 1 to 76
72. Dunn RJH, Alexander L V, Donat MG, Zhang X, Bador M, Herold N, and others (2020). 'Development of an updated global land in situ-based data set of temperature and precipitation extremes: HadEX3' Journal of Geophysical Research: Atmospheres: volume 125, page e2019JD032263
73. Vautard R, van Aalst M, Boucher O, Drouin A, Haustein K, Kreienkamp F, and others (2020). 'Human contribution to the record-breaking June and July 2019 heatwaves in Western Europe' Environmental Research Letters: volume 15, page 94077
74. Hatfield JL, Prueger JH (2015). 'Temperature extremes: effect on plant growth and development' Weather and Climate Extremes volume 10, pages 4 to 10
75. Jung S, Estrella N, Pfaffl MW, Hartmann S, Handelshauser E, Menzel A (2018). 'Grass pollen production and group V allergen content of agriculturally relevant species and cultivars' PLoS ONE: volume 13, page e0193958
76. Han Q, Sun S, Liu Z, Xu W, Shi P (2022). 'Accelerated exacerbation of global extreme heatwaves under warming scenarios' International Journal of Climatology: volume 42,

page 5430 to 5441
77. Met Office (2021). 'UK Climate Projections: Headline Findings'
78. Piotrowska-Weryszko K, Weryszko-Chmielewska E, Sulborska A, Konarska A, Dmitruk M, Kaszewski BM (2021). 'Amaranthaceae pollen grains as indicator of climate change in Lublin (Poland)' Environmental Research: volume 193, page 110542
79. Holgate ST, Jackson L, Watson HK, Ganderton MA (1988). 'Sensitivity to *Parietaria* pollen in the Southampton area as determined by skin-prick and RAST tests' Clinical and Experimental Allergy: volume 18, pages 549 to 556
80. Preston CD, Pearman DA, Dines TD, editors (2002). 'New Atlas of the British and Irish Flora'
81. Jenkins PF, Mullins JK, Davies BH, Williams DA (1981). 'The possible role of aero-allergens in the epidemic of asthma deaths' Clinical Allergy: volume 11, pages 611 to 620
82. Newson R, Strachan D, Corden J, Millington W (2000). 'Fungal and other spore counts as predictors of admissions for asthma in the Trent region' Occupational and Environmental Medicine: volume 57, pages 786 to 792
83. Eguiluz-Gracia I, Mathioudakis AG, Bartel S, Vijverberg SJH, Fuertes E, Comberiati P, and others (2020). 'The need for clean air: the way air pollution and climate change affect allergic rhinitis and asthma' Allergy: volume 75, pages 2170 to 2184
84. Sabariego S, Bouso V, Pérez-Badia R (2012). 'Comparative study of airborne *Alternaria conidia* levels in 2 cities in Castilla-La Mancha (central Spain), and correlations with weather-related variables' Annals of Agricultural and Environmental Medicine: volume 19, pages 227 to 232
85. Casadevall A (2005). 'Fungal virulence, vertebrate endothermy, and dinosaur extinction: is there a connection?' Fungal Genetics and Biology: volume 42, pages 98 to 106
86. Cogliati M (2021). 'Global warming impact on the expansion of fundamental niche of *Cryptococcus gattii* VGI in Europe' Environmental Microbiology Reports: volume 13, pages 375 to 383
87. Casadevall A, Kontoyiannis DP, Robert V (2021). 'Environmental *Candida auris* and the global warming emergence hypothesis' mBio: volume 12, page e00360-21
88. van Rhijn N, Bromley M (2021). 'The consequences of our changing environment on life threatening and debilitating fungal diseases in humans' Journal of Fungi: volume 7, page 367
89. de S. Araújo GR, de Souza W, Frases S (2017). 'The hidden pathogenic potential of environmental fungi' Future Microbiology: volume 12, pages 1533 to 1540
90. Casadevall A (2019). 'Global catastrophic threats from the fungal kingdom: fungal catastrophic threats' Current Topics in Microbiology and Immunology: volume 424, pages 21 to 32
91. Paterson RR, Lima N (2017). 'Thermophilic fungi to dominate aflatoxigenic and mycotoxigenic fungi on food under global warming' International Journal of Environmental Research and Public Health: volume 14, page 199
92. D'Amato G, Chong-Neto HJ, Monge Ortega OP, Vitale C, Ansotegui I, Rosario N, and others (2020). 'The effects of climate change on respiratory allergy and asthma induced by pollen and mould allergens' Allergy: volume 75, pages 2219 to 2228

