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Review

Climate Change and Its Effects on Indoor Pests (Insect and Fungi) in Museums

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Abstract: Climate change not only affects the biodiversity of natural habitats, but also the flora and fauna within cities. An increase in average temperature and changing precipitation, but additionally extreme weather events with heat waves and flooding, are forecast. The climate in our cities and, thus, also inside buildings is influenced by the changing outdoor climate and urban heat islands. A further challenge to ecosystems is the introduction of new species (neobiota). If these species are pests, they can cause damage to stored products and materials. Much cultural heritage is within buildings, so changes in the indoor climate also affect pests (insect and fungi) within the museums, storage depositories, libraries, and historic properties. This paper reviews the literature and presents an overview of these complex interactions between the outdoor climate, indoor climate, and pests in museums. Recent studies have examined the direct impact of climate on buildings and collections. The warming of indoor climates and an increased frequency or intensity of extreme weather events are two important drivers affecting indoor pests such as insects and fungi, which can severely damage collections. Increases in activity and new species are found, e.g., the tropical grey silverfish *Ctenolepisma longicaudatum* has been present in many museums in recent years benefitting from increased indoor temperatures.

Keywords: biodegradation; integrated pest management (IPM); historic buildings; libraries; climate monitoring; IPCC

1. Introduction

Climate change is affecting our planet at a global scale and is one of the greatest threats to ecosystems and biodiversity. Increases in temperature and shifts in precipitation already affect different species of animals [1] and plants across the planet [2]. Some ecosystems are especially sensitive to changes in species composition, so further losses of biodiversity can be expected in the future. Insects, the most diverse group of animals on the planet, are also disturbed and altered by climate change; species are lost or their distribution shifts to other regions [3–6].

In different natural and urban habitats, we have also found an increase in neobiotic species in recent years, and many of them benefit from a changing climate [6,7]. They can be found in buildings such as museums and, if they are pests, cause damage to objects or are a nuisance to visitors [8–10]. Silverfish, notably *Ctenolepisma longicaudatum* Escherich, 1905 (Lepismatidae, Zygentoma) and *Ctenolepisma calvum* (Ritter, 1910) (Lepismatidae, Zygentoma), have been introduced in recent years and are spreading in buildings and museums across Europe [11–16]. The grey silverfish *C. longicaudatum*, especially, can damage paper and starch-based objects and materials such as paper, books, photographs, graphic art, or historic wallpaper [9]. *Attagenus smirnovi* Zhantiev, 1973 (Dermestidae, Coleoptera—common name brown carpet beetle) was introduced in Europe many centuries ago [17], while *Tylodrias contractus* Motschulsky, 1839 (Dermestidae, Coleoptera) and *Reesa vespulae* (Milliron, 1939: Dermestidae, Coleoptera—commonly the skin beetle), for example, are new pests in Austrian museums and seem to have spread in recent years (see [18] for *Tylodrias contractus* and personal observations for *Reesa vespulae)*. Many museum pests have a worldwide distribution, but we can see clear changes and a shift in the communities in recent years (see [19] for a database for UK museum pests). In addition, new to the Austrian outdoor fauna are the Western conifer seed bug *Leptoglossus occidentalis* Heidemann, 1910 (Coreidae, Hemiptera) and the Asian mud-dauber wasp *Sceliphron curvatum* (F. Smith, 1870) (Sphecidae, Hymenoptera), both occasionally found in museum buildings (but they are not storage or material pests). The termite *Reticulitermes flavipes* (Kollar, 1837) (Rhinotermitidae, Blattodea) was known as an introduced pest in the greenhouse gardens of the Schönbrunn park for many centuries [20]. See also the database of the Natural History Museum in Vienna for more neobiotic species in Austria [21].

