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REVIEW ARTICLE

Monitoring airborne pollen in New Zealand

Rewi M. Newnham

Schhol of Geography, Environment & Earth Sciences, Victoria University of Wellington, Wellington, New Zealand

ABSTRACT
Against a backdrop of increasing pollen allergy prevalence, this paper reviews the current state of knowledge of allergenic pollen loading in New Zealand. An unavoidable conclusion is that relevant available datasets are fragmentary, incomplete and out-of-date, with the last nationwide survey conducted >30 years ago. In contrast, many other developed regions continue to provide routine, standardised pollen reporting and forecasting to assist with the management and treatment of seasonal allergic rhinitis and related diseases, which affect a large proportion of the population. The data also inform wider research including investigating allergic rhinitis co-association with other health issues and monitoring and projecting the impacts of climate change on pollen production and dispersal; fundamental biological processes that underpin most life on Earth. New Zealand is lagging well behind other regions in realising these benefits by failing to implement a programme of routine aeroallergen monitoring at major population centres. The data generated would also help to answer some pressing questions in relation to respiratory disorder in New Zealand and in particular whether the timing and severity of key pollen allergens are changing and new sources are establishing as a result of climate change.

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Introduction

Allergic disease is a key public health problem that has worsened in recent decades and is now recognised as a major global epidemic (Pawankar 2014; Platts-Mills 2015). Allergic rhinoconjunctivitis (AR) is the most common allergic disease and affects at least 500 million people worldwide with important economic and social consequences (Pawankar et al. 2011). AR refers to inflammation of the inside of the nose and eyes caused by an environmental allergen, such as pollen, dust, mould or flakes of skin from certain animals. The discrete seasonality of pollen, as opposed to these other allergens, has led to the distinction of seasonal allergic rhinoconjunctivitis (SAR) and this term and hayfever are used synonymously here to refer to AR caused by exposure to certain wind-dispersed pollen containing allergenic properties (Knox 1979).

Over the past several decades, the science of aerobiology has evolved to provide a deeper understanding of the role of pollen in SAR, other allergic diseases and respiratory disorders. An important contribution has come from airborne pollen monitoring

CONTACT Rewi M. Newnham ✉ rewi.newnham@vuw.ac.nz

networks established in many regions of the world (Buters, Antunes, et al. 2018). These programmes monitor current levels of atmospheric pollen to provide information useful for diagnosis, treatment and prevention, as well as for biomedical and biological research at local to regional levels (Thibaudon et al. 2013). Airborne pollen data are also used in a predictive manner by the generation of short-term pollen forecasting (Smith and Emberlin 2005).

In New Zealand, where AR prevalence is high, efforts to monitor airborne pollen have been limited. Arguably the information currently available to practitioners and patients is out of date or even erroneous, given various environmental transformations of the past few decades, involving plant communities, land use and climate change. The purpose of this paper is to review current knowledge of airborne pollen levels and seasons in New Zealand within the context of recent environmental change and to assess the adequacy of this information for effective management and treatment of SAR and related allergies. It presents a case for implementing a nationwide airborne pollen monitoring network in New Zealand as has recently occurred in Australia. The next section discusses the key co-morbidity associations between SAR and several other allergic diseases, then considers recent prevalence trends in New Zealand.

Seasonal allergic rhinitis and recent trends in prevalence

SAR and associated diseases

SAR is a Type I immediate hypersensitivity reaction mediated by a specific IgE antibody to a seasonal allergen. Pollen from wind-pollinated plants and spores from various saprophytic fungi (moulds) are the most common aeroallergens (Knox 1979). SAR is closely linked to asthma and approximately 20%–30% of people who experience hayfever either suffer from or develop asthma (Demoly and Bousquet 2006). Conversely, a high proportion of people with asthma will have some degree of allergic rhinitis. A strong positive association between SAR and occupational asthma has been shown (Barnard et al. 2004) and, as SAR often precedes asthma, it is possible that effective avoidance or treatment of allergic rhinitis may reduce asthma progression (Polosa et al. 2005). Increased airborne grass pollen levels have been linked with significant increases in hospital emergency department visits and admissions for asthma resulting in a number of deaths (Erbas et al. 2007; Darrow et al. 2012; Beggs et al. 2015). In Australia, the disintegration of allergenic grass pollen during thunderstorms, enabling allergenic cytoplasmic fragments to penetrate further into the lungs, is now widely considered to be a major cause of recent thunderstorm asthma epidemics (Bellomo et al. 1992; Marks et al. 2001; Taylor et al. 2002; Howden et al. 2011; Thien et al. 2018). Although previously considered unlikely to occur in New Zealand increased asthma presentations at Waikato Hospital in December 2017 have been linked to thunderstorm asthma (Sabih et al. 2020). There is also growing awareness of the rising prevalence in cross-reactivity between pollen and food allergies with a recent study reporting that 30%–60% of food allergies are linked to pollen allergy (Poncet et al. 2020). Co-association of airborne allergenic pollen with air pollution, including from bushfires, has also been reported (Jalaludin et al. 2000). Pollen can also inhibit the innate immune response of the mucous membranes in the upper respiratory tract (Gilles et al. 2020), thereby increasing susceptibility to respiratory uptake of virus-containing particles. This mechanism may help to explain a recent report that used airborne pollen monitoring data from 31 countries to show that pollen may be partly responsible for reported increasing infection rates in Sars-CoV2 during spring (Damialis et al. 2021).

