Chapter 3
Climate Change and Pollen Allergies

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Abstract This chapter reviews the emerging importance of pollen allergies in relation to ongoing climate change. Allergic diseases have been increasing in prevalence over the last decades, partly as the result of the impact of climate change. Increased sensitisation rates and more severe symptoms have been the partial outcome of: increased pollen production of wind-pollinated plants resulting in long-term increased abundance of pollen in the air we breathe; earlier shifts of airborne pollen seasons making occurrence of allergic symptoms harder to predict and deal with efficiently; increased allergenicity of pollen causing more severe health effects in allergic individuals; introduction of new, invasive allergenic plant species causing new sensitisations; environment-environment interactions, such as plants and hosted microorganisms, i.e. fungi and bacteria, which comprise a complex and dynamic system, with additive, presently unforeseeable influences on human health;

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environment-human interactions, as the consequence of a combination of environmental factors, like air pollution, global warming, urbanisation and microclimatic variability, which create a multi-resolution spatiotemporal system that requires new processing technologies and huge data inflow in order to be thoroughly investigated. We suggest that novel, real-time, personalised pollen information services, like mobile-app risk alerts, must be developed to provide the optimum first line of allergy management.

Keywords Climate change · Environmental medicine · Pollen allergy

Highlights
- Climate change contributes significantly to increasing allergy prevalence worldwide.
- This chapter overviews the emerging challenges with regard to allergic diseases.
- More abundant and more allergenic pollen over time will affect allergic patients.
- New allergenic pollen and spatial shifts in pollen occurrence will increase sensitisation.
- Real-time pollen risk alerts are needed as the first line of allergy management.

3.1 Introduction

International reports have documented a progressive global increase in the burden of allergic diseases across the industrialised world over the past half century. Clinical evidence reveals a general increase in both the incidence and the prevalence of respiratory diseases, including allergic rhinitis and asthma (Bieber et al. 2016; Bunne et al. 2017; Burney et al. 1994; Ninan and Russell 1992; Strachan and Ross Anderson 1992; Wüthrich et al. 1995). Such phenomena may be related not only to air pollution and changes in lifestyle, but also to an actual increase in the amount and allergenicity of airborne allergenic pollen (Ziello et al. 2012; Beck et al. 2013). However, the exact relationship between these factors is not yet clear. The amount of allergenic pollen has increased in specific bioclimatic regions or for specific pollen types (Ziello et al. 2012), and allergenicity has been documented for only some pollutants and plant species (e.g. the ozone impact on birch; Beck et al. 2013). A large gap in our knowledge still exists regarding global trends across different biogeographical regions and for a wider diversity of pollen taxa. In addition, because of ongoing climate change, emerging challenges must be dealt with, such as newly introduced allergenic pollen, changing environmental parameters leading to unpredictable changing health effects, an urgent need for allergy risk alerts, and personalised environmental medicine services. In this chapter, we provide an overview of the state of the art of this topic and discuss multi-disciplinary and timely interaction between humans and the environment.

3.2 Clinical Implications of Pollen-induced Respiratory Allergy

Allergies represent a major public health problem, one that has increased rapidly in recent decades in both developed and developing countries and one that is recognised as an important global epidemic carrying a considerable economic burden (Bieber et al. 2016; Linneberg 2016; Traidl-Hoffmann 2017).

For the clinical manifestation of allergic symptoms, there is a need for allergic sensitisation to pollen allergens resulting in IgE antibody production. IgE antibodies bind to an IgE-specific receptor on the surface of immune cells (mast cells and basophils), and if later exposure to the same allergen occurs, the allergen can bind to the IgE molecules on the surface of these cells, thereby activating them. Activated mast cells and basophils undergo degranulation, during which they release histamine and other inflammatory chemical mediators into the surrounding tissue, causing vasodilation, mucous secretion, nerve stimulation and smooth muscle contraction (Averbeck et al. 2007).

In pollen allergies, the most common symptoms induced by allergens are sneezing, itchy nose, rhinorrhea and nasal congestion (Averbeck et al. 2007). Inhaled allergens can also result in exacerbation of bronchial allergic asthma, with coughing, wheezing, shortness of breath, chest tightness, pain or pressure.