93. Apangu GP, Frisk CA, Adams-Groom B, Satchwell J, Pashley CH, Skjøth CA (2020). 'Air mass trajectories and land cover map reveal cereals and oilseed rape as major local sources of *Alternaria* spores in the Midlands, UK' Atmospheric Pollution Research: volume 11, pages 1668 to 1679
94. Skjøth CA, Sommer J, Frederiksen L, Karlson UG (2012). 'Crop harvest in Denmark and Central Europe contributes to the local load of airborne *Alternaria* spore concentrations in Copenhagen' Atmospheric Chemistry and Physics: volume 12, pages 11107 to 11123
95. Hanson MC, Petch GM, Ottosen TB, Skjøth CA (2022). 'Climate change impact on fungi in the atmospheric microbiome' Science of The Total Environment: volume 830, page 154491
96. Grinn-Gofroń A, Strzelczak A (2013). 'Changes in concentration of *Alternaria* and *Cladosporium* spores during summer storms' International Journal of Biometeorology: volume 57, pages 759 to 768
97. Dales RE, Cakmak S, Judek S, Dann T, Coates F, Brook JR, and others (2003). 'The role of fungal spores in thunderstorm asthma' Chest: volume 123, pages 745 to 750
98. Rabe U (2020). 'Are fungal spores relevant outdoor allergens?' Laryngorhinootologie: volume 99, pages 292 to 298
99. Pulimood TB, Corden JM, Bryden C, Sharples L, Nasser SM (2007). 'Epidemic asthma and the role of the fungal mould *Alternaria alternata*' Journal of Allergy and Clinical Immunology: volume 120, pages 610 to 617
100. Barbeau DN, Grimsley LF, White LE, El-Dahr JM, Lichtveld M (2010). 'Mould exposure and health effects following Hurricanes Katrina and Rita' Annual Review of Public Health: volume 31, pages 165 to 178
101. Vélez-Torres LN, Bolaños-Rosero B, Godoy-Vitorino F, Rivera-Mariani FE, Maestre JP, Kinney K, and others (2022). 'Hurricane María drives increased indoor proliferation of filamentous fungi in San Juan, Puerto Rico: a 2-year culture-based approach' PeerJ: volume 10, page e12730
102. Green BJ, Mitakakis TZ, Tovey ER (2003). 'Allergen detection from 11 fungal species before and after germination' Journal of Allergy and Clinical Immunology: volume 111, pages 285 to 289
103. Wolf J, O'Neill NR, Rogers CA, Muilenberg ML, Ziska LH (2010). 'Elevated atmospheric carbon dioxide concentrations amplify *Alternaria alternata* sporulation and total antigen production' Environmental Health Perspectives: volume 118, pages 1223 to 1228
104. Lang-Yona N, Levin Y, Dannemiller KC, Yarden O, Peccia J, Rudich Y (2013). 'Changes in atmospheric CO_2 influence the allergenicity of *Aspergillus fumigatus*' Global Change Biology: volume 19, pages 2381 to 2388
105. Wyatt TT, Wösten HA, Dijksterhuis J (2013). 'Fungal spores for dispersion in space and time' Advances in Applied Microbiology: volume 85, pages 43 to 91
106. Weaver EA, Kolivras KN (2018). 'Investigating the relationship between climate and valley fever (Coccidioidomycosis)' Ecohealth: volume 15, pages 840 to 852
107. Grewling Ł, Nowak M, Szymańska A, Kostecki Ł, Bogawski P (2019). 'Temporal variability in the allergenicity of airborne *Alternaria* spores' Medical Mycology: volume 57, pages 403 to 411

