Science of the Total Environment

Trans-disciplinary research in synthesis of grass pollen aerobiology and its importance for respiratory health in Australasia

A review article

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Abstract

Grass pollen is a major trigger for allergic rhinitis and asthma, yet little is known about the timing and levels of human exposure to airborne grass pollen across Australasian urban environments. The relationships between environmental aeroallergen exposure and allergic respiratory disease bridge the fields of ecology, aerobiology, geospatial science and public health.

The Australian Aerobiology Working Group comprised of experts in botany, palynology, biogeography, climate change science, plant genetics, biostatistics, ecology pollen allergy, public and environmental health, and medicine, was established to systematically source, collate and analyse atmospheric pollen concentration data from 11 Australian and six New Zealand sites. Following two week long workshops, post-workshop evaluations were conducted to reflect upon the utility of this analysis and synthesis approach to address complex multidisciplinary questions.

This Working Group described i) a biogeographically dependent variation in airborne pollen diversity, ii) a latitudinal gradient in the timing, duration and number of peaks of the grass pollen season, and iii) the emergence of new methodologies based on trans-disciplinary synthesis of aerobiology and remote sensing data. Challenges included resolving methodological variations between pollen monitoring sites and temporal variations in pollen datasets. Other challenges included "marrying" ecosystem and health sciences and reconciling divergent expert opinion. The Australian Aerobiology Working Group facilitated knowledge transfer between diverse scientific disciplines, mentored students and early career scientists, and provided an uninterrupted collaborative opportunity to focus on a unifying problem globally. The Working Group provided a platform to optimise the value of large existing ecological datasets that have importance for human respiratory health and ecosystems research. Compilation of current knowledge of Australasian pollen aerobiology is a critical first step towards the management of exposure to pollen in patients with allergic disease and provides a basis from which the future impacts of climate change on pollen distribution can be assessed and monitored.

Key words:

Pollen

Aerobiology

Allergic rhinitis

Phenology

Knowledge transfer

Trans-disciplinary research

Abbreviations

ACEAS; Australian Centre for Ecological Analysis and Synthesis

ASCIA; Australasian Society of Clinical Immunology and Allergy

TERN; Terrestrial Ecosystem Research Network

1. Introduction

Across Australasia; Australia and New Zealand, grass pollen is the major outdoor aeroallergen source. Although prevalence and morbidity of hay fever and asthma in Australia and New Zealand are among the highest globaly (Asher et al. 2006), the precise factors influencing airborne pollen concentration in Australasian cities are not well understood. This knowledge gap arises in part because of the complex trans-disciplinary nature of the processes that link grass flowering and the release of pollen from anthers, to the dispersal away from source on wind currents to urban environments where sensitive individuals are exposed to allergenic pollen. Clearly, environmental, ecological, geospatial and meteorological factors will all affect local airborne grass pollen levels. While other airborne pollen types and other taxa, including fungal spores, are also important for allergic respiratory disease in susceptible individuals, we focused on grass pollen because of the high frequency of patient sensitisation to grass pollen. In anemophilous plants, wind borne pollen is the vector for delivery of allergen components to the respiratory mucosa. Therefore, we investigated the aerobiology of grass pollen in Australasia to improve understanding of exposure patterns in those susceptible to grass pollen allergy.

The Australian Aerobiology Working Group was funded by the Australian Centre for Ecological Analysis and Synthesis (ACEAS) and was supported within the Terrestrial Ecosystem Research Network (TERN) established by the Australian Government through the National Collaborative Research Infrastructure Strategy (NCRIS). The ACEAS funding supported two one-week workshops in March and November of 2013. The Australian Aerobiology Working Group consisted of experts in botany, ecology, palynology, biogeography, biostatistics, climate change science, plant genetics, pollen allergy, public and environmental health, and medicine from 15 academic or government research institutes from Australia, New Zealand, France, Germany and the USA. There were 19 participants in all, 16 of whom attended one of the workshops and 11 of whom attended both. The primary focus of the research was aerobiology in Australia but this was extended to include New Zealand where possible. In this paper we describe the context for the Australian Aerobiology Working Group research (Section 2), provide an overview of the Australian Aerobiology Working Group outcomes (Section 3) reflect on the benefits and challenges of the Australian Aerobiology Working Group experience (Section 4), and discuss future trans-disciplinary aerobiology research challenges and opportunities (Section 5).

2. Context of the Australian Aerobiology Working Group research

2.1 Burden of pollen allergy in Australia

The primary clinical manifestation of grass pollen allergy, allergic rhinitis, affects three million Australians (15% of the population) (AIHW, 2011). Allergic diseases have a high economic burden for society costing annually $7.8 billion, including $1.2 billion in direct medical costs in Australia (Cook et al. 2007). The increasing impact of allergic diseases is evident by the doubling of pharmacy wholesale purchases to $226.8 million for hay fever drugs (oral anti-histamines and nasal corticosteroids) between 2001 and 2010 (AIHW, 2011). Allergic rhinoconjunctivitis is a seriously debilitating disease leading to poor quality of life and reduced productivity aa well as contributing to other complications including asthma exacerbations (Walls et al. 2005, Bousquet et al. 2008, Meltzer et al. 2009). Airborne grass pollen levels have been positively correlated with symptoms of allergic rhinoconjunctivitis and anti-histamine use in patients with grass pollen allergy (Johnsen et al. 1992, Johnston et al. 2009, Medek et al. 2012). Allergic sensitisation to grass pollen can precede the development of allergic asthma in children (Hatzler et al. 2012) and airborne levels of grass pollen are associated with hospital admissions for asthma (Erbas et al. 2007a, Darrow et al. 2012). A causal relationship between grass pollen challenge and induction of allergic airway inflammation has been demonstrated (Suphioglu et al. 1992) and epidemics of grass pollen allergen-induced thunderstorm asthma are well documented in Australia and elsewhere (Hill et al. 1979, Celenza et al. 1996, Newson et al. 1998, Marks et al. 2001, Howden et al. 2011, Dabrera et al. 2013). Notably, 20% of patients presenting with acute thunderstorm asthma attacks had histories of allergic rhinitis without prior asthma (Waters et al. 1993). Emergency department presentations and admissions for acute episodes of asthma in children appear to be increasing during peak pollen season in Melbourne placing considerable burden on the child, family, community, health service provider and economy (Erbas et al. 2007a, Erbas et al. 2012).

Treatment options for allergic rhinitis include pharmacotherapy to alleviate symptoms or allergen specific immunotherapy to ameliorate the underlying immunological processes. The later therapy provides a long lasting treatment with the benefit of reducing the long term financial burden of disease, acquisition of other allergies and progression to more severe disease (Rolland et al. 2010, Calderon et al. 2011). Knowledge of local current airborne pollen levels would empower patients to implement self-managed allergen avoidance strategies and provide a valuable resource for health professionals responsible for clinical management of patients with moderate to severe allergic rhinitis and asthma (Hill et al. 1979, Potter et al. 1991, Guillam et al. 2010, Erbas et al. 2013).