In industrialised countries, allergic rhinitis (AR) can affect more than 20% of the population, as has been reviewed by Linneberg (2011). This percentage varies among cities, countries and continents because of environmental and other factors, and can exceed 40% (e.g. Brożek et al. 2017; Morais-Almeida et al. 2013; Sibbald and Strachen 1995). For example, the lifetime prevalence of allergic diseases in adults in Germany is 8.6% (95% CI) for asthma and 14.8% (95% CI) for rhinitis, as measured by self-reported doctor-diagnosed allergies within the Study on Adult Health in Germany of the Robert Koch Institute for rhinitis (Bergmann et al. 2016; Langen et al. 2013; Haftenberger et al. 2013). Regarding allergic sensitisation, in tests on 50 common single allergens and two mixtures comprising either inhalant allergens or grass pollen allergens, 48.6% of participants exhibited at least one allergic sensitisation (specific IgE antibody detection). Overall, 33.6% of participants were sensitised to inhalant allergens (Haftenberger et al. 2013). Table 3.1 shows sensitisation rates to 17 different pollens in atopic patients across the globe: the various pollen types refer to the most widespread and allergenic ones worldwide, and the spatial variability and relative occurrence can be concluded based on the different cohorts studied all over the world.

A comparison of data on adults from 1998 (Federal Health Survey/Bundes-Gesundheitssurvey 1998, [BGS98] of the Robert Koch Institute) and 2008–2011 (DEGS1) documented an increase in the rate of sensitisation to inhalant allergens, from 29.8% to 33.6% (Haftenberger et al. 2013). The Germany-wide lifetime prevalence of allergic diseases in children and adolescents (Study on the Health of Children and Adolescents in Germany/Studie zur Gesundheit von Kindern und

Table 3.1 Epidemiological studies on the allergenic properties of airborne pollen from different plant taxa

Pollen taxon	Studied species or genus (according to the authors)	Country	Number of atopic patients	Positive skin prick tests (%)	Citation
Alnus	*A. glutinosa*	Spain	210	20.9	Cosmes Martín et al. (2005)
Alnus	*A. glutinosa*	Turkey	130	32.3	Erkara et al. (2009)
Ambrosia	*A. artemisiifolia*	Australia	1000	13.4	Mueller et al. (2000)
Ambrosia	*A. elatior*	Croatia	750	20.3	Peternel et al. (2008)
Ambrosia		Czech Republic	300	19.0–25.0	Rybníček et al. (2000)
Ambrosia		France	59	56.0	Boralevi et al. (2008)
Ambrosia		Hungary	1139	82.7–84.8	Kadocsa and Juhasz (2002)
Ambrosia		Switzerland	1274	16.7	Frei et al. (1995)
Artemisia		Hungary	1139	48.8–54.8	Kadocsa and Juhasz (2002)
Artemisia	*A. vulgaris*	Poland	676	12.0	Stach et al. (2007)
Artemisia	*A. vulgaris*	Portugal	371	17.6	Loureiro et al. (2005)
Artemisia	*A. vulgaris*	Spain	891	13.0	Barber et al. (2008)
Artemisia		Switzerland	1274	22.6–28.0	Frei et al. (1995)
Betula		Finland	357	28.0	Varjonen et al. (1992)
Betula		Hungary	1139	8.7–17.0	Kadocsa and Juhasz (2002)
Betula		Italy	6750	18.0	Marogna et al. (2006)
Betula		Switzerland	1274	46.1–54.0	Frei et al. (1995)
Betula	*B. verrucosa*	Turkey	130	33.8	Erkara et al. (2009)
Betula	*B. verrucosa*	USA	371	32.9	Lin et al. (2002)
Chenopodiaceae/ Amaranthaceae	*Amaranthus retroflexus*	Australia	1000	16.6	Mueller et al. (2000)
Chenopodiaceae/ Amaranthaceae		Greece	1311	18.3	Gioulekas et al. (2004)

(continued)

Table 3.1 (continued)