SAR prevalence in New Zealand

In New Zealand, increases in the prevalence of AR have been widely reported in recent decades, in particular amongst children (Asher et al. 2001; 2006; Björkstén and the ISAAC Phase III Study Group 2008) with AR childhood incidence reported as twice the global average and increasing (Sibbald and Strachan 1995; Beasley 1998; Pattemore et al. 2004; Santos et al. 2015). This trend has been more pronounced in New Zealand than in most countries (Sibbald and Strachan 1995; Beasley 1998). One study by a European Community Respiratory Health Survey reported an extremely high prevalence (35%–40%) of nasal allergies, including AR in 20–44-year-old New Zealanders (Parikh and Scadding 1997). AR and asthma prevalence and co-morbidities are also among the highest in the world (Asher et al. 2001; Björkstén and the ISAAC Phase III Study Group 2008; Telfar-Barnard et al. 2015).

As is often the case with public health, inequalities are evident in AR prevalence among the New Zealand population. Previous studies report a disproportionate prevalence of AR among Pacific Islanders (Sibbald and Strachan 1995) and higher asthma hospitalisation rates and asthma morbidity and respiratory disease morbidity in Māori than in non-Māori (Asher et al. 2001; Ellison-Loschman et al. 2002, 2004, 2009; Pattemore et al. 2004; Telfar-Barnard and Zhang 2019). Further inequalities arise in education and in the workforce through non-attendance or impaired performance.

It is apparent from these various studies that the 'global burden' of asthma and allergies is increasing. The minimum cost burden of respiratory disease to New Zealand for 2015 was estimated to be $7.05b (Telfar-Barnard and Zhang 2019). Of this, $6.59b were indirect costs from mortality and disability affected life years, and the remaining $465 m were direct costs from hospitalisations, prescriptions and doctors' visits. These costs are very likely increasing with growing populations and increasing prevalence. In addition, large sums are spent on pharmaceutical treatments. In Australia, pharmacy wholesale purchases for oral anti-histamines and nasal steroids, the principal pharmacological medications prescribed for SAR, doubled between 2001 and 2010 to $226.8 million (Australian Institute of Health & Welfare 2011). Although no data were available for New Zealand, proportionate levels of pharmaceutical usage and similar trends seem likely.

Most allergies, including SAR, were virtually unknown 200 years ago. Genetics play a role in susceptibility, but a range of direct and indirect factors have been proposed to explain increases in prevalence, including changes in abundance or sources of allergenic pollen and heightened sensitivity linked to atmospheric pollutants and aspects of modern lifestyle such as hygiene and the use of antibiotics. Environmental change, a pervasive and characteristic feature globally since the mid-twentieth century, is likely to have been an important factor in the increasing prevalence of SAR and related allergies during this period. The spread of new invasive plant species, changes in land use, climate and atmospheric CO_2 levels will all have influenced the sources, timing and amounts of airborne pollen allergens. New Zealand has not been exempted from the impacts of these recent environmental changes (Leathwick et al. 2003; Ministry for the Environment & Stats NZ 2020). There is a clear need to improve understanding of how the timing, severity and composition of allergenic pollen seasons have been impacted by recent environmental changes and how changes in these key sources of allergen have contributed to increasing trends in respiratory disorder.

Airborne pollen monitoring

Conventional methods

Although pollen had long been linked with symptoms of allergic rhinitis and other forms of respiratory disorder, it was not until 1873 that Charles Blackley (1820–1900) was able to demonstrate its impact on human health. Using skin prick tests on himself with pollen obtained from a self-made pollen trap, he demonstrated that the amount of pollen in the atmosphere was correlated with the severity of his own symptoms (Waite 1995).

Early methods of measuring pollen in the atmosphere involved exposing a greased microscope slide to outdoor air flow for a set period and analysing the material impacted on the slide. Since the 1950s, most pollen monitoring efforts have deployed pollen traps based on the Hirst design (Hirst 1952). The Hirst-type sampler enables continuous sampling at a fixed location and is designed to sample air at the rate of human breathing. Airborne particles impact on a rotating tape at a sampling interval that may range from 2 h to 1 week, following which the tape is transferred to microscopic slides for pollen analysis. The need to ensure continuity and comparability of pollen data has led to widespread adoption of the Hirst-type particle samplers by various international aerobiological networks with a view to promote standardisation and quality control (Oteros et al. 2013; Galán et al. 2014). Largely for these reasons, pollen traps of the Hirst design are still deployed at ~70% of the >1000 monitoring sites currently operating around the world (Buters, Antunes, et al. 2018). The oldest continuous pollen record dates to 1943 in Cardiff, UK, and multi-decadal records are available at many sites, supporting a range of research initiatives in aerobiology, as discussed later.

An alternative device, the Intermittent Cycling Rotorod sampler (Chapman 1982), is still used routinely in the United States but is less common elsewhere. Both Rotorod and Hirst-type samplers are deployed at elevations, usually ~5–10 m above ground level, to optimise the measurement of well-dispersed wind-pollinated pollen that comprise the main allergenic sources. In both cases, samples are analysed under the transmitted light microscope by trained palynologists to determine pollen abundance, usually presented as concentrations of grains/m^3 air. The analyses are labour intensive and expensive, with a daily sample requiring ~30–120 min work, depending on the time of year. These costs have led to an irregular and inequitable spatial resolution of sampling sites around the world (Buters, Antunes, et al. 2018). Many regions are sparsely monitored or not at all, whilst at another extreme, some cities have several sites that operate concurrently (e.g. Milan, Seoul and Tokyo).