We reviewed the literature on climate change and its effects on indoor museum pests: insects and fungi. We searched Scopus (www.scopus.com (accessed on 1 March 2022)) and the BCIN literature database for conservation science (https:///bcin.info (accessed on 1 March 2022)). We used the keywords: "museum" and "climate" and "pest" or "insect" or "fungi", in our literature search. Further published papers in heritage science, museum conservation, and pest management journals were searched for specific publications combining the search terms "museum pests" and "climate change". The literature on museum climates is large, but few papers were relevant to our theme. Additionally, microclimate studies in museums usually investigate the microclimate inside showcases, but seldom the climate of insect habitats such as the floor or in cracks. Museum-integrated pest management (IPM) papers were often found in conference proceedings. In this review, we try to present the complexity of this interdisciplinary research field and discuss the methodology and research needs. The Scopus database revealed 123 papers with the keywords, and 24 of those were relevant to our review. In the BCIN database, 172 papers were found, but only 6 proved relevant. The overlap between the two datasets was small and further papers were added from the grey literature. We found that few papers specifically look at the relationship between museum pests and climate change.

1.1. Climate Change and Cultural Heritage

Although the socio-economic significance of climate change is widely recognised, its potential to affect our cultural heritage and natural history collections is not explicitly mentioned in Intergovernmental Panel on Climate Change (IPCC) reports. The need for knowledge in this area has initiated various European research projects, such as Noah's Ark [22], Engineering Historic Futures [23], Climate Change and the Historic Environment [24], and Climate for Culture [25–27]. Recent studies by Camuffo et al. [28–33] and other authors [34–37] are of particular relevance because of their focus on the indoor environment within historic buildings, both in European and national contexts. They use simple outdoor–indoor transfer functions or complex building simulations requiring an input of data on building physics and material properties (ASHRAE, EnergyPlus, or HAMBase/WUFI simulations) to predict interior conditions from the outdoor climate.

Climate change will have a direct effect on historic buildings, which often have little or no active climate control. Even with HVAC (i.e., heating, ventilation, and air conditioning), the indoor climate was found to be unsteady. Lankester and Brimblecombe's [36,37] results suggest a temperature increase inside historic buildings. Models show that climate change will have a direct effect on the room climate of buildings where there is insufficient climate regulation [38–42]. However, stringent climate regulation is not possible in all buildings and institutions and often comes with high energy demands and costs [43]. For the outdoor environment, it is expected that extreme climate conditions will increase in frequency and magnitude, while winter temperatures will increase in Northern Europe and summer temperatures will increase in Southern Europe [44]. Projections vary, however, across a number of different climate models [45], leading to modelling uncertainty and ranges of outcomes [46]. Models show that climate change will have a direct bearing on the room climate of historical buildings and depots without or with insufficient climate regulation [35,36,38–40,43]. Lankester and Brimblecombe modelled changes in the temperature and humidity within a historic gallery in Southern England for the period of 1770–2100, based on their climate modelling [36,37]. They used laboratory data and observations on insect development to estimate the potential for future egg production of *Tineola bisselliella* (Hummel, 1823) (Tineidae, Lepidoptera, the webbing clothes moth), which their results suggest to potentially increase threefold by the end of the present century.

1.2. Climate Change and Indoor Insect Pests

Impacts of a changing climate on cultural heritage are expected [47], but few studies examine pests, such as insects. According to a summary in Brimblecombe and Lankester [48], and Brimblecombe et al. [49–53], changes of a few degrees in temperature have the potential to cause increased activity and reproductive cycles. Changes of a few degrees of temperature have the potential to (i) increase activity for periods with day temperatures above 15 °C [48]; (ii) increase the number of eggs (0 at <10 °C; few at 15 °C; 80 at 25 °C) [54,55]; (iii) increase the number of reproductive cycles per year [9,50], e.g., up to two cycles for *Stegobium paniceum* Linnaeus, 1758 (Ptinidae, Coleoptera—common names drugstore beetle, also known as the bread beetle or biscuit beetle) as calculated by Brimblecombe and Lankester [48] based on laboratory work by Lefkovitch [54]; and (iv) increase the flying period with the potential to enhance dispersal [54,55]. Finally, climate change is expected to foster the invasion by new species [6,7,11].

This notwithstanding, an increase in pest insect populations is already observed. Pinniger [46] suggests the following reasons: warmer winters, widespread use of natural fibres, less potent insecticides (as part of the IPM strategy), and occupation of new indoor niches.

