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Climate Change and Future Pollen Allergy in Europe

Iain R. Lake[1]*, Natalia R. Jones[1], Maureen Agnew[1], Clare M. Goodess[1], Filippo Giorgi[2], Lynda Hamaoui-Laguel[3,4], Mikhail A. Semenov[5], Fabien Solomon[2], Jonathan Storkey[5], Robert Vautard[3,4], and Michelle M. Epstein[6]

[1]School of Environmental Sciences, University of East Anglia, Norwich, UK

[2]Earth System Physics Section, International Centre for Theoretical Physics, Trieste, Italy

[3] Laboratoire des Sciences du Climat et de l'Environnement, IPSL, CEA-CNRS-UVSQ, UMR8212, Gif sur Yvette, France

[4] Institut National de l'Environnement Industriel et des Risques, Parc technologique ALATA, Verneuil en Halatte, France

[5] Rothamsted Research, Harpenden, Hertfordshire, UK

[6]Department of Dermatology, Division of Immunology, Allergy and Infectious Disease, Experimental Allergy, Medical University of Vienna, Vienna, Austria

* Address correspondence to Dr Iain Lake, School of Environmental Sciences, University of East Anglia, Norwich, Norfolk, NR4 7TJ, United Kingdom. Telephone: +44 1603 593744. Email: I.Lake@uea.ac.uk

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Abstract:

Background: Globally pollen allergy is a major public health problem, but a fundamental unknown is the likely impact of climate change. To our knowledge, this is the first study to quantify the consequences of climate change upon pollen allergy in humans.

Objectives: To produce quantitative estimates of the potential impact of climate change upon pollen allergy in humans, focusing upon common ragweed (*Ambrosia artemisiifolia*) in Europe.

Methods: A process-based model estimated the change in ragweed's range under climate change. A second model simulated current and future ragweed pollen levels. These were translated into health burdens using a dose-response curve generated from a systematic review and current and future population data. Models considered two different suites of regional climate/pollen models, two greenhouse gas emissions scenarios (RCP4.5 and 8.5), and three different plant invasion scenarios.

Results: Our primary estimates indicate that sensitization to ragweed will more than double in Europe, from 33 to 77 million people, by 2041-2060. According to our projections, while sensitization will increase in countries with an existing ragweed problem (e.g. Hungary, the Balkans), the greatest proportional increases will occur where sensitization is uncommon (e.g. Germany, Poland, France). Higher pollen concentrations and a longer pollen season may also increase the severity of symptoms. Our model projections are driven predominantly by changes in climate (66%), but also are influenced by current trends in the spread of this invasive plant species. Assumptions about the rate at which ragweed spreads throughout Europe have a large influence upon the results.

Conclusions: Our quantitative estimates indicate that ragweed pollen allergy will become a common health problem across Europe, expanding into areas where it is currently uncommon. Control of ragweed spread may be an important adaptation strategy in response to climate change.

Introduction

Climate change is likely to affect allergic disease (Smith et al. 2014) and the view of clinical experts is that these diseases will increase under climate change (Bielory et al. 2012), due in part to the impact on allergenic plant species (Shea et al. 2008). Impacts on allergens may be one of the most important consequences of climate change for human health (Beggs 2015). Climate change has already been suggested as one factor behind the increasing prevalence of allergic asthma (Beggs and Bambrick 2005). Pollens are a major cause of symptoms in people with allergic disease, but there is no quantitative assessment of how future climate change may affect the levels of pollen allergy in humans, because the influence of climate change is complex (Reid and Gamble 2009; Smith et al. 2014). For example, an altered climate will affect the range of allergenic species as well as the timing and length of the pollen season, and elevated Carbon Dioxide (CO_2) may increase plant productivity and pollen production (Beggs 2015). Climate change may also affect the release and atmospheric dispersion of pollen (Bielory et al. 2012). The overall impact will be an altered pollen season timing and load, and hence change in exposure. Modelling all these processes is required to assess the consequences of climate change on pollen-related allergic disease. Previous studies (reviewed in Bielory et al. 2012) have only examined some of the processes along this pathway.

Allergic disease is a key public health problem which has increased rapidly in recent decades in both developed and developing countries and is now recognised as a major global epidemic (Pawankar 2014; Platts-Mills 2015). The economic burden of allergic disease is considerable. In 2007, the total cost of allergic disease to the United States (US) was $19.7 billion, while in the European Union (EU) estimates range from €55 to €151 billion (Zuberbier et al. 2014). In terms of specific allergic diseases, the World Health Organisation (WHO) estimates that 400 million people in the world suffer from allergic rhinitis and 300 million from asthma (Bousquet and Khaltaev 2007). Within Europe the prevalence of pollen allergy in the general population is estimated at 40% (D'Amato et al. 2007).