108. Ulevicius V, Peciulyte D, Lugauskas A, Andriejauskiene J (2004). 'Field study on changes in viability of airborne fungal propagules exposed to UV radiation' Environmental Toxicology: volume 19, pages 437 to 441
109. Skjøth CA, Damialis A, Belmonte J, De Linares C, Fernández-Rodríguez S, Grinn-Gofroń A, and others (2016). '*Alternaria* spores in the air across Europe: abundance, seasonality and relationships with climate, meteorology and local environment'. Aerobiologia: volume 32, pages 3 to 22
110. Anees-Hill S, Douglas P, Pashley CH, Hansell A, Marczylo EL (2022). 'A systematic review of outdoor airborne fungal spore seasonality across Europe and the implications for health' Science of the Total Environment: volume 818, page 151716
111. Ščevková J, Vašková Z, Sepšiová R, Kováč J (2021). 'Seasonal variation in the allergenic potency of airborne grass pollen in Bratislava (Slovakia) urban environment' Environmental Science and Pollution Research: volume 28, pages 62583 to 62592
112. Millington WM, Corden JM (2005). 'Long term trends in outdoor *Aspergillus*/*Penicillium* spore concentrations in Derby, UK from 1970 to 2003 and a comparative study in 1994 and 1996 with the indoor air of 2 local houses' Aerobiologia: volume 21, pages 105 to 113
113. Olsen Y, Skjøth CA, Hertel O, Rasmussen K, Sigsgaard T, Gosewinkel U (2020). 'Airborne *Cladosporium* and *Alternaria* spore concentrations through 26 years in Copenhagen, Denmark' Aerobiologia: volume 36, pages 141 to 157
114. Grinn-Gofroń A, Strzelczak A, Stępalska D, Myszkowska D (2016). 'A 10-year study of *Alternaria* and *Cladosporium* in 2 Polish cities (Szczecin and Cracow) and relationship with the meteorological parameters' Aerobiologia (Bologna): volume 32, pages 83 to 94
115. Marchesi S (2020). '*Alternaria* spores in Emilia-Romagna, Northern Italy: current diffusion and trends' Aerobiologia: volume 36, pages 31 to 36
116. Sindt C, Besancenot JP, Thibaudon M (2016). 'Airborne *Cladosporium* fungal spores and climate change in France' Aerobiologia: volume 32, pages 53 to 68
117. Damialis A, Mohammad AB, Halley JM, Gange AC (2015). 'Fungi in a changing world: growth rates will be elevated, but spore production may decrease in future climates' International Journal of Biometeorology: volume 59, pages 1157 to 1167
118. Clemmensen KE, Bahr A, Ovaskainen O, Dahlberg A, Ekblad A, Wallander H, and others (2013). 'Roots and associated fungi drive long-term carbon sequestration in boreal forest' Science: volume 339, pages 1615 to 1618
119. Ebi KL, Vanos J, Baldwin JW, Bell JE, Hondula DM, Errett NA, and others (2021). 'Extreme weather and climate change: population health and health system implications' Annual Review of Public Health: volume 42, pages 293 to 315
120. Wood S (2015). 'R package “mgcv”'
121. Buters JT, Weichenmeier I, Ochs S, Pusch G, Kreyling W, Boere AJ, and others (2010). 'The allergen Bet v 1 in fractions of ambient air deviates from birch pollen counts' Allergy: volume 65, pages 850 to 858
122. Buters JTM, Thibaudon M, Smith M, Kennedy R, Rantio-Lehtimäki A, Albertini R, and others (2012). 'Release of Bet v 1 from birch pollen from 5 European countries. Results from the HIALINE study' Atmospheric Environment: volume 55, pages 496 to 505
123. D’Amato G, Holgate ST, Pawankar R, Ledford DK, Cecchi L, Al-Ahmad M, and others

(2015). 'Meteorological conditions, climate change, new emerging factors, and asthma and related allergic disorders. A statement of the World Allergy Organization' World Allergy Organisation Journal: volume 8, page 25