Pollen taxon	Studied species or genus (according to the authors)	Country	Number of atopic patients	Positive skin prick tests (%)	Citation
Chenopodiaceae/ Amaranthaceae		Hungary	1139	10.6–15.8	Kadocsa and Juhasz (2002)
Chenopodiaceae/ Amaranthaceae	*Chenopodium*	India	2568	16.3	Mandal et al. (2008)
Chenopodiaceae/ Amaranthaceae		Spain	338	49.3	Alfaya Arias and Marqués Amat (2003)
Corylus		Hungary	1139	6.3–16.7	Kadocsa and Juhasz (2002)
Corylus		Switzerland	1274	46.7–47.2	Frei et al. (1995)
Corylus	*C. avellana*	Turkey	130	30.8	Erkara et al. (2009)
Cupressaceae		Greece	1311	12.7	Gioulekas et al. (2004)
Cupressaceae		Italy	547	13.3	Copula et al. (2006)
Cupressaceae	*C. sempervirens*	Spain	891	14.9	Barber et al. (2008)
Cupressaceae	*C. sempervirens*	Turkey	455	14.3	Sin et al. (2008)
Fraxinus	*F. excelsior*	Austria	5416	17.6	Hemmer et al. (2006)
Fraxinus		Switzerland	1274	30.4–35.9	Frei et al. (1995)
Fraxinus	*F. americana*	USA	371	26.0	Lin et al. (2002)
Olea	*O. europaea*	Greece	1311	31.8	Gioulekas et al. (2004)
Olea	*O. europaea*	Portugal	371	27.5	Loureiro et al. (2005)
Olea	*O. europaea*	Spain	210	71.9	Cosmes Martín et al. (2005)
Olea	*O. europaea*	Turkey	127	15.0	Kirmaz et al. (2005)
Pinaceae		Greece	1311	9.3	Gioulekas et al. (2004)
Pinaceae	*Pinus radiata*	Portugal	371	7.5	Loureiro et al. (2005)
Plantago	*P. lanceolata*	Australia	1000	15.3	Mueller et al. (2000)
Plantago		Greece	1311	14.8	Gioulekas et al. (2004)

(continued)

Table 3.1 (continued)

Pollen taxon	Studied species or genus (according to the authors)	Country	Number of atopic patients	Positive skin prick tests (%)	Citation
Plantago		Hungary	1139	14.2–27.7	Kadocsa and Juhasz (2002)
Plantago	*P. lanceolata*	Japan	160	12.8	Nakamaru et al. (2005)
Plantago	*P. lanceolata*	Portugal	371	10.6	Loureiro et al. (2005)
Platanus	*P. orientalis*	Turkey	130	27.7	Erkara et al. (2009)
Poaceae	*Phleum pratense*	Finland	357	35.5	Varjonen et al. (1992)
Poaceae		Greece	1311	40.4	Gioulekas et al. (2004)
Poaceae		Hungary	1139	56.7–56.8	Kadocsa and Juhasz (2002)
Poaceae		Italy	726	46.6	Asero (2004)
Poaceae	*Dactylis glomerata*	Kyrgyzstan	633	70.5	Kobzar (1999)
Poaceae	*Phleum pratense*	Kyrgyzstan	633	57.8	Kobzar (1999)
Poaceae		Portugal	371	44.9	Loureiro et al. (2005)
Poaceae		Spain	459	83.7	Belver et al. (2007)
Poaceae	*Dactylis glomerata*	Spain	614	87.0	Subiza et al. (1995)
Poaceae	*Phleum pratense*	Spain	891	27.2–80.0	Barber et al. (2008)
Poaceae		Switzerland	1274	71.6–81.0	Frei et al. (1995)
Poaceae	*Festuca pratensis*	Turkey	130	60.8	Erkara et al. (2009)
Poaceae	*Phleum pratense*	Turkey	130	37.7	Erkara et al. (2009)
Poaceae		USA	189	71.0	Wu et al. (1999)
Populus	*P. alba*	Spain	614	29.0	Subiza et al. (1995)
Populus	*P. nigra*	Spain	210	32.3	Cosmes Martín et al. (2005)
Populus	*P. deltoides*	USA	371	20.6	Lin et al. (2002)
Quercus	*Q. alba*	USA	371	34.3	Lin et al. (2002)

(continued)

Table 3.1 (continued)

Pollen taxon	Studied species or genus (according to the authors)	Country	Number of atopic patients	Positive skin prick tests (%)	Citation
Rumex	*R. crispus*	Australia	1000	26.5	Mueller et al. (2000)
Ulmaceae	*Ulmus pumila*	Australia	1000	11.6	Mueller et al. (2000)
Ulmaceae	*Ulmus*	Hungary	1139	6.0–17.9	Kadocsa and Juhasz (2002)
Ulmaceae	*Trema orientalis*	India	2568	13.8	Mandal et al. (2008)
Ulmaceae	*Ulmus americana*	USA	371	24.6	Lin et al. (2002)
Urticaceae	*Parietaria*	Greece	150	27.5–28.0	Kaleyias et al. (2001)
Urticaceae	*Parietaria*	Italy	507	23.0	Verini et al. (2001)
Urticaceae	*Parietaria*	Portugal	371	23.4	Loureiro et al. (2005)

For each study, the taxon whose properties were studied, the country where the research was conducted, the sample size of atopic patients examined and the percentage of positive reactions to skin prick tests are given. Taxa are presented in alphabetical order. Empty cells signify lack of information