Here, we quantify the potential consequences of climate change on pollen allergy, focussing upon the annual herbaceous plant common ragweed (*Ambrosia artemisiifolia*) in Europe (henceforth ragweed). In Europe, ragweed is an introduced species in the middle of an ongoing invasion event (Storkey et al. 2014) and, therefore, represents a case of a human population being progressively exposed to a novel allergen. It is highly invasive; thriving on disturbed land, with each plant producing up to 62,000 seeds a year. Ragweed is particularly harmful for public health because each plant produces a large amount of pollen (up to 1 billion grains a year; Fumanal et al. 2007) and its allergenic potential is high (Taramarcaz et al. 2005). Unlike other pollen, ragweed pollen peaks in the late summer (Essl et al. 2015). In some parts of Europe, ragweed generates around 50% of the total pollen production. In the USA, where ragweed is native, over 26% of the population is sensitized to ragweed (Arbes Jr et al. 2005). This study focusses upon ragweed sensitization as a health consequence. Sensitization occurs when the human immune system has synthesised antibodies against the pollen and reacts when re-exposed, and is a major risk factor for allergic diseases such as allergic rhinoconjunctivitis and asthma (Burbach et al. 2009).

Methods

This research is the culmination of a large multidisciplinary European Commission funded project (ATOPICA; FP7 grant agreement #282687). Specifically, for the present analysis we integrate estimates of current and future ragweed pollen levels (previously developed within ATOPICA) with published data on sensitization rates and population density. To estimate pollen levels, the ATOPICA group first used a process-based model of weed growth, plant population dynamics, and competition, to project the future expansion of ragweed's range under different climate change scenarios (for details see; Storkey et al. 2014). These range results were then inputted into a system modelling plant invasion, pollen production, pollen release, and the atmospheric dispersion of pollen to simulate current (1986-2005) and future (2041-2060) ragweed pollen levels in Europe (for details see; Hamaoui-Laguel et al. 2015). To provide an estimate of uncertainty, these projections were produced for two different suites of regional climate/pollen models (henceforth CHIMERE and WRF/RegCM; Hamaoui-Laguel et al. 2015). These differ in their driving global climate models, and representation of dynamical and physical atmospheric processes. Both model suites used CMIP5 data (Taylor et al. 2012) to account for changing land use patterns. In addition, pollen levels were simulated under two alternative greenhouse gas concentration scenarios (RCP8.5 assuming high emissions, and RCP4.5 assuming moderate emissions) and three different ragweed plant invasion scenarios (slow, rapid, or reference rates of spread) (Hamaoui-Laguel et al. 2015). The outputs from these models were daily ragweed pollen levels for 50-km grid cells across Europe. Two estimates of current levels were produced (based on CHIMERE or WRF/RegCM) and twelve estimates of future levels (based on CHIMERE or WRF/RegCM, plus the two RCPs and three plant invasion scenarios)

For the present analysis, these fourteen estimates of current and future ragweed pollen were combined with health and population data to quantify their public health significance using ragweed sensitization rate (RSR) as a health consequence. Sensitization to ragweed is related to long-term pollen exposure, thus these daily pollen outputs were aggregated to provide estimates, on a 50km grid, of average total season ragweed pollen.

To produce quantitative estimates of the potential impact of future ragweed pollen levels on RSRs, we first needed to generate a dose-response curve that would be representative of populations in locations with varying ragweed pollen levels, and characteristics that might confound the association between pollen levels and RSRs. Although we considered using estimates from an existing multicentre study [e.g., from the ATOPICA project (ATOPICA 2014), the GA^{2}LEN study (Heinzerling et al. 2009), or ECRHS (Bousquet et al. 2007)] none of these were considered suitable as they either did not sample across a wide range of ragweed pollen levels, focused upon a subset of the population, or were restricted to patients with existing allergic disease.

We instead performed a systematic review of Web of Science, Medline, BIOSIS, the Cochrane library, OpenGrey, and Google Scholar to generate a pooled estimate of the dose-response curve between ragweed and RSR based on all available studies that met a clearly established set of criteria. We used the following major search terms as MeSH (Medical Subject Headings) and all-field text words, as appropriate: immunology, pollen, aeroallergen, allergy, allergens, atopy, sensitize (or sensitise), sensitized (or sensitised), sensitization (or sensitisation), hypersensitivity, skin test, and Immunoglobulin E. The initial search identified 1923 potentially relevant papers (Figure S1). A first filter of the search results (Table S1) retained 50 papers that included estimate of RSRs for human populations within Europe (RSRs for 144 locations in total). Two authors (MA and IL) independently screened the remaining papers and extracted the following study information using standardized forms: location (country, place name), time period, sample characteristics (number, age, and population-based or allergy patients), the reactivity marker used (e.g., skin prick test, specific ragweed Immunoglobulin E), and the RSR. We then further excluded 15 papers that did not clearly report the sensitivity to ragweed alone, that involved a highly restricted sample population (e.g., institutionalized elderly, weed-sensitive allergy patients, patients with symptoms restricted to the ragweed season), that were undertaken more than two decades ago (i.e., pre-1993), or that had a small sample size (< 50 individuals). Finally, for studies that reported multiple RSRs at a single location (such as a series of annual sensitization observations, observations over several time periods, or for more than one age cohort) we selected a single RSR value representing the baseline period and the general population. The review concluded with 66 location-specific RSRs from 35 studies and 20 European countries (Table S2).