124. Sofiev M, Bergmann KC (2013). 'Allergenic Pollen. A Review of the Production, Release, Distribution and Health Impacts' Sofiev M, Bergmann KC, editors
125. Feo Brito F, Mur Gimeno P, Martínez C, Tobías A, Suárez L, Guerra F, and others (2007). 'Air pollution and seasonal asthma during the pollen season. A cohort study in Puertollano and Ciudad Real (Spain)' Allergy: volume 62, pages 1152 to 1157
126. Lang-Yona N, Shuster-Meiseles T, Mazar Y, Yarden O, Rudich Y (2016). 'Impact of urban air pollution on the allergenicity of *Aspergillus fumigatus conidia*: outdoor exposure study supported by laboratory experiments' Science of The Total Environment: volume 541, pages 365 to 371
127. Martins C, Varela A, Leclercq CC, Núñez O, Větrovský T, Renaut J, and others (2018). 'Specialisation events of fungal metacommunities exposed to a persistent organic pollutant are suggestive of augmented pathogenic potential' Microbiome: volume 6, page 208
128. Office for Budget Responsibility (2021). 'The transition to electric vehicles'
129. Lieth H (1974). 'Phenology and Seasonality Modeling 1st ed.' Springer Berlin; page 444
130. Keeling CD, Chin JFS, Whorf TP (1996). 'Increased activity of northern vegetation inferred from atmospheric CO_2 measurements' Nature: volume 382, pages 146 to 149
131. Thackeray SJ, Henrys PA, Hemming D, Bell JR, Botham MS, Burthe S, and others (2016). 'Phenological sensitivity to climate across taxa and trophic levels' Nature: volume 535, pages 241 to 245
132. Menzel A, Yuan Y, Matiu M, Sparks T, Scheifinger H, Gehrig R, and others (2020). 'Climate change fingerprints in recent European plant phenology' Global Change Biology: volume 26, pages 2599 to 2612
133. Parmesan C, Yohe G (2003). 'A globally coherent fingerprint of climate change impacts across natural systems' Nature: volume 421, pages 37 to 42
134. Piao S, Liu Q, Chen A, Janssens IA, Fu Y, Dai J, and others (2019). 'Plant phenology and global climate change: current progresses and challenges' Global Change Biology: volume 25, pages 1922 to 1940
135. Renner SS, Zohner CM (2018). 'Climate change and phenological mismatch in trophic interactions among plants, insects, and vertebrates' Annual Review of Ecology, Evolution, and Systematics: volume 49, pages 165 to 182
136. Skjøth CA, Smith M, Sikoparija B, Stach A, Myszkowska D, Kasprzykf I, and others (2010). 'A method for producing airborne pollen source inventories: an example of Ambrosia (ragweed) on the Pannonian Plain' Agricultural and Forest Meteorology: volume 150, pages 1203 to 1210
137. Skjøth CA, Sun Y, Karrer G, Sikoparija B, Smith M, Schaffner U, and others (2019). 'Predicting abundances of invasive ragweed across Europe using a “top-down” approach' Science of The Total Environment: volume 686, pages 212 to 222
138. Thibaudon M, Sikoparija B, Oliver G, Smith M, Skjøth CA (2014). 'Ragweed pollen source inventory for France - the second largest centre of *Ambrosia* in Europe' Atmospheric