Elevated atmospheric grass pollen concentrations show strong consistent associations with allergic asthma symptoms and are the main trigger of primary care or emergency department attendance during grass pollen seasons (Erbas et al. 2012). Such seasonality is being shifted in inconsistent ways by climate change, expansion of urban areas and changes to farming practices in the rural fringe (Reid and Gamble 2009, Beggs 2010, Cecchi et al. 2010, Weber 2012). Little research has been performed on the impact of climate change on grass pollen season timing and duration in Australasia. Moreover, direct and indirect effects of urban pollutants on allergen content, allergenicity and immunomodulation of pollen will additionally impact upon human respiratory health. Thus far we know very little of the interaction between consecutive days of high pollution and peak pollen periods.

Air pollutants including diesel exhaust particles and ozone (both in the atmosphere and in the lung) can directly interact with pollen, modify the allergen content and alter expression of genes encoding non-allergen components of pollen further influencing immunostimulatory properties of pollen (Diaz-Sanchez et al. 1997, Knox et al. 1997, Boldogh et al. 2005, Ghiani et al. 2012, D'Amato et al. 2013, Kanter et al. 2013).

In addition to allergic rhinitis and asthma, grass pollen allergy has been associated with atopic eczema (Eyerich et al. 2008) and eosinophilic esophagitis (Almansa et al. 2009, Moawad et al. 2010). Grass pollen exposure may affect other co-morbid conditions. Kim et al. (2013) examined The National Health and Nutrition Examination Survey (NHANES) III data for an association between allergic disease and cardiovascular risk in over 30,000 participants in the United States of America (Kim et al. 2010). Common symptoms of allergic rhinoconjunctivitis or wheezing were associated with cardiovascular disease, predominantly in women less than 50 years of age (Kim et al. 2010). Furthermore, research by (Straka et al. 2013), found that incidences of angiotensin-converting enzyme inhibitor-associated angioedema increased during the tree and ragweed pollen season. The authors speculated that atopic sensitisation to specific aeroallergens predisposes susceptible patients to risk of angiodema upon environmental pollen allergen exposure (Straka et al. 2013). Whilst the mechanisms behind some of these associations remain to be fully understood, the innate immune recognition and airway epithelial response to aeroallergens (Lambrecht and Hammad 2014) and the effects of pollen associated molecules including phytoprostanes and oxidases (Blume et al. 2013) have all been implicated.

2.2 The trans-disciplinary nature of pollen aerobiology research

The science of aerobiology is highly multidisciplinary *per se* and lends itself well to trans-disciplinary research. A holistic approach to aerobiology requires knowledge of intrinsic and extrinsic factors affecting pollen production, transport and impact (Figure 1). The intrinsic factors include plant biology such as the genetic diversity of plants and their use of three or four carbon (C3 or C4) fixing photosynthetic pathways. Extrinsic factors can be divided into natural; local environmental, climatic and ecological factors affecting plant biomass such as; rainfall, temperature, relative humidity, wind direction and speed, soil quality and biodiversity, and anthropogenic; such as land use practices, competition from invasive/exotic species, interactions with pollutants and the impact of climate change (Murphy and Bowman 2007, Edwards and Still 2008, Prentis et al. 2010). These natural and anthropogenic factors influence aspects of pollen aerobiology from pollen production through to exposure of pollen-allergic individuals including plant biology, phenology, pollen diversity and the content of allergen within the pollen (Schappi et al. 1999, Razmovski et al. 2000, Buters et al. 2010, Galan et al. 2013), as well as anther dehiscence and wind dispersal of pollen (de Morton et al. 2011, Siljamo et al. 2013, Oteros et al. 2013a). Dynamic urban and peri-urban land use practice, including urban green areas, agricultural changes and urban heat islands will further modify the production and transport of airborne pollen.

In terms of the impact on health, the human adaptive immunity to pollen shows exquisitely specific recognition of allergen molecules, through the production of specific immunoglobulin E antibody and cell mediated immunity, that is capable of distinguishing pollen of temperate (predominantly C3) and subtropical (predominantly C4) grass species (Potter et al. 1993, Chabre et al. 2010, Davies et al. 2011, Davies et al. 2012, Etto et al. 2012). Thus knowledge of current and future distributions of C3 and C4 grasses is likely to be important for understanding of the exposures and sensitisation of patients to subtropical and temperate grass pollens (Davies, 2014) and their impact upon human respiratory health in Australasia and other locations where subtropical and temperate grasses co-exist (Seidel et al. 2008, Frenguelli et al. 2010, Kosisky et al., 2010)

Aerobiological research involves integration of knowledge and skills from multiple fields of research from biomedical, life, physical and social sciences (Figure 2). Environmental monitoring of airborne pollen concentrations draws upon techniques in plant sciences, microscopy, meteorology as well as quality control systems for standardisation of collection and counting techniques (Taylor et al. 1994, Ong et al. 1995, Schappi et al. 1999, Hasnain et al. 2007, Oteros et al. 2013b, Galan et al. 2014). Whilst the widely used Hirst-style volumetric sampling and microscopic counting methods remains unchanged for 62 years (Hirst 1952), aerobiology research has progressed markedly. Modern pollen monitoring programs are considering the utility of automated counting instruments (Zhang et al. 2014) and are integrating advanced geospatial science (Luvall et al. 2011), climate change science, molecular biology of allergens and mathematical modelling of pollen transport and dispersal (Ziska and Beggs 2012, Siljamo et al. 2013, Skjoth et al. 2013).

2.3 Previous aerobiology studies in Australia

Studies pertaining to grass pollen aerobiology conducted in Adelaide, Brisbane, Canberra, Melbourne, Perth and Sydney by gravity methods are summarised in Table 1. Many studies integrated phenology with their aerobiological records e.g. (Mercer 1939, Moss 1965, Sands 1967). Others considered the impact of exposure to pollen on hayfever and asthma by considering patient sensitivities (Wright and Derrick 1975), biogeographical distribution and phenology (Derrick 1962), or prescription sales of pollen allergen immunotherapy (Derrick 1929, Trinca 1962). Demand for grass desensitisation was greatest of all aeroallergens, with frequency of requests for temperate (C3) grasses extracts transitioning to requests for subtropical (C4) grasses extracts by prescribers located over a latitudinal gradient from Victoria to Queensland, while overall frequency of requests for grass pollen extracts decreased from south to north (Trinca 1962).