Each location-specific RSR was matched (on geographic coordinates) to modelled average total season ragweed pollen levels for the baseline period (1986-2005) from Hamaoui-Laguel et al. (2015). We then used a generalized linear model to estimate the association between the natural log-transformed mean pollen level (ln-mean pollen) at each location and the corresponding RSR for that location, adjusting for the study population type (general population, i.e., a random sample of individuals, or atopic population, e.g., allergy clinic patients). Although we considered adjusting for other factors known to affect RSR (e.g. skin prick test vs. allergen-specific IgE, atopic characteristics, and population characteristics such as age and gender), relevant data were often missing. The final model included 63 location-specific RSRs, after excluding 3 locations with very low baseline pollen levels (< 10 grains m^3y^{-1}). The resulting model coefficient for ln-mean pollen was 5.85 (SE 1.10, p-value <0.001; 95% confidence interval 3.66, 8.04) with an adjusted R^2 = 0.384. The coefficient for study type (atopic versus general population) was 9.35 (SE 3.70, p-value 0.014; 95% confidence interval 1.94, 16.76). A plot of the association between mean pollen counts and RSR, adjusted for study population type, is presented in Figure 1.

We then used the model coefficient and the estimated ln-mean pollen count in each 50-km grid cell to estimate an RSR for each grid cell. This was performed on our two current and twelve future estimates of ragweed pollen across Europe. To estimate the absolute numbers of sensitized individuals we combined the gridded RSR data with NUTS3 boundaries (subdivisions of the 28 EU countries into regions of 150-800k residents) and population data, to estimate the number of sensitized individuals at the NUTS3 level. These data were aggregated to the NUTS2 level (regions with 0.8–3 million residents) as many NUTS3 areas are smaller in size than the 50 km grid cells. NUTS data were sourced from the Statistical Office of the European Union [Eurostat]. For 12 non-EU European countries we used boundaries and population data from the Global Administrative Areas database (DIVA-GIS 2015). Projections of population change were obtained from the World Bank databank (Table S4; World Bank 2015) and applied equally to all NUTS2 areas within a country, to estimate population counts in 2041-2060.

Burbach et al. (2009) indicated that only a proportion of patients sensitized to ragweed experience symptoms, and presented estimates of clinically relevant sensitization rates for ragweed in different European countries. These estimates were obtained and applied at the country level to the numbers of ragweed sensitized individuals.

To estimate changes in the severity of ragweed allergy symptoms for sensitized individuals, and the time period over which they are experienced, we additionally generated monthly maps of estimated ragweed pollen counts over the pollen season.

Results

The pollen RSR dose-response function was applied to the 14 ragweed pollen maps on a 50km grid, and the corresponding population sensitized to ragweed at the NUTS2 level was mapped and tabulated at the European and country level. Initially focusing upon the reference plant invasion scenario, six RSR maps and country level data on the sensitized population were produced (2 current + 4 future). These differed according to the regional climate/pollen model (CHIMERE or WRF/RegCM), time period (baseline or future) and RCP scenario used. These maps are presented in Figure S2 and Table S3. Estimates of the sensitized population based on airborne pollen levels generated using the WRF/RegCM model suite were 27-39% higher than corresponding estimates based on the CHIMERE model suite for both the baseline period and the future period. A comparison of the spatial patterns of current and future sensitization indicated that these model divergences were greatest in North and Western Europe (Germany, Belgium, Netherlands and France) with WRF/RegCM indicating a greater sensitized population due to the higher levels of pollen there. These results also indicated that the choice of RCP scenario makes little difference to the results by 2041-2060, irrespective of model suite; the sensitized populations differed by only around 5%. To provide an indication of the uncertainty, Table S3 also provides 95% confidence intervals based upon the pollen RSR dose response relationship. These indicate that there is relatively large uncertainty regarding the current and future sensitized population, a consequence of the divergent studies presented in Figure 1.

The two model suites are here considered to be equally plausible, as they both show a similar performance in simulating pollen amounts compared to limited available observations (Hamaoui-Laguel et al. 2015). Therefore, the estimated population affected was averaged across the two model suites for all further analysis. However, in the numerical results the data for both model suites are additionally reported in square brackets [CHIMERE, WRF/RegCM] as an indicator of uncertainty. All subsequent results are presented for RCP4.5 (i.e., a moderate degree of climate change) for the sake of simplicity, bearing in mind that the numbers of sensitized individuals in the future are very similar between RCP4.5 and RCP8.5.