Sources: Scopus and Web of Science; references without an abstract in English are not included

Jugendlichen in Deutschland, (KiGGS initial survey, 2003–2006 of the Robert Koch Institute)) was shown to be 4.7% (95% CI) for allergic bronchial asthma and 10.7% (95% CI) for allergic rhinitis (Bergmann et al. 2016). Allergic rhinitis was shown to have a negative impact on quality of life, by using validated questionnaires like the five-dimension EuroQol QOL survey (EQ-5D, the Sino-Nasal Outcome Test (SNOT-22) or the Nasal Obstruction Severity Evaluation (NOSE) scale (e.g. Höhle et al. 2017).

In addition to respiratory symptoms, a number of pollen-allergic patients, especially those with birch allergy, suffer from concomitant pollen-related food allergies, which means that they develop allergy symptoms after ingestion of certain foods. Symptoms may manifest as oral itching, swelling of the lips, itchy exanthema, shortness of breath, diarrhoea or even circulation problems (Treudler et al. 2017). Overall, the majority of IgE-mediated food allergies in adults are based on sensitisation to aeroallergens (in particular pollen), followed by (cross-) reactions to structurally related, often unstable, allergens, especially in (plant) foods such as fruit, vegetables and spices (Treudler et al. 2017). This type of food allergy has been referred to as a secondary food allergy, as distinct from the primary form, which is presumed to involve sensitisation via the gastrointestinal tract. The types of fruit most commonly involved in pollen-related food allergy belong to the Rosaceae plant family (e.g. apples) and to the Corylaceae family (e.g. hazel) (Treudler and Simon 2017). Recently, birch-related soy allergy has gained much attention as soy products (i.e. soy drinks) have been promoted as healthy foods and are being consumed in increasing amounts in many European countries (Treudler et al. 2017).

Different allergen families, which are also present in plant tissues, can become airborne, as well as be found in foods, and they are associated with different types of clinical reactions (i.e. sensitisation to pathogenesis-related (PR) protein-10, like Bet v 1 homologues). These reactions are mostly seen in Northern Europe and they are associated with oral itching and swelling. In contrast, sensitisation to lipid transfer proteins (LTPs) occurs more frequently in Southern Europe and is associated with anaphylaxis (severe immediate-type reactions involving several organ systems).

3.3 Allergenic Pollen and Epidemiology

There are differences within pollen-producing plants with regard to their ability to induce allergic sensitisation. There have been numerous studies worldwide over the past several decades that have documented such sensitisation rates. Nonetheless, a huge variability may exist, because of (but not limited to) climatic, air quality, environmental, social and genetic differences. A short overview is provided in Table 3.1, which gives the sensitisation rates of the most important allergenic pollen types.

The international literature documents grass pollen as the leading aeroallergen worldwide (e.g. Lewis et al. 1983; Weeke and Spieksma 1991; Wu et al. 1999; García-Mozo 2017). The reason for this is the wide distribution of grass species, along with their pollen's high allergenicity. The grass (Poaceae) family comprises one of the largest and most common plant families worldwide and, noticeably, consists mostly of wind-pollinated species (e.g. Wodehouse 1971; Lewis et al. 1983). It includes both annual and perennial herbaceous species, many of which are highly cosmopolitan and, hence, they are found in a wide variety of latitudes and biogeographical zones, in both urban or natural habitats (e.g. Pignatti 1982; Lewis et al. 1983). The grass species most implicated in respiratory allergies are orchard grass (*Dactylis glomerata*), fescue grass (*Festuca* spp.), ryegrass (*Lolium perenne*), timothy grass (*Phleum pratense*) and bluegrass (*Poa* spp.) (e.g. Lewis et al. 1983). Sensitisation rates to grass pollen can exceed 80% of the atopic population according to many epidemiological and clinical studies carried out across the globe (Table 3.1).

Other allergologically important plants are birch (*Betula* spp.), alder (*Alnus* spp.), hazel (*Corylus* spp.) and – recently of growing interest – the invasive ragweed (*Ambrosia* spp.). Sensitisation rates for the above pollen types can exceed 50% for the Corylaceae and Betulaceae families, whereas sensitisation to ragweed pollen can reach up to 80% (Table 3.1).