Insert Table 1 here

More recent studies conducted with volumetric pollen and spore samplers (Burkard or Rotorod) are summarised in Table 2. Three points in relation to the proportion of grass pollen, timing of grass pollen season and types of grasses contributing to pollen aerobiology are apparent. Grass pollens as a proportion of total pollen within a one year period ranged from 6% in Hobart (Tng et al. 2010) to 72% in Brisbane (Green et al. 2004), but for most sites (Adelaide, Canberra, Melbourne, Perth, and Sydney) grass constituted between 18 and 26% of total pollen (Speck 1953, Ong et al. 1995, Bass and Morgan 1997, Stevenson et al. 2007). Whilst there were grass pollen peaks consistently in spring/early summer (October to December) for Adelaide, Canberra, Hobart, Melbourne, Perth, and Sydney, airborne grass pollen was often present all year. Moreover, in Adelaide, Canberra, Perth and Sydney secondary grass pollen peaks were observed around March (Mercer 1939, Speck 1953, Sands 1967, Ong et al. 1995, Bass and Morgan 1997, Tng et al. 2010). Whilst ryegrass (*Lolium perenne*) was considered to be the most important source of grass pollen for Adelaide, Canberra, Melbourne, and Perth, a wide variety of grasses were observed to flower in the vicinity of most Australia cities including subtropical species in the surrounds of Adelaide, Canberra, Perth and Sydney. The grass pollen aerobiology of Brisbane and Darwin appeared to differ from other cities in respect to the timing and composition of dominant grass species (Moss 1965, Green et al. 2004, Stevenson et al. 2007).

Insert Table 2 here

In terms of respiratory health impact of grass pollens, Bass and colleagues (2000) observed in northern New South Wales a correlation between allergic rhinitis and asthma in children with sensitisation and exposure to Bahia and Bermuda grass pollen in late summer. Katelaris and Burke (2003) showed significant deleterious symptoms of elite athletes with pollen sensitisations associated with airborne pollen during the spring Olympics in Sydney. Children from inland New South Wales with respiratory symptoms (asthma, hay fever or bronchial hyperresponsiveness) showed higher sensitisations to ryegrass pollen than children from coastal regions of Sydney (Britton et al. 1986). Whilst pollen levels were low in Darwin there were positive associations between pharmacy sales for anti-allergy drugs and airborne grass pollen levels (Johnston et al. 2009) and total airborne pollen levels showed a relationship with hospital admissions for respiratory disease (Chronic Obstructive Pulmonary Disease) (Hanigan and Johnston 2007). Independent studies by Erbas and Hill and their colleagues, showed a positive relationship between grass pollen exposure and childhood asthma in Melbourne (Hill et al. 1979, Erbas et al. 2007a). Skin reactivity to grass pollen extracts tracked the introduction and expansion of grass species in Queensland, first *Chloris gayana* and subsequently *Cenchrus ciliaris* (Morrison 1984). Specht, Brouwer and Derrick (Specht et al. 1975) showed the bi-phasic nature of asthma admissions in Brisbane. Whilst it was reported that asthma did not appear to coincide with grass pollen peaks in Brisbane (Wright and Derrick 1975), the two were not investigated contemporaneously and epidemiological studies are yet to be performed.

2.4 Previous aerobiology studies in New Zealand

Few studies of airborne pollen have been undertaken in New Zealand (Tables 1 and 2), despite a high prevalence of respiratory disorders with asthma symptoms in up to 22% of children (Asher et al. 2006). Early work consisted of single season or single site observations of pollen deposition using gravity methods (Filmer and Harris 1949, Clark 1951, Licitis 1953). Following a 15-month survey of airborne pollen in Auckland, Hillas and Wilson presented a pollen calendar portraying the seasonal timing of key allergenic pollens in that city, but recommended that airborne pollen should be monitored routinely and at other major population centres (Hillas and Wilson 1979). Fountain and Cornford monitored *Pinus* pollen dispersal at Palmerston North for 3 years (1988-1990) to show a distinctive season spanning late July to mid-September, 2-3 months before the typical grass pollen season in the area (Fountain and Cornford 1991). To date, the only geographically extensive pollen survey was conducted simultaneously at 9 locations across New Zealand during the austral summer of 1988/89, but monitoring was primarily restricted to grass pollen only (Newnham et al. 1995). Using the same data, Newnham explored climatic influences in spatiotemporal patterns in these grass pollen data to reveal a latitudinal lag in the timing of season onset (Newnham 1999).

2.5 Pollen aerobiology research needs in Australasia

Research on pollen aerobiology and associated respiratory diseases triggered by pollen allergy in Australasia lags far behind comparably developed countries in the Northern Hemisphere. There are predictive pollen indices published on the internet but in most cases these are not based on current local pollen count data (with the exceptions of our Melbournepollen.com and the new Canberrapollen.com). The unsubstantiated pollen indices are potentially misleading the public in relation to risk of pollen associated symptoms. Very little is known on the spatial distribution of pollen sources over time, nor do we understand drivers for variation in phenology and aerobiology across Australia or New Zealand. Add to this, the lack of knowledge on native/ exotic grasses and their altered dynamics/potencies in response to climate trends and urban expansion patterns. Lastly, there are no studies on pollen grain transport aerodynamics and their wind uplift/deposition patterns, i.e., no one has modelled a pollen cloud and its relationship to target urban centres of interest in Australasia.

In 1976 Knox organised the Plenary Symposium on 'Aerobiology and the City', as part of the Melbourne Australian and New Zealand Advancement of Science conference (http://sciencearchive.org.au/fellows/memoirs/knox.html). That meeting exemplified an earlier recognition of the need to integrate pollen aerobiology with its impact on human respiratory health; however its primary focus was on Melbourne. Until now a trans-organisational and trans-disciplinary approach to systematically collate, analyse and monitor pollen aerobiology has not been attempted for the Australasian region.

3.0 Highlights of Australian Aerobiology Working Group research outcomes

The Australian Aerobiology Working Group sourced pollen count and meteorological data from 11 Australian sites and 6 New Zealand sites. The methodologies used in pollen sampling and counting were tabulated for each site and the data were formatted to allow for analysis and synthesis of pollen aerobiology across Australia and New Zealand (Haberle et al., 2014).

3.1 ACEAS Australian Aerobiology Outcomes

The following discoveries were presented as outcomes from this research; outcomes 1 to 4 originated from Workshop 1 (March 11-15, 2013) and outcome 5 arose from Workshop 2 (November 4-8, 2013).

3.1.1. A biogeographical variation in the diversity and relative abundance of airborne pollen was evident in the macroecology of Australian and New Zealand urban centers (Haberle et al. 2014). Whilst the complexity of airborne pollen is considerably affected by global warming and land-use practices, there are insufficient data to anticipate the extent of future changes. The pollen data were presented as pie charts depicting months in which the key taxa were pollinating at each location. This representation of the data was communicated to the ASCIA Immunotherapy Working Party (Dr J.M. Davies, Melbourne, September 12, 2014) for preparation of revised clinical guidelines on the timing of allergenic pollen exposure in particular locations.

3.1.2. To enable access by the academic and general community to representations of the aerobiological pollen and climatic data for each location, an online portal was prepared (http://aceas-data.science.uq.edu.au/portal/). The primary data was also made available as 11 Metacat datasets (http://www.tern.org.au/Newsletter-2014-May-ACEAS-Aerobiology-pg28903.html). These resources are available for use in additional scientific research purposes, but not for unauthorised commercial use under a Creative Commons – Attribution-Non-Commercial-ShareAlike 3.0 license, Australia.

