REVIEW

Hymenoptera allergy and anaphylaxis: are warmer temperatures changing the impact?

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Purpose of review

Climate change has brought about many changes in our ecosystem. Prolongation of pollen seasons has been reported, related to earlier frost off in the spring and later onset of frost on in the fall. This review considers recent global evidence that stinging insects are redistributing toward the poles, thereby potentially increasing human exposure and risk of sting events.

Recent findings

With changing climate, particularly climate warming, range expansion of insects is occurring in both the Northern and Southern Hemispheres. Likewise, stinging insects, such as Hymenoptera and Lepidoptera, are also expanding range. Though there is scant data on associated increase of insect-related anaphylaxis, increased insect–human interaction is certain.

Summary

It is likely that climate change will continue to alter the distribution and population of Hymenoptera and other insects. As temperatures warm and regions become suitable for nesting and establishment of colonies, many insects will expand their territory. As already reported in Alaska, one would anticipate expansion of range, especially toward the poles, thereby increasing the probability of human encounters and likewise anaphylaxis.

Keywords

anaphylaxis, ants, bee, caterpillars, climate change, hymenoptera, insect, venom, wasp, yellowjacket

INTRODUCTION

Of climate scientists actively researching and publishing, 97% agree that climate change is occurring [1] Most of the leading scientific organizations worldwide have issued public statements endorsing this position. Recognition of the environmental impacts of climate change has helped advance our understanding of the influence these environmental changes have on insect dynamics regarding population and redistribution. Insects are ectothermic animals, whose physiologies are strongly influenced by variations in the microclimate, particularly temperature [2]. There are only a few large-scale studies specifically addressing insects as an indicator of our changing climate. This review will highlight adaptive changes in insect behaviours with the changing ecosystem, particularly those that impact allergy.

ANAPHYLAXIS

The adverse health effects of stinging insects remain significant. These effects range from minor skin irritation and pain to severe and potentially lethal anaphylaxis. Three of the most common triggers of anaphylaxis are – foods, medications and insect allergies [3–6]. The risk of severe anaphylaxis is increased in patients with elevated basal serum tryptase level, honeybee allergy, frequent exposure, age and comorbidities [7]. I was unable to find any published studies in PubMed specifically addressing rates of insect anaphylaxis based on latitude. Mulla *et al.* [8] reported on anaphylaxis epidemiology in the United States and addressed increased incidence of anaphylaxis at higher latitudes, though anaphylaxis specifically associated with insect sting was not

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KEY POINTS

- There is increased incidence of anaphylaxis at higher latitudes compared with lower latitude.
- Most Hymenoptera are expanding their range toward higher latitudes.
- Climate warming is causing ecological change, optimizing range expansion of insects, including Hymenoptera and Lepidoptera.
- Honeybees and bumblebees are in decline due to several factors, one of which is climate warming.

addressed. Internationally, the incidence of anaphylaxis is increasing, potentially more so at higher latitude [9,10]. It has been postulated that this increase could be related to vitamin D deficiency, associated with less year-round sunlight [10]. The expansion of insect ranges toward higher latitudes offers another interesting hypothesis.

CLIMATE CHANGE

Global, annually averaged surface air temperature has increased by about 1.8 °F (1.0 °C) over the last 115 years (1901–2016) with annual average near-surface air temperatures across Alaska and the Arctic increasing more than twice as fast as the global average temperature [11]. Globally, temperature is projected to increase by a further 1.8–4.0 °C by 2090–2099 [12]. Currently, our planet is now the warmest in the history of modern civilization. This past decade has seen record-breaking, climate-related weather extremes, and the warmest years on record for the globe [11]. These trends are expected to continue over climate timescales. There are many indicators of climate change, particularly physical responses such as changes in surface temperature, atmospheric water vapour, precipitation, severe weather events, retreating glaciers, sea level rise and diminishing sea and land ice [11–13].