Tineola bisselliella (Hummel, 1823) (Tineidae, Lepidoptera—common name webbing clothes moth), *Anthrenus verbasci* (Linnaeus, 1767) (Dermestidae, Coleoptera—common name varied carpet beetle), *Stegobium paniceum* Linnaeus, 1758 (Ptinidae, Coleoptera—common name drugstore beetle) [9,10,56], and, more recently, *Attagenus smirnovi* and *Trogoderma angustum* Solier, 1849 (Dermestidae, Coleoptera) have the potential to become a real danger for museums and collections, inflicting irreparable damage within a short time span. Despite their necessary involvement in hatching, it is mostly their larvae, which, due to their size, often remain unnoticed and cause damage. The most common textile pest in European museums and throughout the world is the webbing clothes moth *Tineola bisselliella* [57], infesting, in particular, objects made from wool as well as of fur and feathers. Infestations can remain unnoticed until the damage is significant because, for example, excrement may be the same colour as dyed cloth fibres that are a food source [58]. The availability of sexual pheromones make it possible to use pheromone traps for accurate detection of insects. Traps are typically placed out and recovered monthly during the warm "flying season" of moths (March–September; personal experience). According to unpublished results, there is a large variation across museums in regard to the duration of the "flying season" and the numb er of generations produced by a population. It is assumed that these differences depend primarily on the room climate related to different heating patterns, food availability, habitat choices, etc. Under optimal laboratory conditions (temperature ~25 °C), several generations can develop over the year and have been found to be increasingly common in museum environments [9,59]. This is because moth development depends primarily on temperature and food quality [60]. The impact of relative humidity seems small as *Tineola bisselliella* can survive dry conditions by metabolising food to provide water [58,59,61,62]. A Scandinavian research project [17] examined the expansion of *Attagenus smirnovi* to habitats of Northern and Western Europe in a changing climate.

1.3. Climate Change and Indoor Fungi

Similar arguments apply to the impact of climate change on fungi, which are another major museum pest [63–65]. Proudlove [66] suggested that a temperature increase of up to 5 °C together with increasing humidity will cause the growth of fungi to be a problem for the conservation and restoration of paper. The same applies to many other types of objects that consist of organic materials. Mould risk is expected to increase in Southern England because of increased relative humidity in warmer winters [35,42,66]. Hitherto mould outbreaks in central European museums are often dominated by a very limited number of xerotolerant and xerophilic species within the genera *Eurotium*, *Penicillium,* and *Aspergillus* [64], which are able to live at low-water availability. However, with increasing temperature and potentially relative humidity, it can be presumed that not only the growth rates but also the diversity of fungi will increase.

1.4. Possible Responses to Climate Change

In the future, museum buildings with active climate control will require more energy, increasing the cost of regulating the indoor climate [67–69]. Some of these systems were not developed to regulate higher temperatures and will be at their operational limits. In many historic buildings, the climate is difficult to regulate and air-conditioning systems are complex to integrate in culturally protected spaces.

Museums and historic buildings without climate control will suffer from high temperatures in the summer months and brief excursions to higher humidity in spring. Today, we already see an increase in indoor condensation and mould growth when temperatures outside of historic, unheated buildings are high in spring and early summer. Warm air from the outside passes through the cold, poorly insulated buildings, resulting in condensation on the outside walls as the humidity increases and encourages fungal growth. In addition, extreme weather events can lead to an increase in water damage and an increase in indoor humidity.

Research projects investigating both insect pests and fungi in the same museum environment are also rare and hold the potential to better understand similarities and differences in their response to climate change [70–72].

Although some pest–climate projections exist for the UK [48–50] and Japan [51], data for a central European setting are missing. The collection of insect monitoring and development data, together with indoor climate, is needed to obtain a better insight into the species affected most. Pests have not been the focus of study so far in the above-mentioned programmes on climate change and cultural heritage [21–26], although recent analyses have examined the effect of museum closures on indoor climate during the first COVID-19 lockdown [52,53] in an Austrian museum on *Lepisma saccharinum* Linnaeus, 1758 (Lepismatidae, Zygentoma).