3.1.3. Evidence of yearly and regional variations in airborne levels of grass pollen, for Australian are reported in the Australian and New Zealand Journal of Public Health (Beggs et al. 2015). Two methods of describing the grass pollen season start, peak and end dates were compared to enable a systematic retrospective analysis of variability in characteristics of the grass pollen season at different locations. It is important to convey this information to patients and clinicians responsible for managing the impact of exposures to pollen in different locations. However, it was apparent that local current pollen monitoring undertaken with standardized sampling and counting techniques is necessary to accurately forecast the exposure of patient communities to clinically relevant pollen.

3.1.4. The ecological drivers for temporal and spatial variation in grass pollen aerobiology in Australia and New Zealand were examined (Medek et al. 2013). A latitudinal gradient in grass pollen season timing and duration was observed. Moreover, multiple peaks in the grass pollen season were clearly observed in locations closer to the equator (e.g. Brisbane and Sydney). The presence of secondary grass pollen peaks occurring in summer, coincided with the distribution of C4 subtropical grasses. This research was presented at the Australian Society for Clinical Immunology and Allergy Annual Scientific Meeting Perth, September 2014 and the International Congress of Aerobiology (Medek et al. 2013, Medek et al. 2014).

3.1.5. The utility of remote sensing for mapping geospatial distributions of grass pollen sources and their seasonal inter-annual variations were examined. Our Working Group explored new insights and developed methods for merging pollen aerobiology with geospatial science and remote sensing phenology retrievals. (Devadas et al. 2014a, Devadas et al. 2014b).

3.2 Other Australian Aerobiology Working Group outcomes

The Working Group activities have also been communicated in a number of outreach formats including the ACEAS and Terrestrial Ecosystems Research Network (TERN) newsletters, the ACEAS Grand Workshop, Canberra, 2014, international Congress of the European Academy of Allergy and Clinical Immunology Interest Group on Aerobiology and Pollution (Geneva, 2013), and nine presentations at the International Congress on Aerobiology, Sydney (Medek et al. 2014). Members of the team have published three articles in The Conversation on the need for a standardized pollen monitoring network for this region; "Pollen counting is not something to be sneezed at" (Newbigin and Davies, October 2013; 3,500 readers), "Hay fever misery prediction: some to get off lightly, others to suffer" (Newbigin and Haberle, October

2014; 2,200 readers) and "Hay fever survival guide: why you have it and how to treat it" (Davies and Katelaris, November 17; 7856 readers).

The utility of the information provided to the community is evident by the strong response to an App for a pollen symptom survey based on the health survey (Medek et al. 2012). The mobile App is active for Melbourne and Canberra.

4. Reflections on the utility of the trans-disciplinary Australian Aerobiology Working Group

This ACEAS Working Group approach brought together experts from disparate disciplines with complementary skill sets to address a central problem for management of seasonal allergic disease from multiple angles. The perceived benefits and challenges of the ACEAS analysis and synthesis Working Group are summarised in Table 3. Importantly, the Australian Aerobiology Working Group provided an uninterrupted opportunity to focus solidly on a unifying problem; the regional and temporal sources of variability in pollen aerobiology and their impact on human health. Trans-disciplinary science such as this will be essential to adequately enable informed adaptation to climate change and its impact on human and ecological health.

In the context of Australasian aerobiology, we speculate that as the geographic distribution of subtropical and temperate grasses changes over time, altered clinical patterns of allergic sensitisations and allergic respiratory disease are likely. Additionally, with widespread migration and urban development, complex patterns of previous and current allergic sensitisations exist within the clinical allergy setting.

Limitation of resources can cause researchers to perceive others as competitive threats. Whilst competition can be a positive driver of success too much competitive stress in an academic environment has flow on effects that block open collaboration. Competition is amplified within disciplines. However, within a multi-disciplinary Working Group, each member is a unique contributor of their expertise and knowledge to the group. By the virtue of the diversity within our group, a positive collaborative environment occurred. Thus whilst competition for limited resources is high, the ACEAS collaborative research approach was rewarding and fruitful for the individual participants and the group as a whole. Through active participation of researchers from multiple disciplines, the outcomes were greater than originally envisaged by the individual participants.

In our Australian Aerobiology experience, some primary datasets needed rescuing from archived boxes in garages, recovery from outdated hardware, conversion from obsolete software and even digitisation of hand written data to create accessible sources of data for reuse. Such databases provide a rich resource for synthesis and re-analysis of existing ecological dataset that might otherwise perish. Our experience demonstrates the extra-disciplinary value of resurrecting data thought to be obsolete in the discipline for which it was originally obtained. The practice of re-use of data also optimises the value of existing data, in particular by placing it in a wider or historical context, and broadens the scope of scientific work providing a platform for emergence of new analytical methodologies and knowledge. Such trans-disciplinary analysis enables other researchers to see data with fresh eyes and to extract additional value from existing datasets (Nelson 2009, Gibney and Van Noorden 2013). This will become increasingly important as the availability of resources for collection of data by field trials becomes scarce.

Within a team of researchers from diverse disciplines, each individual may feel and work out of their comfort zone. As well as a learning tool for students (Students key to synthesis success), the experience stretches the boundaries of knowledge and thrusts academic experts from all levels back into unfamiliar position of naivety with respect to other disciplines. It's a remarkable learning tool and opportunity for discovery for the individual and the group as a whole. It may not always be a positive experience but the situation provides wide opportunities that can be realised. An analysis and synthesis centre/working group does not guarantee these positive outcomes. The factors leading to success would be better considered or debated by organisational psychologists. However, upon reflection, a process in itself unfamiliar to many life, medical or physical scientists, key ingredients within our group that helped us succeed might include trust within the group, commitment to the common goal, a willingness for open and active participation, as well as leadership and an appropriate mixture of personalities, experience and skills. Many of the identified "Challenges" (highlighted in Table 3 with an asterisk) in reality led to benefits. For example, our trans-disciplinary approach led to methodological advances and has fostered leadership and skill sharing as well as learning by doing and living in the synthesis experience.

5. Future trans-disciplinary aerobiology research challenges and opportunities

Currently just a few sites are actively monitoring pollen in Australia (Melbourne, Sydney, Adelaide and Canberra) and none are active in New Zealand. Their operation is not continuous and in all cases the counting is unfunded or not sufficiently funded (Beggs et al. 2015). Aerobiology research is supported in different ways globally. By way of examples, the National Allergy Bureau (NAB) supports a network of pollen count stations run by volunteers in USA, the meteorology service runs the pollen monitoring network in the UK, private foundations in conjunction with weather services coordinate pollen monitoring in Switzerland, whilst the government funds the Réseau National de Surveillance Aérobiologique (RNSA) institute in France.