Environment: volume 83, pages 62 to 71
139. Pashley CH, Satchwell J, Edwards RE (2015). 'Ragweed pollen: is climate change creating a new aeroallergen problem in the UK?' Clinical and Experimental Allergy: volume 45, pages 1262 to 1265
140. Amano T, Smithers RJ, Sparks TH, Sutherland WJ (2010). 'A 250-year index of first flowering dates and its response to temperature changes' Proceedings of the Royal Society B: Biological Sciences: volume 277, pages 2451 to 2457
141. Abernethy R, Hemming DL, Garforth J, Kendon M, McCarthy M, Sparks T (2016). 'State of the Climate 2016: Phenology supplement'
142. Büntgen U, Piermattei A, Krusic PJ, Esper J, Sparks T, Crivellaro A (2022). 'Plants in the UK flower a month earlier under recent warming' Proceedings of the Royal Society B: Biological Sciences: volume 289, page 20212456
143. Schmidt CW (2016). 'Pollen overload: seasonal allergies in a changing climate' Environmental Health Perspectives: volume 124, pages A70 to A75
144. Suanno C, Aloisi I, Fernández-González D, Del Duca S (2021). 'Pollen forecasting and its relevance in pollen allergen avoidance' Environmental Research: volume 200, page 111150
145. Zhang Y, Steiner AL (2022). 'Projected climate-driven changes in pollen emission season length and magnitude over the continental United States' Nature Communications: . volume 13, page 1234
146. Woodward FI, Williams BG (1987). 'Climate and plant distribution at global and local scales' Vegetatio: volume 69, pages 189 to 197
147. Ejsmond MJ, Wrońska-Pilarek D, Ejsmond A, Dragosz-Kluska D, Karpińska-Kołaczek M, Kołaczek P, and others (2011). 'Does climate affect pollen morphology? Optimal size and shape of pollen grains under various desiccation intensity' Ecosphere: volume 2, page 117
148. Fitter AH, Fitter RS (2002). 'Rapid changes in flowering time in British plants'. Science: volume 296, pages 1689 to 1691
149. Sofiev M, Siljamo P, Ranta H, Linkosalo T, Jaeger S, Rasmussen A, and others (2013). 'A numerical model of birch pollen emission and dispersion in the atmosphere. Description of the emission module' International Journal of Biometeorology: volume 57, pages 45 to 58
150. Sofiev M, Belmonte J, Gehrig R, Izquierdo R, Smith M, Dahl Å, and others (2013). 'Airborne pollen transport'. In: Sofiev M, Bergmann KC, editors. Allergenic Pollen, pages 127 to 159
151. Menzel A (2019). 'The allergen riddle' Nature Ecology and Evolution: volume 3, pages 716 to 717
152. Osborne NJ, Alcock I, Wheeler BW, Hajat S, Sarran C, Clewlow Y, and others (2017). 'Pollen exposure and hospitalization due to asthma exacerbations: daily time series in a European city' International Journal of Biometeorology: volume 61, pages 1837 to 1848
153. Sweiss K, Naser AY, Alrawashdeh HM, Alharazneh A (2022). 'Hospital admissions due to vasomotor and allergic rhinitis in England and Wales between 1999 and 2019: an ecological study' Irish Journal of Medical Science: volume 192, pages 349 to 355
154. Marston C, Rowlands CS, O'Neil AW, Morton RD (2022). 'Land Cover Map 2021' NERC