Our best estimates of the current and future population sensitized to ragweed from the pollen RSR dose response relationship of Figure 1 are presented in Figure 2. The sensitized population numbers are presented in Table 1 at the country level and summed for EU28, non EU28 and for Europe as a whole. Overall, our estimates indicate that under the RCP4.5 emissions scenario and the reference ragweed invasion scenario, the number of people sensitized to ragweed in Europe increases from approximately 33 million [27m – 38m based on CHIMERE and WRF/RegCM, respectively] at baseline to 77 million [68m – 86m] in 2041-2060 due to higher pollen counts affecting a larger spatial area. Sensitization is projected to increase in countries with an existing ragweed problem such as Romania and Italy, partly due to increased pollen production by established plant populations, but the greatest proportional increases is likely to be in areas where ragweed sensitization is currently relatively uncommon such as Germany, France and Poland. By 2041-2060, sensitization to ragweed will be widespread across the whole of Europe except for Scandinavia, the Baltic States, most of Spain, Portugal and Ireland.

Table 1 also examines the impact of ragweed invasion scenario upon sensitization rates. Under the reference plant invasion scenario, the population sensitized to ragweed at the European level is estimated to increase from 33 million [27m – 38m] to 77 million [68m – 86m] by 2041-2060. In comparison, a slow plant invasion scenario reduces the projected future value to about 52 million [44m - 59m], while a rapid plant invasion scenario increases the projected value to about 107 million [98m - 117 m].

The sensitization rates presented in Table 1 were converted into estimates of clinically relevant sensitization rates using data from Burbach et al. (2009). These results are presented in Table S4, indicating that in comparison to the population sensitized to ragweed, the population clinically sensitized to ragweed in Europe is around 25% lower for both the baseline and 2041-2060. Table S4 also demonstrates that future changes in the European population base do not greatly affect our projections, but suggest lower impacts in countries such as Germany, Poland and Romania with a decreasing population, and accentuated impacts in countries with increasing populations (e.g. France, UK).

To estimate the potential impacts of future climate-related changes on allergy symptoms for individuals sensitized to ragweed, maps of average total season pollen (Mid July – Mid October) subdivided into monthly periods were produced and are displayed in Figure 3. These estimates indicate that especially across France and NW Italy airborne pollen is likely to be present much earlier in the season (Mid July – Mid August) due to accelerated plant development. In the peak pollen months (Mid Aug – Mid September) more ragweed pollen is likely be present across Europe with the greatest increases occurring away from current pollen hotspots. Our projections suggest that pollen will persist in the air in the mid-September to mid-October period across most of Europe, likely due to delayed frosts (Storkey et al. 2014).

Discussion

It has been argued that climate change is likely to affect pollen-related allergy (Bielory et al. 2012). To our knowledge, this is the first study to fully model the potential impacts of climate change on ragweed plant distribution, plant productivity, pollen production and dispersal, and the resulting impacts on pollen concentrations and allergic sensitization.

We estimate that across Europe sensitization to ragweed is likely to more than double by 2041-2060 and that populations across most of Europe are likely to be affected. Our projections indicate that sensitization will continue to increase in countries with an existing ragweed problem, but the greatest proportional increases will be in areas where ragweed sensitization is currently relatively uncommon. Much of the projected change is due to the expected Northward expansion of ragweed, consistent with the expansion already observed in the US (Ziska et al. 2011). Our estimates indicate that ragweed sensitized individuals may experience more severe symptoms due to higher ragweed pollen concentrations and a longer pollen season lasting into September and October across much of Europe. These projected changes are predominantly related to climate and associated land-use change (66%; Hamaoui-Laguel et al. 2015), but also include the dispersal of this alien plant through Europe even without climate change.

One striking feature of the results is the large influence of plant invasion scenario. The reference plant invasion scenario uses the common assumption that the flux of seeds is inversely proportional to the square of the distance (Hamaoui-Laguel et al. 2015). The slow and rapid plant invasion scenarios were generated by altering the proportionality coefficient based upon the ranges reported in previous research (Richter et al. 2013). The slow plant invasion scenario assumes a limited expansion in the range of ragweed and more than halves the overall estimated increase in sensitization to ragweed projected by 2041-2060 under RCP4.5. It thus strongly suggests that control of ragweed is important for public health and as an adaptation strategy against the impacts of climate change. However, control of existing plants is difficult due to ragweed's long-lived seeds, its ability to evolve herbicide resistance and its capacity to re-sprout following cutting (Brewer and Oliver 2009). Ragweed thrives on regular land disturbance, hence management of land is key to its control (Storkey et al. 2014). Controlling long distance seed dispersal is also important for preventing plant spread. This is predominantly associated with human activity and therefore controls over contaminated seed and monitoring areas prone to ragweed invasion are key elements to limit spread (Bullock 2010).

We also examined the impact of different Representative Concentration Pathways (RCP 4.5 and 8.5) and highlighted that these make little difference to the numbers of individuals sensitized to ragweed. This is likely to be due to saturation of the CO_2 fertilization effect at higher concentrations but also the relatively similar climate between the two RCPs within the relatively short future timeframe of our analysis. Projected changes to the numbers and distribution of population across Europe have a relatively minor influence upon our results.