The COST Action ES0603 (http://www.cost.eu/domains_actions/essem/Actions/ES0603) aimed to achieve "EUPOL" (assessment of production, release, distribution and health impact of allergenic pollen in Europe). While much bigger (and better funded) than our Australian Aerobiology Working Group, the overall objectives, to "establish a multi-disciplinary forum", and the diversity of participants, were similar. Such successful precedents validate our experience that a trans-disciplinary approach really is the best, and perhaps only, way to advance the connection between aerobiology and allergic respiratory disease fields.

5.1 Broader barriers and opportunities for future Australasian pollen aerobiology

Despite having identified clear needs from ecological and health perspectives for a national standardized pollen monitoring network to adequately report and forecast current local levels of pollen, there exist gaps in the funding structure for trans-disciplinary research. This may be because such research falls in between non-medical (e.g. the Australian Research Council or the Marsden Fund, NZ) and medical (e.g. the National Health and Medical Research Council of Australia or the Health Research Council, NZ). Guidelines for applicants to these funding schemes restrict cross-over between medical and other scientific research. This current policy limits access to resources for trans-disciplinary science that involves aspects of human health, direct use of patient samples or pursuit of outcomes with a medical benefit but not directly involving human specimens.

In Australia, science is now under the auspice of the Department of Industry. Within such a context, research was considered as part of the Australian Innovation System Report 2013 (Hendrickson et al. 2013). The Global Innovation Index 2014 (GII 2014) lists research as an advantageous characteristic of successful businesses (Cornell University et al. 2014). It is encouraging that the "conceptual framework" of GII 2014 considers "knowledge creation, impact and diffusion" as innovation outputs. Now more than ever scientists will need to adapt to meet these changing purposes and funding models. That research is within GII 2014 framework provides new opportunities for integration of research outcomes into the business sector, government/policy making sector as well as academic settings. This may increase the perceived relevance of science within the wider community, a need recognised by the Australian Aerobiology Working Group participants. The framework appreciates the necessity for ecological sustainability for (economic) prosperity and values “human capital” as a key input to innovation. It is positive that “linkages” and “knowledge absorption” are seen as essential ingredients to the process of innovation. Commitment to evidenced based practices in both medicine and ecology requires, and indeed embraces, scientific data as a basis for policy generation and informed decision making.

Within this GII 2014 framework, outputs of innovation include not only “knowledge creation” but its “impact” and “diffusion”. That these latter two aspects are valued bodes well for the prioritizing the communication of research outcomes into practice. Whilst it is essential to generate data, in our situation regional differences in pollen aerobiology, and new understandings including the relationship between aerobiology and enhanced vegetative index, the ultimate goal is dissemination of this knowledge to allergy patients and their clinicians, implementation of change in management of allergic rhinitis and asthma, and a reduction in the burden of allergic disease globally. Applied trans-disciplinary research opens up opportunities for scientists to engage in broader spheres of influence to translate scientific knowledge into practice and policy.

The Mckeon Strategic Review of Health and Medical Research in Australia (Mckeon et al. 2013) noted that most of the recommendations of the earlier Wills Review (1998) (Wills 1998) of medical research had been implemented, with the exception of aspects requiring cooperation between separate (government) departments. This gap in implementing recommendations dependent on cooperation between departments, highlights the need for inter-disciplinary collaboration in academic as well as government sectors. Thus whilst there are challenges for those engaged in research that spans the funding dichotomy (medical and non-medical research), there may be an opportunity for those who can interact effectively with peers from different disciplines and sectors (academia, industry, government) to address fundamental research questions and implement solutions for complex problems.

Australia recognises the benefits of multi-disciplinary research but systems to promote and reward integrative multi-disciplinary applied research remain to be fully developed and implemented. There is a certain risk for an academic researcher in expending time on activities that “translate” into change in policy or practice, when that time could otherwise be applied in pursuing output fulfilling more traditional measures of productivity such as publications in high impact, peer-reviewed journals. The aim to “accelerate translation” is part of the strategic vision for health and medical research (Mckeon et al. 2013). For environmental and ecological sciences, analysis and synthesis centers that engage researchers, policy makers and managers in discussion of key environmental issues are ideally and uniquely positioned to advance this goal of translating evidence into improved environmental and public health management (see Lynch et al., this issue (Lynch et al. 2015).

6. Conclusions

The Australian Aerobiology Working Group has been a productive exercise in trans-disciplinary research. The analysis and synthesis of currently available pollen count data sets documented clear evidence of regional and seasonal variability in airborne pollen levels. We revealed limitations in the existing data sets and the insufficient capacity to monitor pollen aerobiology over time in Australia. The Working Group approach facilitated the development of methods to illustrate the utility of remote sensing phenology to inform features of grass pollen aerobiology and this methodology is applicable to sites across both hemispheres. These outcomes significantly impact upon a broad array of research fields particularly ecology, climate science and public health. This trans-disciplinary research endeavour provides a springboard to establishment of national pollen monitoring networks that seek to empower patients with hay fever and allergic asthma to adopt allergen avoidance strategies and improve compliance to prescribed medications.

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Figure legends

Figure 1. A schematic framework depicting the stages in grass pollen production through to pollen release, dispersal and impact on respiratory health. The influence of natural (biogeography and climate) and anthropogenic (land use and pollution) factors on aspects of pollen aerobiology are indicated.

Figure 2. Interaction of multiple fields of research and scientific disciplines required for integrated grass pollen aerobiology research. The research areas encompass Biomedical, Social, Life and Physical Sciences. Key terms and fields of research are drawn from the Australian and New Zealand Standard Research Classification codes and the Web of Science (Thomson Reuters) research areas.

Web links (accessed October 9, 2014)

http://www.aceas.org.au/index.php?option=com_content&view=article&id=113:australian-aerobiology&catid=35:working-groups&Itemid=174 (Australian Aerobiology webpage)

ACEAS e-Newsletter Dec 2013 "The ACEAS experience: an interview with Dr Janet Davies".

http://www.tern.org.au/Newsletter-2013-Nov-ACEAS-students-in-working-groups-pg27389.html "Students key to synthesis success"

http://www.tern.org.au/Newsletter-2014-May-ACEAS-Aerobiology-pg28903.html
"Ensuring pollen data aren't gone with the wind"

http://aceas-data.science.uq.edu.au/portal/

http://www.melbournepollen.com.au/

http://www.melbournepollen.com.au/index.php/melbourne-pollen-count-app (the symptom survey App)

http://www.canberrapollen.com.au/

http://www.canberrapollen.com.au/index.php/canberra-pollen-count-app (the symptom survey App)

http://theconversation.com/pollen-counting-is-not-something-to-be-sneezed-at-18100

Newbigin, E and Davies, JM, October 2, 2013

http://theconversation.com/hay-fever-misery-prediction-some-to-get-off-lightly-others-to-suffer-32378 Newbigin, E and Haberle, S, October 8, 2014

https://theconversation.com/hay-fever-survival-guide-why-you-have-it-and-how-to-treat-it-34000 Davies, JM and Katelaris CH, November 17, 2014

http://sciencearchive.org.au/fellows/memoirs/knox.html

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Table 1
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Table 1. Summary of early grass pollen aerobiology in Australia and New Zealand listed in latitudinal and chronological order.