One should be cautious about assuming a simple linear relationship between temperature and insect activity (development cycles) and, thus, the extent of damage [60]. Far more complex temperature mechanisms appear to be in effect. However, at least with regard to museum pests, it has not yet been established whether average temperature, temperature peaks, or the duration of elevated temperatures has the dominant impact. Reviews of the literature can show what data are needed about the influence of indoor climate on the activity of pests within the buildings. It is necessary to monitor not only the climate, but also the insects and fungi in the same locations.

2. Research Needs

Most past studies of climate change and museums did not specifically focus on impacts on indoor biodiversity, and damage by insect pests and fungi or neobiotic species. Research on the microclimate in museums has usually focused on the microclimate in show cases, but for the living organisms, the microclimate of the floor, cracks, and spaces behind objects and furniture is likely more relevant.

Important Questions

What effect will outdoor climate change have on indoor climates in museums?

How does the development of museum insect pests and fungi depend on the indoor climate, such as temperature (means, maxima, and thresholds) and humidity within a historic or modern climatised building?

What will be its effect on pests, e.g., higher activity, faster development, or more generations?

Will climate change facilitate the spread of new pest species in Europe?

How much damage can be expected in the future and how can museums prevent it?

How can museums limit indoor temperature changes by optimising their insulation, heating, and air-conditioning, and at what cost?

3. Methods for Investigating the Effects of Climate Change on Museum Pests

3.1. Monitoring

Studies of the effect of climate change on museum pests need to monitor both the activity of the pests and the climate in the same locations (sites and micro-habitats with their microclimates). With regular trapping with sticky blunder- and pheromone traps, the activity and diversity of insects can be measured. With surface and air sampling of fungi, their diversity can be determined. These data need to be related to (1) the indoor climate, (2) the indoor microclimate, and (3) the outdoor climate. Data on the microclimate close to where the pests are found are especially needed, but rarely investigated. Many museums already have a climate monitoring system in place, but it is mostly collecting the average room climate, relevant for the protection of the objects. However, for insects and fungi, the microclimate, for example, on the floor close to the area where they are found, is probably more relevant and can be quite different from the centre of the room at a 1.60 m height.

3.2. Laboratory Experiments Needed to Collect the Data

For many insect pests found in museums, we lack data on the relationship of temperature (minimum, maximum, and thresholds) and activity or reproductive cycles. This needs to be determined under standardised laboratory conditions in breeding chambers. The same information is needed for the most important fungi species, where temperature thresholds are often unknown.

3.3. Indoor Climate Response Model

Projecting the effects of warmer climates on the diversity, abundance, and activity of museum pests will require statistical analysis of the complex impact of temperature and humidity (i.e., mean, maxima, and thresholds) on the development time and feeding activity of our museum insect pests. The outdoor climate influences the indoor climate by heating the building, increasing the humidity and interactions of both factors when buildings are not well sealed or insulated (Figure 1).

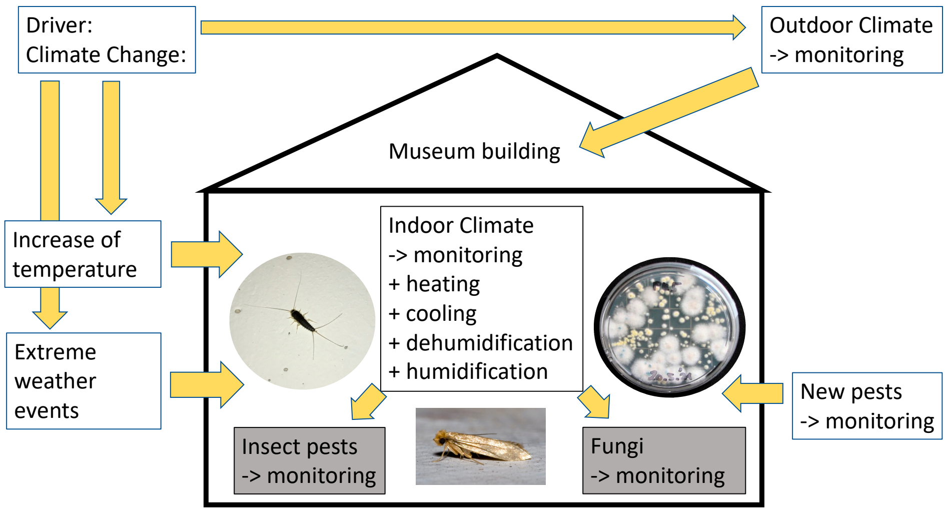

Figure 1. Relationship between climate change, outdoor climate, indoor climate, and insect and fungi monitoring.