However, if investigating the exact relationship of the actual pollen exposure to the respiratory allergic symptoms of sensitised individuals, there are specific prerequisites. The exact pollen season occurrence and intensity need to be defined on a spatial and a temporal scale. Pollen allergy symptoms are mostly observed during the main pollen season. Even though the exact relationship between symptoms (pulmonary, nasal or ocular) and pollen occurrence and abundance is not yet clear, there are some recent reports clarifying this interaction (e.g. Berger et al. 2013; Bastl et al. 2014; Karatzas et al. 2014; Osborne et al. 2017; Voukantsis et al. 2015; Damialis et al. 2019). Overall, there are indications that there is a positive correlation between allergic symptoms and pollen abundance. However, this relationship can differ significantly among different bioclimatic regions, among different atopic patients, and for each different pollen type, and of course the relationship itself is not linear and there is usually a variable time lag between the actual pollen exposure and the occurrence of the allergic symptoms. The above do make pollen season forecasting (and consequent symptom forecasting) rather complex, thus highlighting the need for additional research in order to achieve accurate and operational predictive models.

Knowing the exact pollen season (in terms of occurrence, magnitude and shape) increases the capacity to accurately and in a timely way forecast the potential pollen exposure significantly and constitutes the first-line tool for allergy prevention. As an example, in Germany (Fig. 3.1), the main pollen season is confined to only a few months, usually commencing in March with the highly allergenic and cross-reactive pollen of hazel, alder and birch, and extending to the end of summer with the also very allergenic pollen from grasses and ragweed. A big allergy risk may exist even with shorter pollen seasons; even though a shorter duration of relevant allergic symptoms could then be hypothesised, such seasons tend to be highly peaked, thus potentially causing extreme exacerbations of symptoms even during these short intervals. Overall, in order to define the exposure to pollen beyond which respiratory

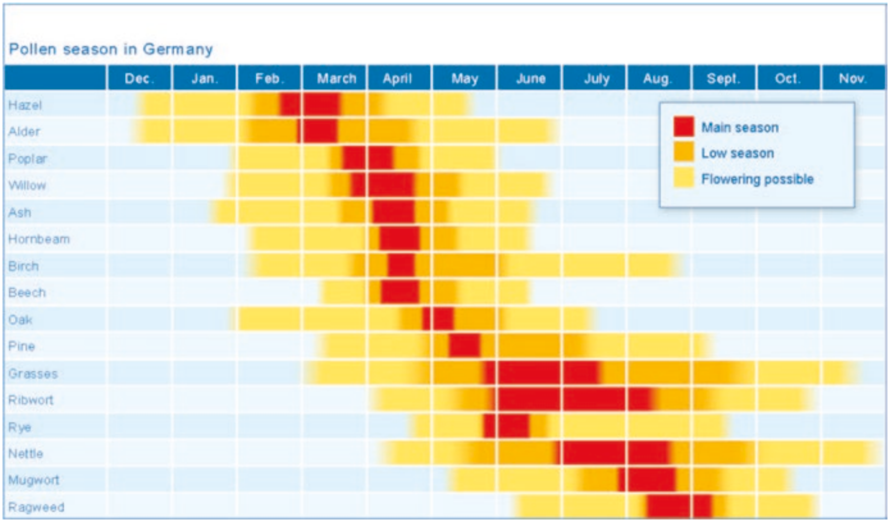

Fig. 3.1 Typical pollen seasons in Germany according to the Polleninformationsdienst (averages from pollen data from 2007–2011; www.pollenstiftung.de). Ragweed pollen has been added to this diagram only recently

symptoms are manifested, it is crucial to define the threshold of airborne concentrations of pollen that provoke these symptoms. However, it is well known that defining such thresholds involves highly demanding and complicated investigations, with values varying between sites, countries, geoclimatic regions, different years and per pollen type (de Weger et al. 2013).

3.4 Adjuvant Factors from Pollen and Impact of Environmental Factors

When we are exposed to pollen, it is not only the allergenic proteins that we inhale that affect us, but also our mucosa and/or skin are exposed to biochemically complex particles. Indeed, the allergenicity of pollen is not only the result of the allergen but also of adjuvant factors from pollen, such as lipids and pollen-derived adenosine (Dittlein et al. 2016; Gilles-Stein et al. 2016). Thus, exposure to allergens is necessary but not sufficient for the development of allergy (Gilles et al. 2009). By analysing the pollen's metabolome, Gilles et al. (2011) found that pollens release a wide array of different bioactive substances such as sugars, lipids, secondary metabolites and hormones. Notably, these bioactive mediators bind to receptors on human immune cells, which could promote allergic sensitisation to pollen-derived proteins or boost already manifested allergic immune responses. These substances, apart from the allergen itself, could be responsible for the potency of the allergenicity of pollen. Furthermore, these adjuvant mediators are influenced by environmental factors such as ozone (Beck et al. 2013). Only recently has part of the pollen microbiome been discovered (Obersteiner et al. 2016). This microbiome of pollen is not only species-specific, but also influenced by environmental factors (Obersteiner et al. 2016).