Year	Location	Method	Primary outcomes	References
1962	Australia-wide	Phenology	Allergic rhinitis (AR) season is longer when closer to the coast and equator. Grass tribes responsible for allergy differ between southern* and northern Australia.** Flowering calendars presented.	(Derrick 1962)
1929	Melbourne, Vic	Phenology	*L. perenne* and *D. glomerata* likely predominant causes of AR. Pollen calendar presented.	(Derrick 1929)
1933-1936	Melbourne, Vic	Gravity	Multiple GP peaks from Aug-Apr; max Oct, Nov. Rainfall and humidity decreased counts.	(Sharwood 1935, Sharwood 1937)
1960-1965	Melbourne, Vic	Gravity	GP influenced by weather; present between Sept-Apr peaking in Nov/Dec coincident with AR symptoms.	(Derrick 1966)
1938	Adelaide, SA	Gravity	GP present Aug-Apr; peak Nov, Apr (smaller peak); early-flowering *Poa annua*, *Avena fatua*; in spring temperate spp*; in summer, subtropical spp**.	(Mercer 1939)
1955	SA	Phenology	Grass dominated springtime airborne pollen from Aug*. Summer-flowering: *C. dactylon.* Earlier season in north SA.	(Piper 1955)
1955	Albury, Holbrook and Tumbarumba districts NSW	phenology	Broad array of native and exotic temperate* and subtropical** spp present in vicinity	(McBarron 1955)
1967	Canberra	Gravity	GP Sep-Aug. *L. perenne* pollen peaks in Oct-Dec, Feb-Mar; Observed local temperate* and subtropical** spp. Plantain, *L. perenne* , *C. dactylon* highest pollen producers.	(Sands 1967)
1940	ACT & NSW (6 sites)	Gravity	GP were 26-78% of total pollen, dominant Sep-Dec, peaking Oct. Pollen counts influenced by weather, varied between sites.	(Phillips 1941)
Several years	NSW	Phenology	Grass spp with prolific pollen production throughout year, Subtropical spp* flowering Oct-June; Temperate spp** flowering Aug- Feb, *P. annua* May-Oct.	(Price 1963)
Two years early 1950s	Perth, WA (11 sites)	Gravity	GP were 24% of total pollen; GP present through year, increasing Sep, peaks Oct-Nov, Jan-Mar; wind direction influenced counts; interannual	(Speck 1953) (Bass et al. 1984)

			variation. Season timing varies inland to south coast.	
1937-1946	Toowoomba, QLD	Gravity, phenology	Grass flowering from Aug. GP season length related to rainfall. Early-flowering spp* will flower throughout the season when rains permit.	(Morton 1946)
1962-1963	Brisbane, QLD	Hirst	GP present throughout the year, contributed 34% of total pollen; GP peaked in Jan; *C. gayana* and *C. dactylon* principal species mid-summer.	(Rees 1996)
1962-1963	Brisbane, QLD	Gravity	GP were 65% of total pollens; rising in Oct**. Peaked Dec-Jan coinciding with flowering of *C. gayana*. Main causes of AR expected to be *C. dactylon* and *C. gayana*	(Moss 1965)
1945-1947	Wellington, NZ	Gravity	Grasses are the predominant airborne allergenic pollens*	(Filmer and Harris 1949)
1918-1923	Auckland, NZ	Phenology	Grassland comprised 73% of all human-occupied area of NZ. Earlier grass flowering in northern sites. GP calendar presented. Grass Spp* flowering from Aug-Jan, with early, mid- and late-flowering spp.	(Patterson 1923)

*Temperate or spring-flowering spp. mentioned in the above studies incl: *Agrostis* (NZ, NSW, ACT), *Anthoxanthum* (NZ, NSW), *Avena fatua* (SA, NSW), *Bromus uniloides* (SA, NSW, QLD), *Dactylis glomerata* (NZ, Vic, NSW), *Dichelachne crinita (QLD), Ehrharta sp.* (SA), *Festuca rubra* (NSW), *Holcus lanatus* (NZ, SA, NSW, ACT), *Hordeum spp.* (SA, ACT), *Lolium perenne* (NZ, Vic, SA, ACT, NSW, QLD), other *Lolium* spp (Vic), *Phalaris spp* (Vic, SA, NSW), *Poa spp* (SA, ACT, NSW).

**Subtropical or summer-flowering spp mentioned in the above studies incl: *Andropogon pertusus* (QLD), *Bothriochloa decipiens* (QLD-spring also), *Cynodon dactylon* (ACT, SA, NSW, QLD-spring also), *Chloris gayana* (SA,NSW, QLD), *Cenchrus australis (NSW), Digitaria spp* (NSW, QLD), *Eragrostis spp* (QLD- spring also), *Imperata cylindrica*,(NSW), *Microloena stipoides* (QLD), *Panicum spp* (NSW, QLD-spring also), *Paspalum spp* (SA, ACT, NSW, QLD- spring also), *Pennisetum spp*(NSW, QLD), *Rhynchelytrum repens* (QLD- spring also) *Setaria* (NSW), *Sorghum* (NSW), *Sporobolus indicus* (QLD)

Table 2
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Table 2. Recent volumetric grass pollen aerobiological studies in Australasia arranged in latitudinal and chronological order

Year	Location	Method	Primary outcomes	References
2007-2009	Hobart, Tas	Burkard	GP were 6% of total pollen; peaked Nov-Jan.	(Tng et al. 2010)
1975-1980; 1991-1995	Melbourne, Vic	Burkard	GP were 22-31% of total pollen; peaked Nov-Dec. High counts with high child asthma. Higher counts at night, and dependent on wind direction, Season onset predicted from Jul rainfall. Season total predicted from annual rainfall. Daily variation correlated with AR severity.	(Hill et al. 1979, Ong et al. 1995)
1992-1993	Melbourne, Vic	Burkard	GP levels had a positive effect on asthma hospital admissions to a threshold of 30 grains m^{-3}	(Erbas et al. 2007a)
1996	Melbourne, Vic	high vol. cascade impactor	Group 5 allergen correlated with pollen counts. Rain ruptured pollen grains, increasing respirable particles incl allergens. Airborne allergen levels correlated with Emergency Department (ED) asthma attendances.	(Schappi et al. 1999)
1991-1993, 1996-2008	Melbourne, Vic	Burkard	High counts of GP with onshore winds. Seasonal counts increase with spring rainfall. Decreased grazing land may drive decreased counts 1991 to 2008. Extreme pollen days related to atmospheric downdraft.	(de Morton et al. 2011)
2004	Melbourne, Vic	Burkard	Weather parameters used to model daily grass pollen counts. Important parameters: Date, avg. temperature, rain, wind speed, relative humidity.	(Erbas et al. 2007b)
2010	Melbourne, Vic	Burkard	GP-induced asthma epidemics are triggered by thunderstorms, associated ryegrass pollen grain rupture and starch granule release, containing *Lol p1*	(Howden et al. 2011)
1975-1977	Melbourne, (2 sites) Vic	Burkard	GP present Nov-Jan, 7% of total pollen. Two seasonal peaks: Nov, Dec/Jan. Differing diurnal fluctuations suggests long-distance transport to urban site.	(Smart and Knox 1979)
1975	Melbourne, Vic	Burkard	Relationship of GP to wind direction identifies source grasslands and roadsides north of Melbourne. High GP on days of high temperature, low GP with humidity and rainfall.	(Smart et al. 1979)
1979-1981	Albury, NSW	Burkard	GP from Oct-Dec, peak Nov with AR and asthma symptom peak	(Katelaris et al. 1982)
1997	Wagga Wagga, NSW	Burkard	Thunderstorm outflows were related to high ED asthma attendances across rural NSW. Over an epidemic asthma day, thunderstorm onset brought large peak in hourly grass pollen counts.	(Marks et al. 2001)
2004-	Canberra, ACT	Burkard	GP were 18% of total pollen; GP from late Sep, peaks Nov, Jan-Mar (smaller	(Medek et al. 2012)