This study emphasizes the multiple steps required to model the impact of climate change on pollen allergy. There are assumptions and uncertainties associated with each step of the process and as far as possible, we have been transparent about these and their impacts upon the results. We compared two regional climate model suites (WRF/RegCM, Chimere) that differ in atmospheric processing, pollen modelling and in the driving global climate model, and found responses in the same direction, although with substantial differences in magnitude. This highlights the need for multi-model approaches to the problem of future pollen simulation. Our research was strongly sensitive to the assumptions concerning plant invasion scenario, and this points to the importance of dispersal control (e.g. measures highlighted in Bullock 2010) as an effective tool to minimize ragweed allergy in the future.

A notable element of uncertainty is the pollen/RSR dose-response relationship (adjusted R^2 38.4%). This low value is a function of the limited number of studies reporting sensitization to ragweed and lack of standardization across studies. We have also assumed that the dose-response relationship between pollen and allergy is identical across Europe whereas differences in factors such as genetic pre-disposition may lead to a differential impact across the continent.

In addition to climate change, plant invasion and population change, other factors may affect ragweed allergy into the future. By 2041-2060, levels of ozone air pollution across Europe are likely to decrease (Colette et al. 2012) potentially suppressing allergenicity of ragweed pollen (Pasqualini et al. 2011). Conversely, ragweed pollen allergenicity may be elevated through higher atmospheric CO_2 levels and increasing drought (El Kelish et al. 2014; Singer et al. 2005). Inclusion of changing allergenicity is a priority for future research. By 2041-2060, the median age of the European population is projected to increase from 38 to 52 years (World Bank 2015) and ragweed allergy is more difficult to treat in aged populations due to greater difficulty in diagnosis and limited treatment options due to co-morbidities and ongoing medication use (Cardona et al. 2011). Appropriate management and use of medication can significantly improve allergy symptoms (Pawankar 2014). Such management can also be economically beneficial and appropriate therapy for allergic diseases and can be 5% of the cost of untreated disease (Zuberbier et al. 2014). Therefore, the overall impact of increasing ragweed allergy will be influenced by the adaptation capacities of individuals and healthcare systems across Europe. Ebi (2014) argues that the capacity of healthcare systems to adapt to climate change will depend upon the development pathways taken by individual countries. Pathways leading to increased inequalities and fragmentation in society present most challenges to adaptation (Ebi 2014), and hence to the potential problem of increasing ragweed allergy.

Conclusions

Our projections indicate that ragweed pollen allergy will become a common health problem across much of Europe, and that sensitization to ragweed will more than double, from 33 million currently to 77 million people by 2041-2060. According to our projections, sensitization will increase in countries with an existing ragweed problem (e.g. Hungary, the Balkans) but the greatest proportional increases are projected for countries where sensitization is now relatively uncommon (e.g. Germany, Poland, France). Our estimates also indicate that sensitized individuals may experience more severe symptoms as a consequence of higher ragweed pollen levels and an extended pollen season that will last into September and October across much of Europe. Our projections are primarily driven by assumptions regarding climate change (66%), but also reflect current trends in the spread of this invasive plant species across Europe. The projected health consequences are highly dependent upon the rate at which ragweed spreads, which is strongly related to control measures against the spread of this plant species (Bullock 2010). This highlights that control of ragweed spread is essential for public health and as an adaptation strategy in response to climate change.

To our knowledge this is the first study modelling the future impacts of climate change upon plant distribution, plant life cycles, pollen production and dispersal, and their subsequent impacts on pollen concentrations and allergy. Climate change consequences will not be restricted to ragweed and a recent review has highlighted a range of other pollen producing species that may be affected (Beggs 2015). Our methods provide a framework for other studies investigating the impacts of climate change upon pollen allergy for these other species.

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Table 1: Current and future populations sensitized to ragweed pollen for three different plant invasion scenarios. Data are average of the CHIMERE and WRF/RegCM model suites for RCP4.5 [CHIMERE and WRF/RegCM values given in brackets].