INSECT DISTRIBUTION

Several factors can influence distribution of insects, climate change is but one. Species redistribution and biodiversity loss has also been impacted by urbanization. In addition to climate change, other factors that influence biodiversity include genetic diversity of species; the richness of local and global species; the spatial extent and the state of natural habitats and the functioning of ecosystems [14,15]. Because of the many variables it is difficult to dissect out the effects of climate change versus habitat change. Environmental modelling is becoming more relevant for environmental scientists. Using models, current scientific data is input based on known data and projecting anticipated scenarios. Using best and worst case scenarios with regard to insect redistribution, may not reflect the many other factors of biodiversity and may not reflect real world interactions [16]. Few studies have specifically addressed the direct impact of venomous insect redistribution on human health, instead focusing on recognized changes in patterns and projected response to changing climate variables.

HYMENOPTERA

Hymenoptera, the largest order of insects, account for more than 10 million stings in humans worldwide annually [17]. It is estimated that potentially life-threatening systemic reactions to Hymenoptera stings occur in 0.4–0.8% of children and 3% of adults [7]. Populations of many Hymenoptera species have extended their range in both the Northern and Southern Hemispheres. The adaptation skills of *Vespula vulgaris* enable it to live in a wide range of habitats, from very humid to arid environments to human manipulated environments such as gardens and human structures [18]. Although some Hymenoptera species have extended range, others are losing range and are potentially in decline.

YELLOWJACKETS (*VESPULA*)

Vespula germanica and *V. vulgaris* are widespread throughout Europe and North America and have subsequently been introduced into the Southern Hemisphere. *V. germanica* became established in New Zealand in 1945 and Australia in 1959 and have continued to extend their range. It is projected that warming climate in addition to global trade and travel will continue to influence expansion of range of *V. vulgaris* [18]. These species are scavengers and therefore flourish in urban environments, resulting in frequent human-encounters [19].

The first two reported deaths from insect-induced anaphylaxis in Alaska occurred in 2006 [20]. This was in a period in which organized outdoor sporting events were cancelled because of high levels of stinging insects, predominantly yellowjackets, in Fairbanks, Alaska [20,21]. Demain *et al.* [22] undertook a retrospective study to assess increases in patients seeking medical care for sting reactions between 1999 and 2007, using the Alaska Medicaid database which represents 132 000 lives. These data were applied to different climate variables. The results demonstrated increases in billings for insect reactions throughout each of the six epidemiological regions of Alaska, with increasing incidence correlating with more northernly latitudes. The largest percentage increases were in the most northern regions, with an increase of 626% from the average incidence of 16 per 100 000 population per year during 1999–2001 to 119 per 100 000 population per year during 2004–2006. In summary, there was statistically significant increases in patients seeking medical care for sting-related events throughout the state, with five of the six regions experiencing at least a 6 °F increase in winter temperature. It was surmised that milder winters provided greater survivability of overwintering queens. The expansion of northern range of *Vespula* does not appear to be unique to Alaska, but rather has been observed in other circumpolar regions. In 2004, a Canadian entomologist and associate curator of the Natural History Museum in Los Angeles confirmed the first sightings of yellowjackets (*Vespula rufa*) in the village of Arctic Bay, Nunavut, Canada, at 73° latitude [23], Barnes *et al.* [24], working in Fairbanks, demonstrated that while freezing causes death in the common yellowjacket, *V. vulgaris*; this species can 'supercool' to temperatures below −16 °C without freezing. In their study, snow depths of as little as 60 cm provided enough insulation to allow the overwintering queens to survive in hibernacula, maintaining an average of −6.5 °C, whereas average air temperatures were −19.4 °C (with minima often below −30 °C). These data illustrate that snow depth could be an important factor in the annual population growth of yellowjackets and potentially other Hymenoptera. Long-term population dynamics of *V. vulgaris* over 39 years in four sites in the United Kingdom and over 23 years of data from six sites in New Zealand [25]. Data revealed that warmer winter temperatures and warmer spring temperatures were associated with increased *V. vulgaris* abundance, whereas increased rainfall was associated with decreased abundance. These data have broad implications that climate warming have a direct impact on the yellowjacket population dynamic [25].

PAPER WASPS (*POLLISTE*)

The paper wasp is the most common Hymenoptera found in North America, with the European paper wasp, *Polliste dominula,* the most dominant of social wasps. Prominent in Europe and Asia, *P. dominula* has also been introduced to New Zealand, Australia, South Africa, South America and North America. Since the mid-1980s, the population of *P. dominula* has expanded to historically cooler regions, especially towards northern Europe. Climate change, specifically climate warming. is speculated to have raised temperatures of certain areas enough to allow *P. dominula* to expand into more northern regions [19,26].