2005, 2011			peak). AR symptoms likewise increased.	(Haberle et al. 2014)
1993-1995	Campbelltown, NSW	Burkard	GP were 18% of total pollen; peaked Nov-Dec; *Lolium, Phalaris* in vicinity; smaller peak Mar-Apr; *Cynodon*, *Chloris* and *Paspalum* flowering Jan.	(Bass & Morgan, 1997)
1994-2000	Sydney, NSW (3 sites, 3 sites)	Burkard	Pollen profile of 3 sites; coastal to inland (2000), Olympic Games sites (2003). GP season from Sep, peaking Oct. Tree pollen dominated.	(Katelaris et al. 2000, Katelaris and Burke 2003)
1999	Sydney, NSW (3 sites)	Burkard	Sites 30km apart have discordance in daily counts for most trees, while day-to-day variation in GP showed concordance between sites, suggesting longer-distance transport.	(Katelaris et al. 2004)
2006-2007	Inner Sydney, NSW (3 sites)	Burkard	GP of minor importance, 4% of total pollen count, max 20 grains m^{-3}.	(Sercombe et al. 2011)
1997	Casino, NSW	Burkard	GP peaked March. Respiratory allergy late in the season coincided with *C. dactylon* and *P. notatum* grass and ragweed peaks.	(Bass et al. 2000)
1994-1995	Brisbane, QLD (2 sites)	Burkard	GP were 40% of total pollen, overall counts low, peak Mar-Apr. Variation over the GP season positively associated with temperature and humidity.	(Rutherford et al. 2009)
1994-1999	Brisbane, QLD	Burkard	GP were 72% of total counts; peaked summer and autumn; variability in peak day. Daily variation correlated with maximum temperature.	(Green et al. 2004)
2004-2005	Darwin, NT (2 sites)	Burkard	GP were 18-26% of total pollens; peaked Apr-May in dry season onset; GP associated with AR and anti-histamine sales. Hospital admissions for respiratory illness when higher total pollen concentrations, but not sig. for GP alone.	(Hanigan and Johnston 2007, Stevenson et al. 2007, Johnston et al. 2009)
1989-1999	New Zealand (8 sites)	Rotorod, phenology	GP season peak Nov-Dec, onset later with increasing latitude, and thus temperature. Lower counts and later seasons in urban vs rural sites. Introduced grasses likely dominate pollen counts: *Festuca arundinacea, L. perenne, Lolium multiflorum, D. glomerata, H. lanatus, A. odoratum*	(Newnham et al., 1995, Newnham, 1999)

Table 3
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Table 3 Perceived benefits and challenges of analysis and synthesis reported by participants of the Australasian Aerobiology Working Group

Key benefits	Key challenges and barriers
General	
Synergistic amplification of productivity and scientific output.	Adopting clear communication free of discipline-specific jargon*.
Motivate through a positive group experience.	Time pressures of overcommitted academics.
Educate and mentor students and early career researcher in ways that; • broaden the scope of their own research, • provide opportunities to engage in a facilitative research network beyond the field of their primary advisor, • provide access to wide-ranging datasets, • to gain exposure to new innovative research methodologies.	Incentives for analysis and synthesis activities which were beyond core activities of participants.
Experiential learning and engaging at the edge of one's comfort zone.	Merging of separate disciplines means spanning the gap between traditional funding schemes between medical and other sciences*.
Bring to the public domain datasets that may be useful to, or extended by, future research but which otherwise would have remained inaccessible.	Finding the right academic outlet for trans-disciplinary research outcomes that don't fit within the scope of speciality journals.
Foster emergence of new analytical techniques with global applicability.	Working with researchers from outside one's area of expertise*.
Extend impact beyond one's own usual sphere of influence.	Being exposed to unfamiliar datasets, concepts and methodologies*.
Facilitate applied scientific research relevant to the general community.	
Increase visibility with industry or government stakeholders.	
Specific	
Advance research in ecology and health sciences related to aerobiology and air quality.	Sourcing and resolving methodological and temporal variations in separate datasets*.
Develop new methodologies for integrating phenology, remote sensing, mathematical statistical modelling and aerobiology.	Retrieving data from obsolete hardware.
Cultivate new understanding through merging of disparate types of data that would not have been reached by consideration of the original datasets separately.	Transferring data from obsolete and unsupported software.
Incubate innovative research ideas (eg Melbourne symptom survey App).	Reorganizing disparate datasets into a standardized format.
Produce practical outcomes benefiting plant science, molecular allergology, climate change, ecology, geospatial and health sciences.	Integrating ecosystem, geospatial and health sciences with their diverse terminologies, methods, and problem solving approaches*.
Generate methods and data sets serving as a proxy for climate and landscape change an integral part of aerobiology research and development.	Attribution of ownership of historical data.
Provide pollen exposure data for clinical trials of allergic disease therapies.	Reaching licensing agreements for release of primary data.

* These challenges were also recognised as leading to benefits for the group and to extend individual leaning.