Automated methods

As a consequence of these limitations, considerable effort has been applied in recent years to developing automated pollen monitoring systems, with two types of technology emerging as frontrunners: devices based on automatic image recognition (Holt and Bennett 2014; Oteros et al. 2015, 2020) and those based on air-flow cytometry (Kawashima et al. 2007, 2017; Oteros et al. 2013). The former strategy uses microscope slide scanning with image processing of pollen images combined with statistically derived algorithms or machine learning. Although this method was originally developed for analysing fossil pollen in the field of Quaternary paleoecology (Holt and Bennett 2014) it is now used in small but growing numbers in pollen monitoring networks in Europe (Oteros et al. 2015; Crouzy et al. 2016; Buters et al. Buters, Antunes, et al. 2018; Buters, Schmidt-Weber, et al. 2018). As Holt and Bennett (2014) point out, a comprehensive image analysis system that is fast and can deal with an unlimited number of taxa, as well as broken, deformed and clumped pollen, is computationally demanding and still some way off. Nevertheless, in these respects, image analysis seems better suited to aeropalynology, where the objective usually is to quantify a select minority of allergenic pollen taxa from comparatively 'clean' airborne samples with fresh, undamaged specimens.

Air-flow cytometry measurement links light scattering and fluorescence characteristics (laser optics) of specific pollen grains of interest with their morphology. Pollen grains are counted and classified continuously as they are drawn out of the air, enabling this method to potentially generate rapid, real-time counts, although the results generated are not always directly comparable to current or historical pollen measurements using slide-based methods (Holt and Bennett 2014). Japan has led the development of this technology, with 120 stations currently deployed. Automatic monitoring using a single-particle light-scattering instrument is arguably more feasible in Japan because the allergenic pollen burden is heavily dominated by a single pollen species (Japanese cedar) (Kawashima et al. 2007; Buters, Antunes, et al. 2018).

Although both these types of automated pollen measurement have their limitations and are yet to be widely deployed (Japan excepted), they offer great potential for workload reduction and rapid online pollen reporting, and thereby for transforming airborne pollen monitoring in the future, particularly if they can be integrated with the more traditional methods. The reader is referred to Swanson and Huffman (2020) for a recent account of the status of these emerging technologies for automated pollen analysis, to Šantl-Temkiv et al. (2019) for further details on the variety of technical challenges they face and to Buters, Schmidt-Weber, et al. (2018) for a recent perspective on the future automation of pollen monitoring and dissemination.

3.3. Remote sensing of pollen seasons

Further opportunity to overcome the restrictive coverage of current in situ pollen networks arises from the development of new satellite sensors in recent decades and availability of these data at a high temporal frequency (Devadas et al. 2018). Several studies have demonstrated the capacity for satellite-sensed greenness or vegetation indices to characterise important phenological variables related to pollen release, including the onset of birch flowering in Norway (Karlsen et al. 2009), grass and birch pollen seasons in the UK (Khwarahm et al. 2017), and grass pollen seasons in France and Australia (Devadas et al. 2018). Other studies have used remote sensing to locate allergen sources of grass pollen in urban areas in Denmark (Skjøth et al. 2013) and juniper pollen sources in the US (Luvall et al. 2011). It should be emphasised that an initial key step in this process is to 'ground-truth' as well as calibrate the remote-sensed data with observations from geographically relevant traditional pollen monitoring sites.

It should be noted that as satellite imagery can only provide a proxy for pollen levels, this methodology requires robust underpinning from ground-truthed local pollen monitoring observations. For example, Devadas et al. (2018) utilised time series of pollen observations compared to satellite measures of grass cover and seasonal greenness for the same interval over five contrasting urban environments, located in Northern (France) and Southern Hemispheres (Australia), to evaluate the utility of these measures for predicting airborne grass pollen concentrations. Interestingly, the Australian sites showed greater pollen season variability than the French sites, perhaps because of different landscape conditions and climate. At the French sites, land cover types and the composition of grass species were relatively homogeneous and uniformly distributed, resulting in well-defined pollen seasons. In comparison, the more heterogeneous land cover and diverse grass species found at the Australian sites, notably combinations of C3 and C4 grasses, results in broader phenology profiles that exhibit greater seasonal and interannual variability.

This study along with similar pioneering work shows the potential for remote sensing to accurately capture the timing characteristics of allergenic pollen seasons, once those characteristics have undergone verification and calibration from several consecutive seasons of ground-based pollen monitoring. As with automated pollen analysis, if the potential for remote sensing to inform pollen forecast systems were realised more extensively, then the significant resources utilised for local labour-intensive pollen monitoring networks could be substantially reduced and their spatial applicability substantially extended. These benefits would also apply to pollen forecasting efforts and other applications that can utilise information about pollen production and dispersal, as discussed in the next section.