HORNETS (*VESPA*)

Data that specifically addressed hornets regarding the impact of climate change is sparse. There are 22 species within the genus *Vespa*. Based on modelling, it is predicted that the Yellow-legged hornet, *Vespa velutina,* will expand its range into Northern Europe and throughout the United States, except for along the Eastern coast [27]. Nesting patterns are quite different from *Vespa crabo,* in that they are larger in size and can have much larger colonies, ranging up to 15 000–30 000 [28]. These data suggest potential increased regional predominance of these hornets, likely resulting in more frequent human-encounters.

HONEYBEES (*APIDAE*)

In the United States, there are over 4000 species of native bees [29]. Bee species have demonstrated mixed response to climate change and warming temperatures. Although some have expanded range, others have experienced a reduction in both range and population. The Africanized honeybee (*Apis mellifera scutellate*) was introduced to Brazil in the mid-1950s, quickly escaped, and ultimately hybridized with the domestic European honeybee (*Apis mellifera mellefera*), creating what is commonly termed the 'Africanized honeybee' [17]. Data from Schumacher *et al.* [30]. determined that the venom from Africanized honeybees is essentially identical to their domestic cousins, as is the venom volume per sting. Most typically, domestic honeybee does not swarm in large numbers, so stings are often few. Contrary to the domestic honeybee, Africanized honeybees often swarm in large numbers, and the victim often receives multiple stings, and they pursue their victim for much longer distances [7]. The domain of the Africanized honeybee in the United States initially had limited distribution, predominantly Texas, New Mexico, Arizona, Nevada and California [7,17,20]. However, by 2009, the Africanized honeybee had almost doubled its range, now in 10 states [17]. Continued northward expansion of the Africanized honeybee is predicted, largely impacted by temperature warming. Considering the aggressive nature, increased human-encounter and worsening envenomation events are likely [28].

Unlike the Africanized honeybee, a withdrawal of range has been experienced by the domestic European honeybee. *Apis mellifera* is a species that has demonstrated great adaptability to many climactic environments in that it can be found almost everywhere in the world and is instrumental in pollination. Approximately 35% of agricultural crops and 84% of cultivated plant species are reliant on honeybees for pollination [31]. Honeybee populations have been diminishing worldwide since 1995; with a consensus that this is related to a combination of factors. In addition to pesticides, which kill many colonies each year, factors linked to climate change leading to environmental stress, as well as new pathogens such as the brood parasite, *Varroa destructor*. Other factors, such as mismatching between phenology of honeybee colonies and flowering plants may also have impact on colony health and resultant increase bee mortality [31–35]. In combination, these stresses may further interfere with the honeybees' capability to adapt to climate warming [35,36].

The mason bee, genus *Osmia* sp., order Hymenoptera, pose little to no threat of stinging because males do not have a *stinger*, and the females will only *sting* if threatened. Though not a significant direct health risk, such as anaphylaxis, they are very important pollinators. Using 17 climate chambers, Frund *et al.* [37] demonstrated that overwintering temperature did not influence mortality, which was uniformly low. More importantly, they demonstrated that overwintering temperature affected both weight loss after winter and the date of emergence. Weight loss reflects higher metabolic rates during overwintering at warmer temperatures and ultimately resulting in loss of energy, consequently increasing vulnerability and decreasing longevity of wild bees. These findings may further explain reduction of bee populations.

BUMBLEBEES (*BOMBUS*)