Figures 1 & 2
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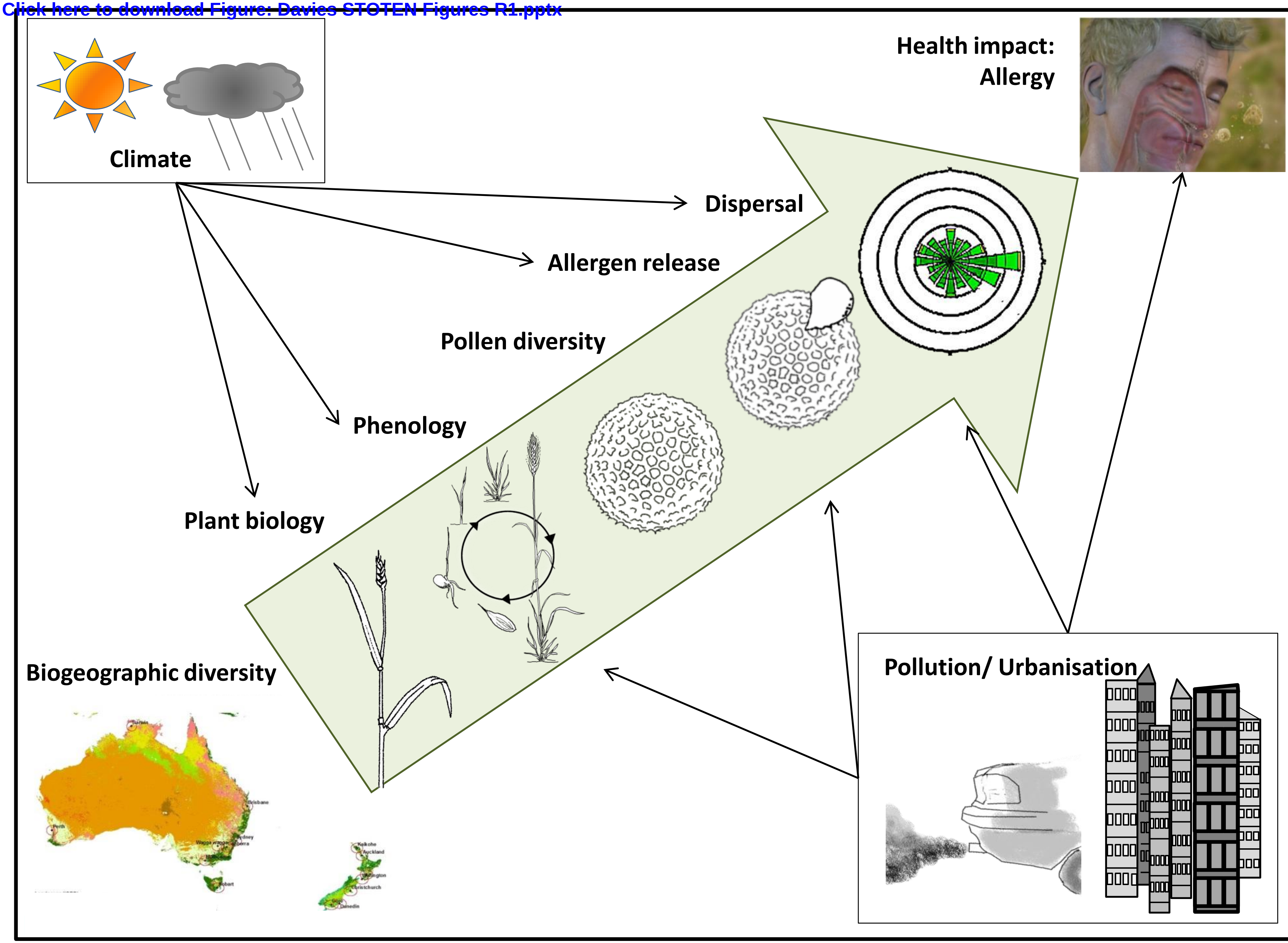

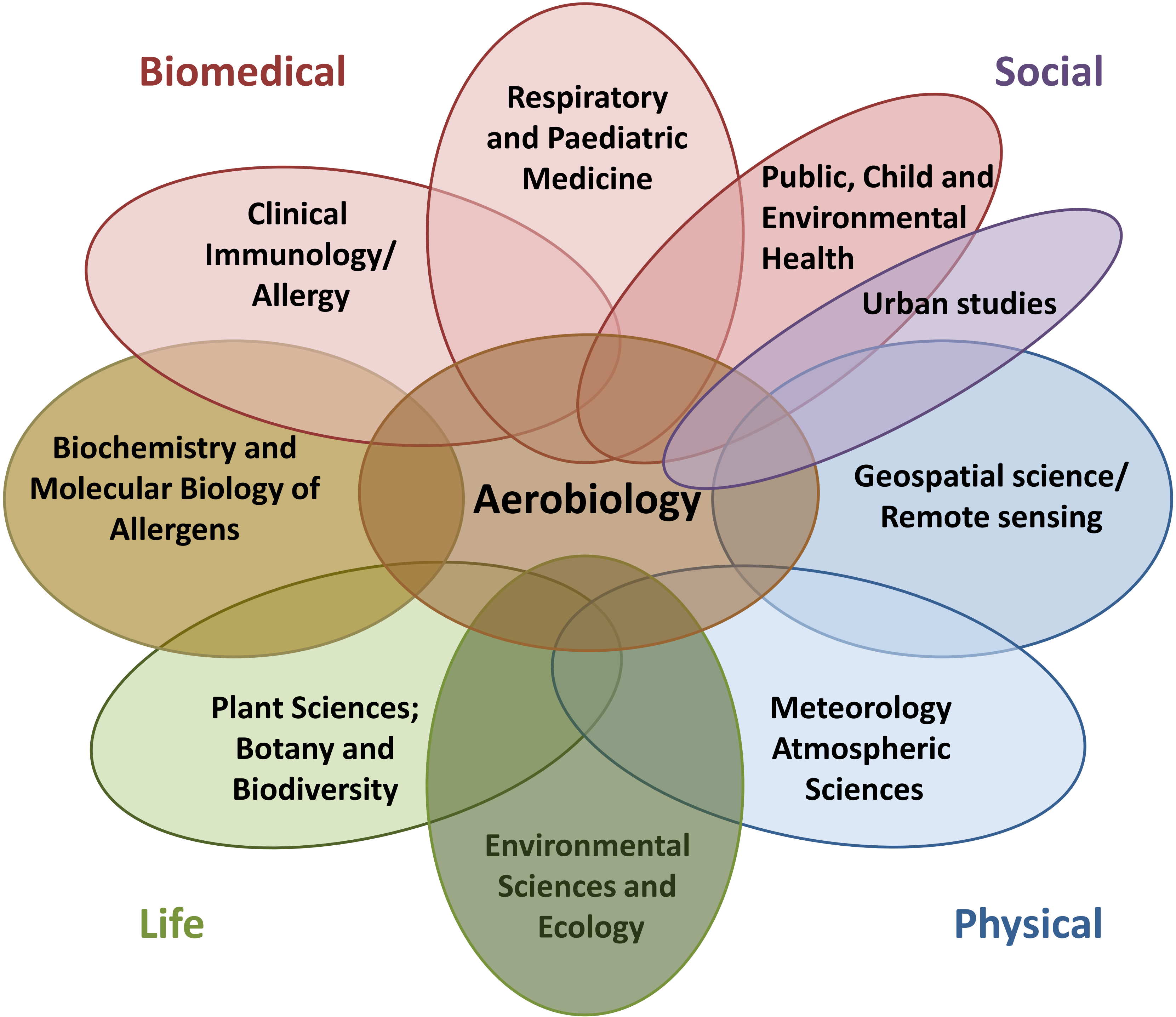
Biomedical
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Respiratory and Paediatric Medicine
Public, Child and Environmental Health
Clinical Immunology/ Allergy
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Biochemistry and Molecular Biology of Allergens
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Life
Physical