Country	Population sensitized in thousands [CHIMERE, WRF/RegCM values]			
	Baseline	2041-2060		
		Reference Ragweed Invasion Scenario	Slow Ragweed Invasion Scenario	Rapid Ragweed Invasion Scenario
Austria	890 [868,912]	1749 [1636,1863]	1354 [1282,1427]	2061 [1954,2169]
Belgium	923 [732,1115]	2364 [2143,2585]	1616 [1452,1780]	2767 [2519,3015]
Bulgaria	1150 [1135,1165]	1763 [1614,1912]	1442 [1350,1535]	2066 [1889,2243]
Croatia	873 [804,943]	1098 [1041,1156]	1037 [973,1102]	1169 [1124,1214]
Cyprus	7 [0,15]	36 [1,71]	15 [0,31]	77 [33,120]
Czech Republic	487 [409,565]	1943 [1756,2130]	1150 [1054,1246]	2844 [2737,2950]
Denmark	0 [0,0]	96 [29,163]	3 [0,7]	533 [426,640]
Estonia	0 [0,0]	0 [0,0]	0 [0,0]	5 [3,7]
Finland	0 [0,0]	0 [0,0]	0 [0,0]	0 [0,0]
France	3233 [2256,4210]	10716 [8849,12582]	5989 [4480,7498]	15646 [14066,17225]
Germany	4688 [2282,7095]	15689 [13337,18041]	9321 [6882,11759]	20928 [19129,22727]
Greece	831 [487,1176]	1764 [1341,2188]	1284 [911,1658]	2320 [1908,2732]
Hungary	2289 [2668,1910]	2899 [3069,2729]	2721 [2979,2464]	3006 [3098,2914]
Ireland	0 [0,0]	4 [0,8]	0 [0,0]	82 [0,164]
Italy	4786 [4097,5474]	10110 [9563,10656]	7480 [6846,8115]	13450 [13079,13821]
Latvia	0 [0,0]	0 [0,0]	0 [0,0]	77 [78,75]
Lithuania	0 [0,0]	6 [11,2]	0 [0,0]	224 [245,204]
Luxembourg	15 [0,31]	78 [57,98]	33 [8,58]	124 [106,141]
Malta	0 [0,0]	28 [18,38]	12 [5,19]	49 [38,60]
Netherlands	2224 [1300,3148]	3489 [2863,4115]	2894 [2135,3654]	3862 [3374,4350]
Poland	1123 [1251,994]	4397 [4175,4619]	2437 [2467,2408]	8733 [8382,9084]
Portugal	0 [0,0]	0 [0,0]	0 [0,0]	356 [0,712]
Romania	3097 [3045,3148]	4772 [4473,5072]	4016 [3796,4237]	5500 [5062,5938]
Slovakia	626 [790,462]	1160 [1221,1100]	895 [1004,786]	1438 [1419,1457]
Slovenia	304 [281,327]	424 [397,451]	385 [364,406]	470 [442,497]
Spain	21 [0,42]	447 [35,858]	137 [1,272]	2670 [939,4401]
Sweden	0 [0,0]	13 [1,25]	0 [0,0]	153 [114,192]
United Kingdom	1196 [1008,1384]	6173 [5113,7232]	2631 [1988,3273]	10023 [9270,10776]
Sum EU28	**28764 [23413,34116]**	**71218 [62743,79693]**	**46855 [39975,53736]**	**100631 [91434,109828]**
Albania	394 [400,388]	626 [580,673]	513 [496,529]	784 [727,840]
Andorra	0 [0,0]	2 [0,5]	0 [0,1]	9 [7,11]
Bosnia & Herzegovina	703 [682,724]	914 [869,958]	855 [819,890]	980 [937,1023]
Iceland	0 [0,0]	0 [0,0]	0 [0,0]	0 [0,0]
Kosovo	259 [196,323]	429 [391,468]	347 [287,407]	498 [492,504]
Liechtenstein	1 [0,1]	3 [1,4]	1 [0,3]	4 [3,6]
FYR Macedonia	300 [291,308]	486 [449,524]	395 [369,420]	584 [562,605]
Montenegro	78 [56,101]	124 [101,146]	105 [81,129]	148 [131,164]
Norway	0 [0,0]	0 [0,0]	0 [0,0]	4 [0,7]
San Marino	2 [2,2]	5 [5,4]	4 [4,4]	6 [6,6]
Serbia	1708 [1731,1685]	2073 [2042,2105]	1964 [1928,1999]	2140 [2129,2151]
Switzerland	376 [135,618]	954 [650,1257]	650 [346,954]	1498 [1222,1774]
Sum non-EU28	**3822 [3493,4151]**	**5615 [5087,6144]**	**4833 [4331,5335]**	**6654 [6216,7091]**
Sum Europe	**32586 [26905,38266]**	**76833 [67829,85837]**	**51688 [44305,59071]**	**107285 [97650,116919]**

Figure 1: The Relationship Between Ragweed Sensitization Rate (%) and Mean Pollen Level (Grains m^3) adjusting for study population. Solid Line Represents Best Fit Relationship (logarithmic).

Notes: [a]3 locations excluded due to very low baseline pollen levels (< 10 grains m^3y^{-1}).

Figure 2: Percentage of population sensitised to Ambrosia pollen; At baseline and in the Far Future; Averaged results for RegCM and CHIMERE; RCP4.5; Reference Invasion scenario. Data source: GISCO - Eurostat (European Commission). Administrative boundaries: © EuroGeographics © UN-FAO © Turkstat.

Figure 3: Monthly current and future ragweed pollen counts (grains m^3) across Europe. Data are average of the CHIMERE and WRF/RegCM model suites for RCP4.5 and a reference plant invasion scenario. Data source: GISCO - Eurostat (European Commission). Administrative boundaries: © EuroGeographics © UN-FAO © Turkstat.

Figure 1.