4. Summary and Conclusions

We found very few papers that specifically analyse the relationship between climate change and museum pests (but see [49,50,53,55,60] for insects). Models of future climate scenarios are rare for most regions, even though we can already see changes in the climate and insect pest and fungal activity. At the conference on museum microclimate in 2007, there was only one contribution on climates relevant for insects [73]. Skendžić et al. [74] reviewed the literature on the impact of climate change on agricultural pests and referenced a large number of papers dealing with effects of rising temperature, changes in precipitation, and rising CO_2 levels in the atmosphere. These affect agricultural pests by increasing their geographic range, overwintering survival, and number of generations. However, the risk of invasive species, insect-transmitted plant diseases, and interactions between host plants and natural enemies is also affected. For museums and cultural heritage institutions, only the geographic range, number of generations, and increased risk of invasive species are relevant. Skendžić et al. [74] also suggested monitoring the climate and pest populations, modifying IPM strategies, and using modelling and prediction tools. See also [75] for the complex interaction between the climate, biodiversity, ecosystems, and human well-being.

Climate change is and will be a big challenge for the protection of our cultural heritage: millions of objects are stored and exhibited in museums, storage depositories, historic palaces, castles, libraries, and archives. Few academic papers investigate the relationship between pest activity and indoor climate in museums. Models for future climates indicate an increase in temperature and rise in extreme weather events, where both factors can and will also influence the indoor climate within these buildings. Changes in indoor temperature (mean, extremes, and rapid fluctuations) can influence organisms such as insects and fungi living within the collection spaces, on or in the objects. Our literature review shows that there are limited data on how much damage can be expected in the future. To prevent this, museums need to act. It is necessary to monitor not only the indoor climate but also the activity of pests within the same buildings. Indoor climates vary greatly in different types of museum buildings (with or without climate control/heating/no climate control at all). Climate studies need to be complemented with laboratory studies on the same pests and fungi species. These data can help to simulate the effects from modelled projections of the future climate on the most important pests.

A research project focusing on exactly these research questions has just started in Austria. We will determine the statistical relationship between the outdoor climate, indoor climate, and insect and fungal diversity, abundance, and activity to establish projections of the response of pest activity to future climate change, i.e., a pest–climate response model, together with an outdoor–indoor climate transfer function. Due to the increasing range of climate forecasts, the potential impacts of climate change need to be based on a variety of existing models. The climate scenarios employed will use those of the recent IPCC reports [76,77] adapted to model changes on the indoor museum pests in developing a climate–museum pest model. The IPCC report suggests that the next 50 to 100 years will bring warmer climates, changes in humidity, and an increase in extreme climate events. Our model will forecast the impact on pest populations, their spatial and temporal abundance, as well as on the possible invasion of new pests.

The last IPCC report (https://www.ipcc.ch/report/ar6, accessed on 1 March 2022) [77] mentioned the impact of climate change on cultural heritage, showing the urgency of this subject. It is a key risk for societies and ecosystems (Chapter 1, page 31; and citing [76–78]). Further in Chapter 6, climate change is mentioned as a risk to key infrastructures including cultural heritage (Chapter 6, page 32, 42; and citing [79–81]) with an increase in flooding, sea level rise, and water infiltration from post-flood standing water. The urban climate is particularly at risk [82]. In chapter 6—Adaptation Pathways–effects on cultural heritage are addressed again (Chapter 6, page 47, 56; and citing [81,83–86]). There is a diversity of ways to consider for preparing for climate change; see, for example, a variety of options for heritage institutions to move forward after being affected by rising sea levels [87,88].

We believe that the scientific community and stakeholders for cultural heritage will profit from investigations that help make better decisions for the future on how to prevent damage by climate change and estimate costs.

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