3.5 New Pollen Allergies: The Case of Ragweed

The European and Mediterranean Plant Protection Organization has reported the species *Ambrosia artemisiifolia* L. (common ragweed; Fig. 3.2) as an invasive and alien plant (Brunel et al. 2010). Apart from being a harmful weed, its pollen is highly allergenic. As ragweed has become naturalised in Europe, it is now quite common in regional flora in many areas across the continent (Smith et al. 2013). This expansion in European flora is expected to be reflected in human health by increasing sensitisation rates in allergic individuals (Burbach et al. 2009). These rates have already been reported as extremely high, often reaching 80% (Table 3.1). The most commonly implicated allergen is Amb a 1. There is already evidence of increasing long-term trends in *Ambrosia*-specific IgE antibodies from 20% in the

Fig. 3.2 Ragweed (*Ambrosia artemisiifolia*) plant, stems, leaves and flowers

late 1980s to about 30% at the end of the 1990s among patients with inhalation allergic diseases in Vienna, Austria (Buters et al. 2008).

Because of these factors, there is already awareness of the threats posed through the establishment and expansion of ragweed populations in Europe and, consequently, a European Commission Cooperation in Science and Technology (COST) Action FA1203 'SMARTER' (http://ragweed.eu) was approved in order to deal with this international problem. Among other goals, it aimed to describe the existing status of the threat, assess the European pollen abundance levels of ragweed, and attempt to make recommendations for the sustainable management of *Ambrosia* plants across Europe. Sikoparija et al. (2017), within this COST Action, have recently implied that only a few significant trends in the magnitude and frequency of atmospheric *Ambrosia* pollen exist at present (8% for the mean sum of daily average *Ambrosia* pollen concentrations and 14% for the mean number of days that *Ambrosia* pollen were recorded in the air). The direction of any trends (increasing or decreasing) varied locally.

Nonetheless, even in regions where ragweed has not yet been established, the probability of this occurring in the near future is quite high. For example, in Germany, which is located near the main source of ragweed pollen, the Pannonian Plain, ragweed does not seem to be as abundant, and therefore as noxious, yet as for neighbouring countries. As reported by Haftenberger in 2013, from the population-based German Health Study DEGS, IgE sensitisation rates to *A. artimisiifolia* were 8.2% of German adults, and this prevalence is quickly rising, with even very low concentrations (5–10 pollen grains per m^3 of air) being sufficient to trigger allergic reactions in sensitive patients. Thus, ragweed pollen may represent a new allergen, potentially responsible for new asthma incidents, and expected to occur much more frequently than other pollen types (Sikoparija et al. 2017).

3.6 Climate Change Effects

Airborne pollen measurements are among the longest term datasets of biological origin, therefore representing a valuable proxy of ongoing climate change. Extensive research over the last decade has shown that airborne pollen has increased in abundance but pollen seasons have also shifted to an earlier timeframe and may last longer (Ziello et al. 2012). It is still not clear, though, if this is the result of increased pollen production per floral unit or per individual plant, or the consequence of land use changes, ongoing climate change, eutrophication, global warming or a combination of these and many other factors. To date, some of the main causative factors for these changes have been considered air pollutants and higher air temperatures associated with global warming, or urbanisation rates and land use changes (e.g. Voltolini et al. 2000; Sofiev et al. 2009).

In parallel with this, allergic reactions to pollen in sensitised individuals have increased in both frequency and severity over the last decades, which is in accordance with the above-mentioned increase in airborne pollen concentrations (Linneberg et al. 1999). Although the reason for this synchronicity is not thoroughly understood and the cause-effect relationship not completely determined, a correlation between pollen abundance and pollen sensitisation has been considered to be real (e.g. Troise et al. 1992; Ault 2004).