Genus *Bombus*, part of the family *Apidae*, have over 250 species. Bumble bees are found in both the Northern and Southern Hemisphere, predominantly in cooler alpine climates [38]. Although bumblebees are uncommon causes of anaphylaxis, it has certainly been reported, particularly with occupational exposure in greenhouse workers [7,39]. Like honeybees, bumblebees have been in decline since the early 1900s, with loss initially attributed to loss of habitat for feeding and nesting resources [38]. Using applied modelling with climate change scenarios, Marshall *et al.* [40] studied 48 *Bombus species* common to Europe, analysis projected that by 2100 most of the bumblebee species will lose range, whereas some were projected to experience a slight gain of range. A Belgium study [41] looked at heat stress tolerance of bumblebees, two taxa with an arctic distribution, three mountainous taxa and one widespread taxon. All groups demonstrated relatively low tolerance to heat stress, with least tolerance in arctic species. These data suggest that heatwaves could lead to further decline of bumblebee species [41]. Published in Science, Soroye *et al.* [42] studied 66 species of bumblebees in North America and Europe, estimating the thermal and precipitation limits of each of the species. The data provided evidence of rapid and widespread declines of bumblebees across Europe and North America, with decreases of 46% in North America and 17% in Europe. They concluded that climate change has driven stronger and more widespread bumblebee declines than previously reported [42]. Unlike many other taxa, bumblebees have failed expand their range with warming temperatures, resulting in losses in their southern range and failure to expand in northern range in both Europe and North America, thereby compressing range in both continents [43]. Based on these data, bumblebees are vulnerable to further and possible accelerated decline due to climate change, adding further concern to cultivated plant pollination.

Although not a high risk with regards to anaphylaxis, it is important to note that some Hymenoptera species, particularly honeybees and bumblebees, may not be able to expand range or adapt to the changing climate. Although this will likely decrease human encounters, it could have a significant impact on pollination.

ANTS (*FORMICIDAE*)

The family Formicidae is comprised of over 14 000 species. Within the genus Solenopsis, two species, *Solenopsis invicta* and *Solenopsi richteri* have become economically and medically important pests in the United States, with *S. invicta* responsible for 95% of sting reactions from ants in North America. Commonly referred to as imported fire ants or invasive fire ants (IFA), they build very large sub-terrarium nests with large mounds. Highly aggressive in nature, they can sting multiple times in a circular pattern, producing a painful sterile pseudo-pustule and in some, potentially severe, life threatening anaphylaxis [7]. There are other species of stinging ants, throughout most continents. In the United States, the distribution of *S. invicta* and *S. richteri* is predominantly in the Southeastern region.

IFA are invasive species in the United States. Native to South America, *S. invicta* was accidentally introduced to Southern United States in the 1930s and again in 1945 and has successfully increased its range to include the Southeastern Region and Southern California [44,45]. *S. richteri* was introduced into the United States. in the 1950s, though has a much smaller footprint.

Through scientific modelling, it is predicted that changing climate will create favourable conditions for *S. invicta,* resulting in further northern expansion. Using Vegetation-Ecosystem Modelling and Analysis Project (VEMAP) along with historical data from the North American Oceanic and Atmospheric Administration, Morrison *et al.* [45], predicted northern range expansion of *S. invicta* of 80–150 km, with acceleration of expansion by the second half of the 21st century. VEMAP is a multiinstitutional, international effort whose goal is to evaluate the sensitivity of terrestrial ecosystem and vegetation processes to altered climate forcing and elevated atmospheric CO_2 [46]. Findings revealed that in some areas, expansion range of IFA would be limited by drier conditions, whereas range increased in higher elevations where temperatures are cooler [45].

S. invicta are projected to continue to expand its range within the United States, at least in part due to climate warming. This will undoubtedly increase insect–human contact. Based on a prospective study, sting rate during a 6-week exposure is more than 50%, with reported development of allergic sensitivity of 7% [47]. Thus, in addition to economic impact, the continued spread of imported fire ants will almost certainly result in increased morbidity and mortality risk.

Pachypcodyla chinensis, or the Asian needle ant, is native to areas of Japan and Asia. Like the imported fire ant, it is in the order Hymenoptera and family Formicidae. The Asian needle ant is another invasive species that has inhabited the United States. The Asian needle ant was first introduced in North Carolina early in the 20th century and is rapidly spreading along the Eastern seaboard of the United States [48,49] Stings from the Asian needle ant has been identified as an important cause of anaphylaxis in East Asia. A 23-kDa protein, homologous to antigen 5, is the major allergen produced by these ants [50]. Using species distribution modelling, Bertelsmeier *et al.* [49], demonstrated that climate change will greatly increase the risk of worldwide expansion of *P. chinenis* through an increase in suitable landmass and climate. Climate change is a crucial factor in extending the habitat of this invasive ant. There is concern over anaphylaxis risk to this stinging insect, as we lack the ability to perform venom testing and are unable to offer immunotherapy.