Other pollen monitoring applications

Pollen forecasting

The availability of regional-national scale routine pollen monitoring in some parts of the world, notably USA, Japan, Europe and UK, has supported the generation of locality-based pollen forecasting, usually confined to spring and summer months. In addition to these empirical measurements, today many Apps or meteorological services deliver pollen forecasts, although in most cases it is unclear how the data are obtained.

Pollen forecasting is possible because time series of airborne pollen data combined with local meteorological data have been developed for various urban locations spanning several decades. As key pollen season characteristics such as onset and length are strongly related to meteorological variables, these datasets have enabled the development of predictive models for short-term forecasting pollen levels from meteorological variables underpinned by an understanding of interannual pollen season variability (Schäppi et al. 1998; Emberlin et al. 2002; Rodríguez-Rajo et al. 2003; Sofiev et al. 2006; Newnham et al. 2013; Picornell et al. 2019). Additional input may come from local land use and topography information, local phenological observations and experience drawn from past forecasting efforts (Smith and Emberlin 2005), sometimes in conjunction with pollen dispersion simulation models (Zink et al. 2012). The pollen-meteorological datasets can also be used to develop predictive tools for longer-term forecasting, such as the timing of onset for a particular pollen season (e.g. Newnham et al. 2013; Khwarahm et al. 2014) or projected pollen levels and SAR prevalence under future climate change scenarios (e.g. Lake et al. 2017)

Other applications

Although the primary motivation for airborne pollen monitoring is to support allergy prevention and pollen forecasting (Sofiev et al. 2006; de Weger et al. 2014), they have also proved to be useful for supporting a range of research programmes involving plant phenology in agriculture and pest control (e.g. Oteros et al. 2014; Cunha et al. 2016) including GMO monitoring (Hofmann et al. 2016) as well as in natural ecosystems (Buters 2014). There is growing recognition of the value of pollen monitoring data for a range of investigations of current and projected biotic impacts of climate change (Ziello et al. 2012; Zhang et al. 2015) and tracing the spread of invasive plant species (Šikoparija et al. 2009; Karrer et al. 2015).

To date, there are surprisingly few examples of Quaternary palynology investigations that have drawn explicitly on airborne pollen monitoring data (see Giesecke et al. (2010) for one example). Palynological investigations of fossil pollen preserved in sedimentary sequences have made a major contribution to advancing understanding of Quaternary environmental change and human-environment interaction in prehistory, including in New Zealand (e.g. Newnham et al. 1998). The interpretation of Quaternary pollen records requires a grasp of the enormous range in pollen production and dispersal characteristics between different taxa. Whilst this understanding is largely achieved by comparing modern pollen assemblages found in surface sediment samples with observed nearby vegetation communities, airborne pollen monitoring data offer a complementary source of salient information on pollen representation. Quaternary paleoecologists could make better use of this potentially rich archive, not only for promoting understanding of pollen representation characteristics but also to help with detecting and attributing pollen contamination occurring in the field or in the laboratory (e.g. Newnham, Lowe, et al. 1995). It is also relevant to point out that the palynological expertise developed for fossil and airborne pollen applications is interchangeable between these different applications, and not surprisingly Quaternary palynologists have contributed to historical efforts to monitor airborne pollen in New Zealand.

Historical airborne pollen monitoring in New Zealand

The aerobiology of New Zealand is likely to be complex given the strong environmental gradients, diverse topography and climate within a broad oceanic setting (Leathwick et al. 2003). In addition to these abiotic factors, there is considerable biotic complexity arising from the coexistence of very distinct indigenous vegetation with Northern Hemisphere plants introduced for agriculture or as ornamentals, as well as exotic invasive species. The dynamics of these biotic and abiotic factors are further enhanced by a predominantly rural landscape and strong agricultural economy, in large part based on introduced pasture grasses, many of which have high allergen potential.

Given these complexities and the high prevalence of respiratory disorder, empirical observations of airborne pollen in New Zealand are surprisingly limited. Following early work comprising single season or single-site monitoring of pollen deposition using rudimentary methods (Filmer and Harris 1949; Clark 1951; Licitis 1953), Hillas and Wilson (1979) developed a pollen calendar for Auckland showing seasonal timing of key allergenic pollens based on a 15-month survey. Taken together, this pioneering work and previous epidemiology studies suggested that introduced grasses were the most important source of allergenic pollen in New Zealand, although other allergenic sources are prevalent and, as discussed later, may be spreading. There appear to be distinctive pollen seasons albeit with some interannual variability and the composition, abundance, and seasonality of airborne pollen levels differ across New Zealand.

Regional heterogeneity of pollen seasons was demonstrated by the first and, thus far, only systematic nationwide survey of airborne pollen conducted across the spring and summer months of 1988/89 (Newnham, Fountain, et al. 1995). Airborne pollen was monitored daily from October 1988 to February 1989 at seven sites using a Rotorod pollen sampler. Although only grass pollen was monitored at all sites, several sites reported other pollen types as well. As well as demonstrating strong regional differentiation in both timing and amplitude of the grass pollen season, this survey provided some insights into short-term pollen-climate relationships. Nevertheless, this work was limited in several ways. (1) Only spring and summer months were monitored, with an untested assumption that airborne pollen is insignificant between March and September. Although this assumption may hold for grass pollen, there is a clear need to monitor allergenic fungal spores that may be prominent at any time of year and allergenic pollen from introduced winter flowering plants, such as members of the Cupressaceae family. (2) Data were obtained for just one season, insufficient for developing pollen forecasting models or for assessment of seasonal variability. (3) Apart from grass pollen, there was no systematic monitoring of other allergenic pollen types even though many others are likely to be important (e.g. pollen from the Betulaceae, Fagaceae, Cupressaceae, and Urticaceae families). (4) No attempt was made to link daily or seasonal variations to weather and climate that might, for example, support pollen forecasting in future seasons. (5) It employed equipment and methodology that has since been superseded and differences in sampling characteristics, notably the height above ground level that the Rotorod sampler was installed, may have contributed to large volumetric measurement differences between sites (Newnham 1999).