EDS Environmental Information Data Centre

155. Emberlin J, Savage M, Jones S (1993). 'Annual variations in grass pollen seasons in London 1961-1990: trends and forecast models' Clinical and Experimental Allergy: volume 23, pages 911 to 918
156. Woodland Trust (2019). 'Adapting to ash dieback. The Woodland Trust's view. Position statement'
157. Forestry Commission (2022). 'Urban Tree Challenge Fund'
158. Bousquet J, Schünemann HJ, Samolinski B, Demoly P, Baena-Cagnani CE, Bachert C, and others (2012). 'Allergic rhinitis and its impact on asthma (ARIA): achievements in 10 years and future needs' Journal of Allergy and Clinical Immunology: volume 130, pages 1049 to 1062
159. Craig TJ, McCann JL, Gurevich F, Davies MJ (2004). 'The correlation between allergic rhinitis and sleep disturbance' Journal of Allergy and Clinical Immunology: volume 114, pages S139 to S145
160. Tanner L (1999). 'Effect of fexofenadine HCl on quality of life andwork, classroom, and daily activity impairment in patients with seasonal allergic rhinitis' American Journal of Managed Care: volume 5, pages S235 to S247
161. Kessler RC, Almeida DM, Berglund P, Stang P (2001). 'Pollen and mould exposure impairs the work performance of employees with allergic rhinitis' Annals of Allergy, Asthma and Immunology: volume 87, pages 289 to 295
162. Hellgren J, Cervin A, Nordling S, Bergman A, Cardell LO (2010). 'Allergic rhinitis and the common cold--high cost to society' Allergy: volume 65, pages 776 to 783
163. Sears MR, Burrows B, Herbison GP, Holdaway MD, Flannery EM (1993). 'Atopy in childhood. II. Relationship to airway responsiveness, hay fever and asthma' Clinical and Experimental Allergy: volume 23, pages 949 to 956
164. Bauchau V, Durham SR (2004). 'Prevalence and rate of diagnosis of allergic rhinitis in Europe' European Respiratory Journali: volume 24, pages 758 to 764
165. Todkill D, de Jesus Colon Gonzalez F, Morbey R, Charlett A, Hajat S, Kovats S, and others (2020). 'Environmental factors associated with general practitioner consultations for allergic rhinitis in London, England: a retrospective time series analysis' BMJ Open: volume 10, page e036724
166. Huffman JA, Perring AE, Savage NJ, Clot B, Crouzy B, Tummon F, and others (2020). 'Real-time sensing of bioaerosols: review and current perspectives' Aerosol Science and Technology: volume 54, pages 465 to 495
167. Oteros J, Pusch G, Weichenmeier I, Heimann U, Möller R, Röseler S, and others (2015). 'Automatic and online pollen monitoring' Int Arch Allergy Immunol:volume 167, pages 158 to 166
168. Lionetti S, Graf E, Salzmann J, Wullschleger P, Zeder Y, Niederberger E (2021). 'Airborne spore measurement based on UV-induced fluorescence and digital holography from SwisensPoleno Jupiter' In: The European Aerosol Conference
169. Sauliene I, Sukiene L, Daunys G, Valiulis G, Vaitkevicius L, Matavulj P, and others (2019). 'Automatic pollen recognition with the Rapid-E particle counter: the first-level procedure, experience and next steps' Atmospheric Measurement Techniques: volume

12, pages 3435 to 3452
170. Stagg S, Bowry A, Kelsey A, Crook B (2010). 'Bioaerosol emissions from waste composting and the potential for workers' exposure'
171. Palmer L (2021). 'How trees and forests reduce risks from climate change' Nature Climate Change: volume 11, pages 374 to 377
172. Department for Environment, Food and Rural Affairs (Defra) (2022). 'Planting trees in England'
173. NHS Forest (2021). 'NHS Forest: tree planting guidance pack'
174. Glendale (2016). 'Plant the right trees to combat climate change'
175. King A (2019). 'Trees tested as pollutant traps' The Scientist
176. Beckett KP, Freer-Smith PH, Taylor G (2000). 'Particulate pollution capture by urban trees: effect of species and windspeed' Global Change Biology: volume 6, page 995 to 1003
177. Mitchell R, Maher BA, Kinnersley R (2010). 'Rates of particulate pollution deposition onto leaf surfaces: temporal and inter-species magnetic analyses' Environmental Pollution: volume 158, pages 1472 to 1478
178. Havens EB (1988). 'Pollen production a problem: Arizona county bans new olive trees' Los Angeles Times
179. Olive Oil Times (2020). 'Moroccan city bans olive trees citing allergy concerns'
180. CPH Post (2015). 'Aarhus bans birch trees in public places'
181. City of Albuquerque (2022). 'Restricted trees for pollen control'
182. Allergy Free Gardening (2017). 'Allergy free parks'
183. Technische Universitat Dresden (2015). 'Citree: woody species for urban spaces. Database planning tool'
184. Clarke N (2017). 'Allergy friendly plants'
185. Cariñanos P, Casares-Porcel M (2011). 'Urban green zones and related pollen allergy: a review. Some guidelines for designing spaces with low allergy impact' Landscape and Urban Planning: volume 101, pages 205 to 214
186. Herald J, Hume SC, Warner A (2021). 'The walk to school' Allergy UK

About the UK Health Security Agency

UKHSA is responsible for protecting every member of every community from the impact of infectious diseases, chemical, biological, radiological and nuclear incidents and other health threats. We provide intellectual, scientific and operational leadership at national and local level, as well as on the global stage, to make the nation health secure.

UKHSA is an executive agency, sponsored by the Department of Health and Social Care.

For queries relating to this document, please contact: climate.change@ukhsa.gov.uk

Published: December 2023
Publishing reference: GOV-14571