LEPIDOPTERA: CATERPILLARS/ BUTTERFLIES/MOTHS

Lepidoptera are 'scaly, winged insects,' comprised of butterflies and moths in all stages of development. There are an estimated 140 000 species in this class, with a very complex life cycle. Eggs are laid onto foliage, where they hatch and the larval form (caterpillar) emerges. The caterpillar undergoes five or six developmental molts and transformations known as instars. It is during these early developmental stages that they are a threat to humans. The most mature instar pupates into a cocoon, ultimately emerging as an adult butterfly or moth [51,52]. Lepidopterism and erucism are interchangeable terms that refer to the ill effects of larval and adult butterflies and moths resulting from inhalation, ingestion or direct contact, with resultant envenomation. The stinging or urticating caterpillars excrete their venom through hollow hairs or spines, called setae. Envenomation through the setae can result in hypersensitivity reactions, including local and/or systemic reactions or anaphylaxis. Caterpillars excrete their venom through hollow hairs or spines, often leaving a very distinct pattern on the skin. As an example, during the final instar of *Euproctis similis*, there are an estimated 2000 000 venomous setae per caterpillar [51,53,54].

Up to 150 species of Lepidoptera have been implicated in lepidopterism, representing only 0.1% of the known species of moths and butterflies. Four species of caterpillar frequently encountered in the United States pose a potentially serious threat for the sensitized victim: first, the Io moth caterpillar (*Automeris io*); second, the saddleback caterpillar (*Sibine stimulea*); third, the Douglas fir tussock moth caterpillar (*Orgyia pseudotsugata*) and fourth, the puss caterpillar or 'asp' (*Megalopyge opercularis*). These have all been reported as causing serious occupational and public health problems, including anaphylaxis, related to lepidopterism [51,52]. Because of their quick response to climactic factors, butterflies are good indicators of climate change in Europe. The Butterfly Monitoring Scheme has accurate data sets dating back to the 1970s. As of 2005, the average temperature in Europe had increased 0.8 °C. With warming climate and resultant changes in the ecosystem, 63% of butterfly species expanded their range northward [55,56].

Expansion of range of Lepidoptera in response to climate change provides information that is helpful in assessing redistribution of other insects, which in turn is an important demonstration of potential impacts on human health. This is demonstrated in a meta-analysis; Battisi *et al.* [57] reported that over the last 20 years there has been an increase in reporting of setae-related health problems associated with expansion of the processionary moth. The processionary moth, subfamily Thaumetopoea, consists of approximately 100 species, occurring across Africa, Asia, Europe, Australia and the Middle East [57].

CONCLUSION

Frazier *et al.* [58] reported on the relationship between increasing temperatures and population growth of 65 insect species. Insects that adapt well to warmer environments experienced an increase in population growth rates. Deutsch *et al.* [59] in turn demonstrated that with a warming climate, the fitness of ectothermic organisms is expected to generally increase with their latitude. Based on these data, faster population growth and range expansion is projected for insects at mid-to-high latitudes, and negative consequences with range compression and increased extinction rates for ectothermic species near the equator.

Climate change will affect cyclic and seasonal patterns across latitudes. As temperatures increase there will be ecologic changes, which will impact insect populations and distribution. Further, how this will change the insect population and range will be driven by the thermal sensitivities and tolerance of each insect species. Expansion of range toward the poles has been demonstrated in many species. As discussed in this review, apart from honeybees and bumblebees, most insects known to cause anaphylaxis are predicted to expand their range, thereby almost certainly increasing the frequency of inset–human encounters.

Some species may be less adaptable or less tolerant and move toward extinction. This has been demonstrated in both honeybees and bumblebees [31–35,42,43]. As discussed, the expansion of range for social wasps has been documented through modelling, which predicts a continuation of this expansion of range. There are other studies that suggest there could be a decrease in social wasp expansion, in part due to reduced ability to defend against parasitoids, bacteria and viruses, and to intolerance of greater rainfall as a result of climactic changes [60].

It is likely that climate change will continue to alter the distribution and population of Hymenoptera and other insects. As temperatures warm and regions become suitable for nesting and establishment of colonies, many insects will expand their territory. As already reported in Alaska, one would anticipate expansion of range, especially toward the poles, thereby increasing the likelihood of greater probability of human encounters and likewise anaphylaxis.

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There are no conflicts of interest.

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■ of special interest
■■ of outstanding interest

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