Despite these limitations, the 1988/89 survey remains the most recent attempt to measure airborne pollen levels across New Zealand. It confirmed that grasses (Poaceae) are the most common pollen allergen throughout New Zealand during spring and summer, even in cities, although rural grass pollen levels tended to be much higher. The wide geographic spread of results also revealed a temperature-related latitudinal lag in the onset of airborne grass pollen season, suggesting that ongoing pollen monitoring could provide sensitive signals of vegetation response to climate change (Newnham 1999). Although individual grass species were not identified palynologically, the research team also undertook regional surveys of grass flowering throughout the study period and these results in combination with the grass pollen measurements enabled a first approximation of the key grass allergen species for each region (Figure 1).

Several other features of Figure 1 are relevant to point out. It shows that the grass pollen season varies between regions, with a distinct latitudinal lag from north to south, even though these distinctions may not necessarily be evident from grass flowering observations. In contrast, there is a broad similarity in the grass pollen seasons depicted within regions, although with an isolated exception in January for both regions. These observations support the assertions that (1) a single pollen monitoring site, or nationwide calendar (see later) does not provide adequate coverage for a country as regionally diverse as New Zealand; (2) on the other hand, data from a single pollen monitoring site in a population centre may be representative of a

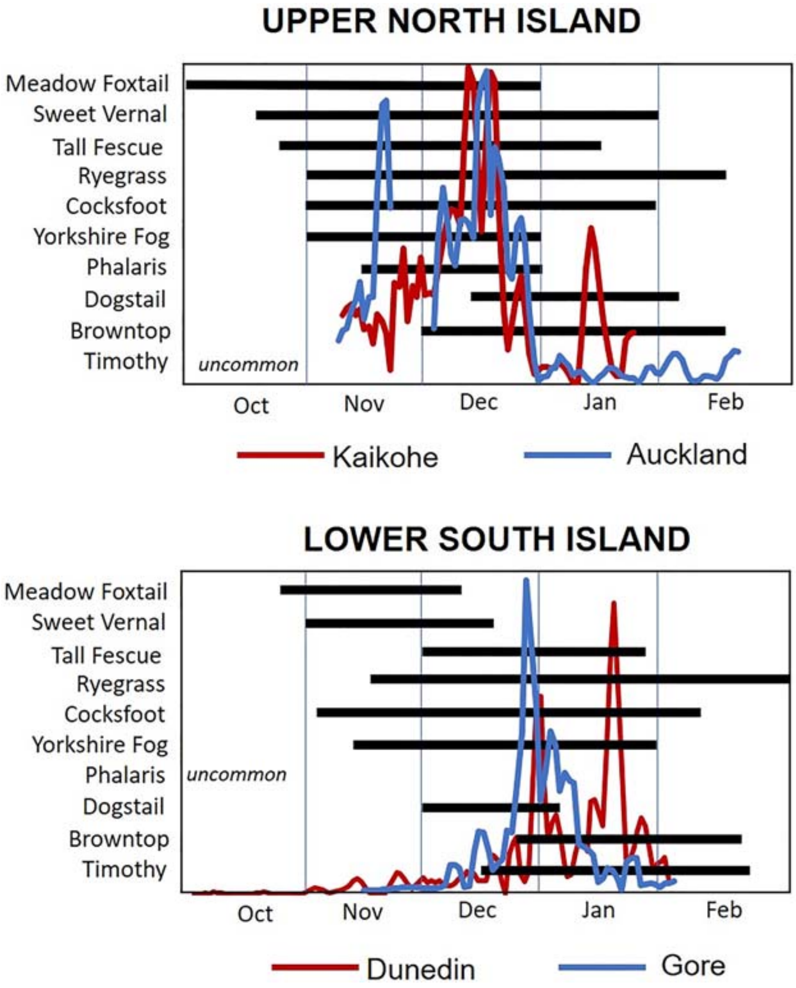

Figure 1. Grass pollen seasons (curves) depicted against individual grass species observed flowering period (bars) for four sites and two regions. Grass flowering periods and pollen data for Kaikohe, Auckland and Gore are for 1988/89 (Newnham, Fountain, et al. 1995). Pollen data for Dunedin are for 1992/1993 (Newnham 2017). Note (1) no data were available for Auckland for the period 27/11/1988–5/12/1988; (2) *y* axes (number of pollen grains/cm^3 air) are not drawn to the same scale.

broader region than just its location; (3) observations of plant flowering are not by themselves a sufficient surrogate for pollen counts; (4) the temperature-controlled latitudinal lag in pollen seasons shows that a seasonal pattern at a given site may well vary with local temperature variability from one year to the next and therefore in the longer-term seasonal shifts with climate change are to be expected.