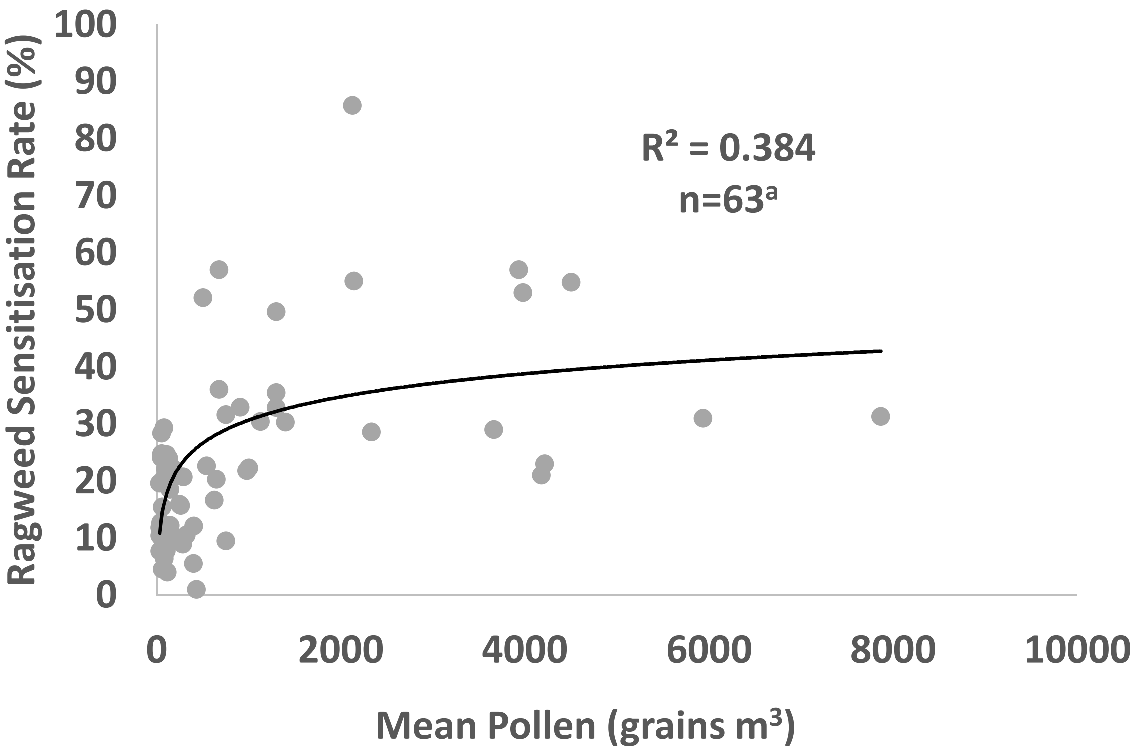
100
90
80
70
60
50
40
30
20
10
0
Ragweed Sensitisation Rate (%)
R² = 0.384
n=63ᵃ
0
2000
4000
6000
8000
10000
Mean Pollen (grains m³)

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Figure 2.