Overall, a very large number of factors are expected (but not limited) to be influenced by climate change (anthropogenic or not) and together to contribute to the exacerbated provocation of allergic symptoms in sensitised individuals. There was an extensive review by Sofiev et al. in 2009 where the authors discuss plant-induced human allergy, from plant pollination and pollen dispersion to modelling and forecasting of airborne pollen concentrations. The following are some of the factors thought to be most important, although the list cannot be exhaustive:

- Plant growth, as influenced by the combination of air pollutants (i.e. carbon dioxide) and elevated air temperature, because of increased plant biomass.
- Pollen production, as expressed by increased pollen or flower production per inflorescence, or by a higher number of inflorescences per plant.
- Onset and duration of the pollen season, as influenced by meteorological and climatic factors, per site, among sites and among years and for each pollen type.
- Pollen allergenicity, as influenced by air pollutants (e.g. ozone and nitrogen dioxide) and air temperature, but, notably, in inverse correlation to pollen production per plant, after taking into account available resources as a limiting factor.
- Plant microbiome (plant, leaf, inflorescence and pollen microbiome), as determined by a wide variety of environmental factors, including biodiversity per se and its temporal variability.

- Pollution, including air, water, soil and other forms of pollution, on various spatial and temporal scales.
- Weather events, including drought or extreme rainfall, wind gusts, thunderstorms and any kind of extreme micro- and macro-meteorological effects.
- Land use changes, land management, habitat fracturing and moving to the north because of global warming.

Plant phenological traits (like flowering, leaf and bud formation, fruit and pollen production) are well known to be very sensitive to environmental stress and especially to temperature variability. This is particularly true for flowering and pollen production (e.g. Damialis et al. 2011; Menzel et al. 2006; Parmesan and Yohe 2003). There have been strong indications that plants produce more pollen, and earlier, when temperatures are higher, that is, at urban locations, lower elevations or southern exposure slopes, or during warmer years (e.g. Damialis et al. 2011; Fotiou et al. 2011). Higher rainfall prior to the inflorescence production and pollen formation and liberation also favour increased pollen and flower production (Damialis et al. 2011). However, the implicated processes are excessively complex and influence of many other factors is involved, for example microclimatic conditions in the examined site. Likewise, temperature seems to have a direct effect on allergen release, as revealed by the inter-annual variability in a study on birch pollen in Germany (Buters et al. 2008).

Air pollutants are also responsible for higher biomass production (including flower and pollen production). Wan et al. (2002) and Wayne et al. (2002) experimentally found that, especially in combination with elevated air temperature, increased carbon dioxide (CO_2) did not alter pollen production per se, but increased plant biomass in *Ambrosia artemisiifolia* and, consequently, individual plants produced more pollen. Ziska et al. (2003) studied the same species but in real-life conditions in a gradient simulating different climatic scenarios and, likewise, found that plants exhibited higher biomass, pollen production and earlier flowering dates. Ziska et al. (2003) additionally concluded that plant expansion rates and regional abundance may also increase with increasing CO_2, thus increasing allergenic pollen exposure rates on a wider spatial scale.

Air pollution and climate change do not only affect plant growth, pollen and flower production, and duration of the whole pollen season, but can also display more direct health effects by increasing the amount of allergenic proteins of the pollen (Zhao et al. 2016, 2017). According to Zhao et al. (2016), elevated levels of certain pollutants, like nitrogen dioxide (NO_2), which is traffic-related and hence more prevalent in urban locations, increase overall pollen allergenicity, thus also increasing the relevant allergy risk for sensitised individuals. El Kelish et al. (2014), as well as Zhao et al. (2017), showed that elevated pollutants change the transcriptome of ragweed pollen; therefore, under global change scenarios, the allergenic potential of pollen is also expected to change. Vehicular-exhaust pollution has been reported to influence the allergenicity of ragweed pollen: pollen along high-traffic roads showed an overall higher allergenicity than pollen from low-traffic roads and vegetated areas (Ghiani et al. 2012). Beck et al. (2013) documented a positive relationship between atmospheric ozone (O_3) levels and the amount of Bet v 1 in pollen samples collected from birch trees in outdoor stands in Bavaria, Germany. However, further clarification is needed regarding what the combined effect of ozone, nitrogen dioxide, carbon dioxide and air temperature on pollen allergenicity is on a plant population or ecosystem level. Epidemiological studies have demonstrated that urbanisation, high levels of vehicle emissions and a Westernised lifestyle are correlated with an increase in the frequency of pollen-induced respiratory allergy, which is more prominent in people who live in urban areas compared to those who live in rural areas (Haftenberger et al. 2013).

3.7 Pollen Information Services

Airborne pollen is routinely monitored worldwide, mainly for providing information on pollen season occurrence with a view to allergy prevention. Hirst-type devices are the most widely used pollen samplers worldwide (e.g. Galán et al. 2014). The device is volumetric and samples with a stable suction of airflow ($10\ \mathrm{l\ min^{-1}}$). Captured pollen grains are processed in the laboratory and then analysed under an optical microscope (manually identified and counted by expert scientists). The identification level is usually per genus for woody taxa and per family for herbaceous taxa. All measurements are expressed as numbers of pollen per cubic metre of air (e.g. British Aerobiology Federation 1995; Galán et al. 2014).