The lack of information on allergenic tree pollen in New Zealand motivated a study by Fountain and Cornford (1991), who monitored *Pinus* pollen dispersal at Palmerston North for 3 years (1988–1990). They showed a distinctive *Pinus* pollen season spanning late July to mid-September, 2–3 months before the grass pollen season in the area. A more comprehensive survey of Dunedin pollen levels, conducted in 1992 also using the Rotorod sampler, revealed that four tree pollen taxa were especially prominent during October and November. Two tree taxa in particular birch and cypress (macrocarpa), have reported high allergenicity potency in other countries (Figure 2; Newnham 2017). At Dunedin, high levels of these pollen taxa occur during periods of strong north-westerly winds which presumably extend their potential up-wind source area. On those particular days in the 1992 survey, the high levels of birch pollen in Dunedin were comparable to the highest levels recorded in the United Kingdom, where birch is the most important tree pollen allergen.

Hitherto unpublished data from that Dunedin survey presented here (Figure 2) show the tree pollen seasons in comparison with the subsequent grass pollen levels measured at the same location during subsequent spring and summer months. The temporal juxtaposition of allergenic tree and grass pollen seasons indicates that in regions such as the lower South Island there is high potential for cumulative exposure to multiple allergens, as well as priming for grass pollen allergens by prior exposure to tree pollen allergens earlier in the season (cf Katelaris 2000). Another feature of note is that rainfall exercises a direct inhibitive control on pollen release during the pollen season for both trees and grasses and that, conversely, sunshine hours along with strong winds (not shown in

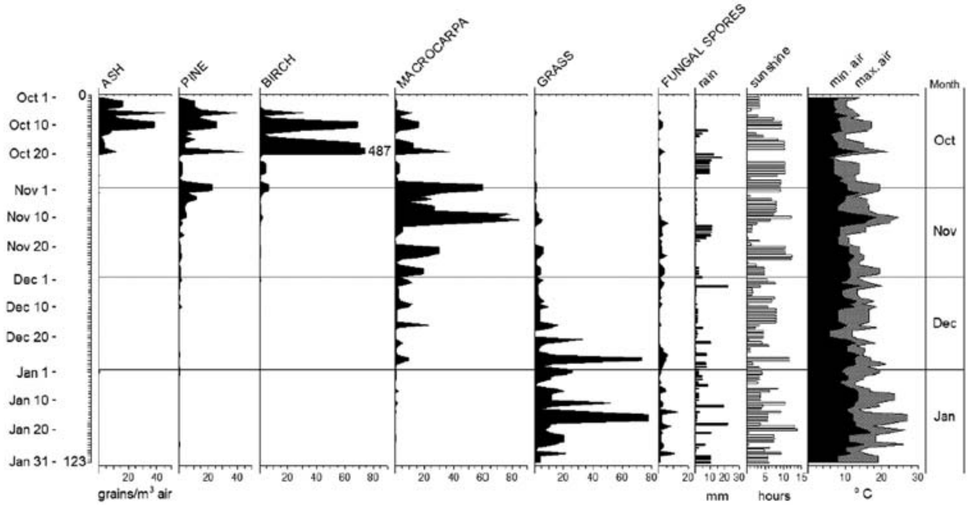

Figure 2. Airborne pollen levels for prominent tree taxa and grasses and fungal spore levels alongside meteorological data, measured at Otago University, Dunedin, spring-summer 1992/1993.

Figure 2, but see Newnham 2017) can enhance pollen release and dispersal during a season, particularly following periods of rainfall. From these observations, it should be evident that the effectiveness of pollen monitoring and forecasting can be enhanced by continuous monitoring throughout the year (not just the presumed grass season) and in combination with locally applicable meteorological data.

In summary, monitoring of airborne pollen across New Zealand for the most part has been uncoordinated, irregular, and motivated by different goals (Medek et al. 2015). It should be apparent that the information obtained by the only substantive nationwide survey, conducted >30 years ago, is now likely to be out-of-date in many important respects. The inadequacies of the available information on current pollen levels across New Zealand were highlighted by an Australasian Aerobiology Working Group established to collate and review the available atmospheric pollen concentration data from Australia and New Zealand (Davies et al. 2015). This working group was successful in proposing the establishment of an Australian national pollen monitoring network (www.pollenforecast.com.au/) as a critical step in the management of exposure to pollen in patients with allergic disease as well as providing a basis to trace the impacts of current and future climate change on pollen distribution. The next section of this review argues that a similar facility urgently needs to be established for New Zealand.

The need for further pollen monitoring in New Zealand

As discussed earlier, in many regions of the world, the collection of long-term airborne pollen data has enabled the measurement of population exposure to aeroallergens under changing environmental conditions (Buters, Antunes, et al. 2018). This information has helped to improve understanding of 'allergy seasons' for medical practitioners and patients. A specific and targeted long-term management strategy for allergen-driven respiratory allergic disease is the use of immunotherapy. This allergen-specific therapy relies on correct allergen identification which, along with skin testing for specific allergy response, can be effectively informed by continuous, local pollen monitoring. Along with the pollen forecasts enabled by pollen monitoring, the real-time data, therefore, inform treatment as well as self-management of AR and allergic asthma symptoms on a daily basis, thereby reducing allergy-induced Emergency Department visits and hospital admissions for respiratory disease (Erbas et al. 2007; Darrow et al. 2012; Vicendese et al. 2013).