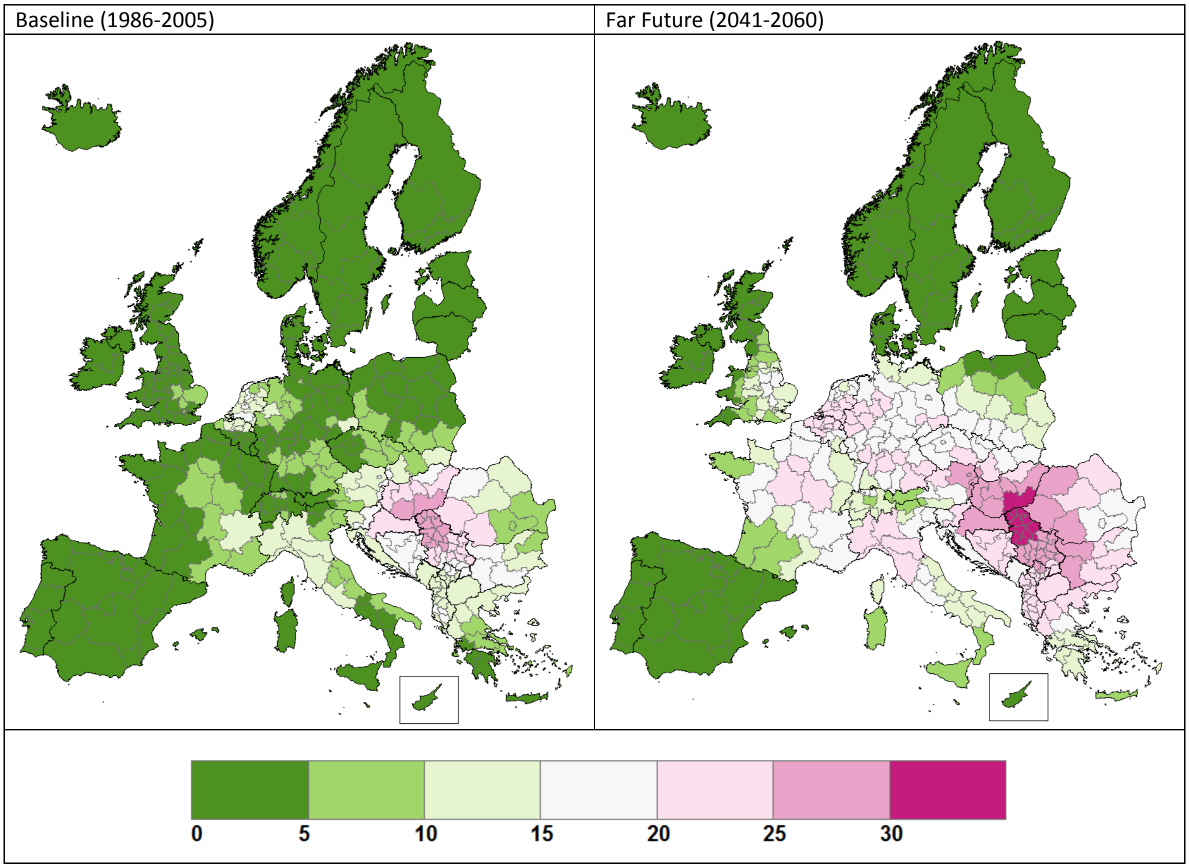
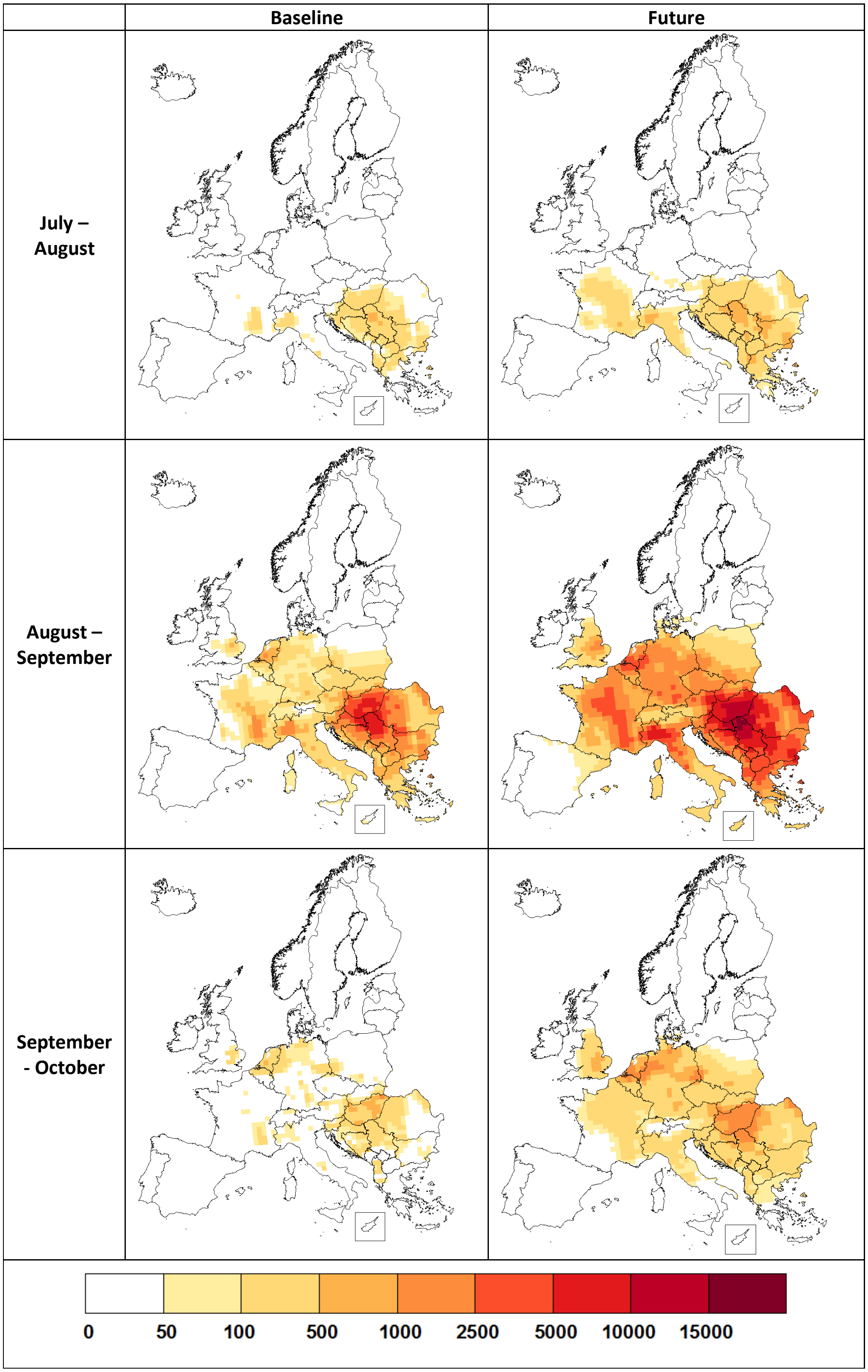


Figure 3.


Baseline
Future
July – August
August – September
September - October
0
50
100
500
1000
2500
5000
10000
15000