Pollen data from Hirst-type traps do not allow for real-time pollen measurements and timely dissemination of airborne pollen concentrations, even though their main purpose is to provide information on airborne particle abundance to allergic individuals. Hence, predictions with a minimum of a weekly forecasting horizon had to be developed. Additionally, a lot of effort and time are required because of the laborious nature of the microscopical identification technique. It is evident that there is an overall need for faster, near real-time reporting of airborne pollen concentrations. To date, high-risk pollen exposure alerts have been provided only via mid-term pollen season forecasting models, which are often not of good accuracy for operational and everyday medical practice. The future aim is to disseminate airborne pollen measurements using a novel automatic, real-time pollen sampler, in order to provide timely and accurate warning alerts to allergic patients throughout the duration of the pollen season, with the ultimate aim of more efficiently managing allergic diseases.

A new generation of automated, near real-time pollen measurements is currently being developed, and has already been able, in some cases, to work on an operational basis (Oteros et al. 2015; Häring et al. 2017). The most well-developed, promising or already operating automated pollen measuring devices are located in

(1) Japan (KH-3000) (Kawashima et al. 2017), which until now has been able to provide information only on one pollen type (*Cryptomeria japonica*, Cupressaceae family) and not on the complete pollen diversity, (2) the USA (Pollen Sense) (http://pollensense.com/), where it is still under calibration and not in fully operational mode, (3) Switzerland (PA-300 Rapid E) (Crouzy et al. 2016), where it is under calibration, and (4) Germany (BAA500), which has been in fully operational mode for the last half decade (e.g. Oteros et al. 2015; Häring et al. 2017).

The aforementioned automated pollen measuring device in Germany, the BAA500 Pollen Monitor, is an automated pollen monitoring system that is able to successfully recognise more than 10 pollen taxa, among which the allergenic *Alnus*, *Artemisia*, *Betula*, *Corylus*, *Fraxinus*, Poaceae and *Taxus* (Oteros et al. 2015). This system uses an image recognition algorithm on batch-collected pollen. The obtained pollen data exhibit a delay of only 3 h (Oteros et al. 2015). Oteros et al. (2015) have reported that the BAA500 manages to correctly identify all different pollen types in >70% of all cases (except for *Salix* pollen), with false-positive reports only occurring rarely.

3.8 Conclusions and Future Challenges

Climate change has been responsible for changes in biodiversity and species richness. Air quality, vegetation and land use changes, plant diversity and distribution have been altering pollen seasons, pollen abundance and allergenicity. In a changing world working towards optimum health management, it is crucial to take quick counter-measures, as suggested below.

First, a reliable, fully operational, real-time aeroallergen monitoring programme across the globe, needs to be urgently implemented, and must include all allergy-implicated pollen types, mainly birch, grasses and ragweed. This also includes setting up an automated system of free dissemination of the obtained results. Automated monitoring ought to be extended to other allergenic bioaerosols as well, such as the notorious fungal spore types of *Alternaria* and *Cladosporium*: if we consider that we spend more than two-thirds of our life indoors, at home or at work, it is critical that we evaluate the exposure risk and consequent symptoms due to indoor aeroallergens as well.

Secondly, special attention must be paid to changing aeroallergen seasons and spatial variability as this could increase sensitisation rates. Invasive plant species like ragweed and relevant eradication programmes have to be focused on. Likewise, *Alternaria* growth and production of spores have to be extensively investigated in the frame of future climate change, as it has been reported that this will dramatically change in 2100 climatic scenarios, growing faster but likely producing fewer spores, thus indicating an alteration in life strategy (Damialis et al. 2015).

It is crucial that all research approaches reflect real-life conditions as much as possible; it is important to focus mainly on the interaction effects between plant biological, physiological and ecological processes under varying environmental stress conditions, so as to be able to foresee the consequent health impacts.

Above all, more emphasis needs to be placed on environmental research, transforming the current status quo from anthropocentric research to the harmonic interaction of human-environment. The development of modern, automatic, real-time environmental health services is urgently needed, with the aim of providing, in the future, efficient guidelines for allergy prevention and management. Exposure risk alerts, e-health infrastructure and personalised forecasts on allergy management are seen as the (near) future of allergy research.

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