In this way, pollen exposure is also an independent predictor of hospital admissions for respiratory disease (Beggs et al. 2015). These authors also point out that allergy patients with access to actual and forecast pollen levels feel a sense of empowerment and control over their symptoms which may result in greater compliance with preventative medication use. The increased awareness of pollen-related allergies, promoted by the pollen forecasts, arguably also helps to reduce the stigma of these diseases often perceived by allergy patients and among the wider population. Although difficult to measure, it is clear that well-founded pollen monitoring networks will reduce the financial and social burden of these diseases.

In those parts of the world that currently lack pollen monitoring networks, allergy practitioners and patients tend to rely on static pollen calendars to manage and treat their symptoms. For example, a pollen calendar for New Zealand promoted by Allergy

New Zealand (www.allergy.org.nz/site/allergynz/Annual%20Pollen%20Calendar%202018%20A3.pdf) shows which allergenic pollens are likely to be prevalent during the various months of the year. Although the usage of such calendars is understandable, in the absence of empirically based pollen counts and forecasts, it is not always clear what the pollen calendars are based on, nor what regions they are applicable to. If we consider the diversity of pollen recorded to date from New Zealand pollen sites (Figure 1), reflecting the heterogeneous regional climates and vegetation cover and a wide variety of land uses, a single New Zealand wide pollen calendar can have little more value than a single New Zealand wide weather forecast. Not surprisingly, the Australasian Aerobiology Working Group concluded that such static pollen calendars are of limited utility and have no value as indicators of peak pollen periods which are of particular interest to allergy sufferers (Beggs et al. 2015).

The futility of resorting to static pollen calendars – and pollen forecasting based on them – is further highlighted by a consideration of the likely impact of major environmental changes on aeroallergens in recent decades. This review now reflects upon two key aspects of recent and contemporary environmental change that are likely to have a major impact on pollen allergy prevalence in New Zealand over the coming decades: climate change and the introduction of new plant allergen sources and spread of existing ones – which in many cases may be enhanced by climate change.

Future threats to allergen risk in New Zealand

Climate change

One of the consequences of greater certainty in attributing recent climate change to anthropogenic greenhouse gas emissions (Hegerl et al. 2007) is that we can have stronger confidence in climate projections that are simulated under various future emissions scenarios. This realisation in turn has strengthened efforts to anticipate and model a wide range of environmental and societal impacts likely to occur under these various scenarios. In the health sector, there is mounting concern that the prevalence of allergy diseases will increase under climate change (Bielory et al. 2012; Smith et al. 2014; Beggs 2015) in large part because of the impact on allergenic plant species (Shea et al. 2008). Indeed, climate change has already been suggested as one factor behind the increasing prevalence of allergic asthma (Beggs and Bambrick 2005).

Climate change, and in particular, increased temperature regimes, rising atmospheric CO_2 levels, altered patterns of precipitation and greater interannual variability, are likely to impact upon pollen allergen levels in New Zealand in a variety of ways and across different timescales (Figure 3). In the short-term, it is clear from airborne pollen monitoring networks that the timing, severity and duration of pollen seasons are extremely sensitive to climate shifts. For example, the duration of the ragweed (*Ambrosia*) pollen season in the United States increased by as much as 13–27 days in northern United States between 1995 and 2010, attributed primarily to the lengthening of the frost-free period (Ziska et al. 2011). A longitudinal study of the birch (*Betula*) pollen season using the UK pollen monitoring network demonstrated a robust relationship between spring temperature and the timing of pollen release over a 40 year period (Newnham et al. 2013). At London, for example, mean March temperatures rose by > 2°C

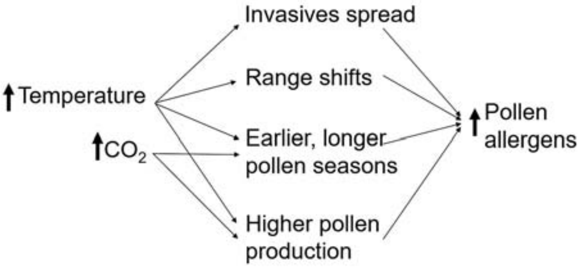

Figure 3. A conceptual view of how climate change promotes pollen allergies.

between 1970 and 1995 while for the same period, the onset of the birch pollen season advanced by 22 days from mid-April to late March. The authors commented that light requirements, notably a shortening of day length with progressively earlier seasons, would ultimately impose an upper limit on the birch pollen season advance. In the lower latitudes of central and southern New Zealand, where birch is commonly found (Figure 2) and spring daylength is longer, the potential for progressive season advancement with warmer spring temperatures will therefore be even greater. The capacity for plants as primary producers to respond rapidly to seasonal climate shifts is such that their phenological adaptation is outpacing dependent consumers further along the food chain, leading to ‘trophic mismatches’ that could have dire consequences for natural communities and for human food security (Thackeray et al. 2010).

CO_2 is the energy source for plants and recent research indicates that higher rates of photosynthesis due to increasing atmospheric levels of CO_2 are generating higher pollen production in certain plants. Some important pollen allergens are now known to be susceptible to this so called ‘CO_2 fertilisation effect’, including ragweed (*Ambrosia),* which has been shown to increase pollen production significantly when exposed to progressively higher atmospheric CO_2 levels (Ziska and Caulfield 2000; Rogers et al. 2006). A controlled laboratory experiment involving timothy grass (*Phleum pratense*), a widely dispersed pasture grass in the temperate world and one of the known principal pollen allergens in New Zealand (Figure 1; Newnham, Fountain, et al. 1995), showed that elevated levels of CO_2 increased the amount of grass pollen produced by significant amounts, even with increased O_3 levels, which can inhibit the CO_2 enhancement (Albertine et al. 2014). At 800 ppm atmospheric CO_2, ~ double the current level and within the mid-range of most emissions scenario projections for 2100, airborne grass pollen concentrations are estimated to increase by up to 200%. Whilst the CO_2 fertilisation effect is helping to mitigate the consequences of increased carbon emissions, these studies indicate that it is also resulting in significant impacts on human health worldwide.

Changing pollen allergen sources

Climate change in concert with various human activities promotes the spread of invasive plant species that are already established in a region and provides opportunities for new introductions. When these plants produce allergenic pollen, as is the case for *Ambrosia*, currently spreading in Europe (Lake et al. 2017; Skjøth et al. 2019) and in Australia (Bass et al. 2000), or olive (*Olea*), plantain (*Plantago*) and subtropical C_4 grasses, also expanding their ranges in Australia (Haberle et al. 2014; Medek et al. 2015), then a progressively higher public health risk can be expected along with changes in timing of pollen seasons. In the long term, multi-decadal scale, new allergenic pollen sources can be expected to become established and spread in regions where they are not currently found or spreading. The four plant sources mentioned above (C_4 grasses, *Ambrosia*, plantain and olive) already occur in New Zealand but apart from plantain have not yet been reported in any aerobiology surveys and are not known to be an allergy risk at present. Nevertheless, all these plant groups are likely to expand their ranges in New Zealand under warmer temperatures projected for this century, as is currently occurring in Australia.

Predicting how future climate change may affect the levels of pollen allergy in a diverse environment such as New Zealand is difficult. The processes discussed here and in the previous section are all likely to enhance the allergenic pollen load in New Zealand, individually and in concert (Figure 3). An altered climate will affect the range of allergenic species as well as the timing and length of the pollen season, and elevated CO_2 may increase plant productivity and pollen production of current and newly introduced allergenic plants. Climate change may also affect the release and atmospheric dispersion of pollen (Bielory et al. 2012). The overall impact will be alteration of pollen season timing and load, and hence, changes in exposure. In New Zealand's temperate climate, there is a high risk of new allergenic plant sources spreading under warmer projected climates so that overall allergen exposure will increase. Modelling all of these processes is needed to assess the consequences of climate change on pollen-related allergic disease.

A recent study that modelled the spread of *Ambrosia* in Europe may be illustrative for New Zealand. Lake et al. (2017) developed a methodology that integrated modelling of plant invasion, pollen production, pollen release, and the atmospheric dispersion of pollen to simulate current (1986–2005) and future (2041–2060) *Ambrosia* pollen levels in Europe. In addition, future pollen levels were simulated under two alternative greenhouse gas concentration scenarios and three different ragweed plant invasion scenarios. Under the mid-range representative concentration pathway (RCP4.5) scenario, sensitisation to *Ambrosia* more than doubles in Europe, from 33 to 77 million people, by 2041–2060, with the greatest proportional increases occurring where sensitisation is currently uncommon (e.g. Germany, Poland, France). Severity of symptoms is also projected to increase due to higher pollen concentrations and a longer pollen season. These projections, which integrate the cumulative impacts of projected climate change with current trends in the spread of this invasive plant species, may have important implications for New Zealand as *Ambrosia* is well suited to the dry, summer-warm eastern regions of the country which most climate models project to become drier and warmer.

Conclusion

Despite its high and increasing prevalence of pollen-related respiratory disorder, New Zealand lags behind many other regions of the world in not monitoring airborne pollen levels. As a consequence, current sources of information used to treat and manage pollen allergies are inadequate and out of date. It is likely that pervasive environmental changes over the past few decades have been an important factor in increasing the prevalence of AR and related allergies. International research shows that warmer temperatures and progressively increasing atmospheric CO_2 levels can lead to higher levels of pollen production, lengthening pollen seasons and increasing their severity. The spread of existing and new invasive plant species, in part promoted by climate change, have influenced the sources, timing and amounts of airborne pollen allergens. New Zealand, with strong economic dependency on introduced pasture grasses with allergenic potential, has not been exempted from these recent environmental changes, yet has no means to measure their aerobiological and public health impacts. Systematic, routine airborne pollen monitoring at the key population centres would provide a means for measuring these impacts and would provide a more realistic basis for the treatment and management of patient symptoms, enable short-and longer-term pollen forecasting and promote stronger awareness and understanding of pollen allergies across the wider community. The databases generated would support further research into other diseases associated with pollen allergies, including asthma and pollen-food allergy syndrome as well as other research questions that emerge in the future. Local ground-truthing from airborne pollen monitoring is also necessary if the potential for new monitoring methodologies is to be realised. Although traditional pollen monitoring is labour intensive, newly emerging technologies for automated pollen analysis and satellite sensor imagery have strong potential to augment traditional ground-based pollen monitoring observations by providing more immediate and extensive coverage.

Disclosure statement

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