Original research or treatment paper

Long-term changes in climate and insect damage in historic houses

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Insect pests are an important source of concern in historic houses as the larval stages in particular can feed on a variety of important heritage materials, causing significant and sometimes irreparable damage to collections. Damage to wood and textiles is a special problem. The lifecycles of insects are sensitive to climate and require relatively warm conditions. There has been a significant increase in the presence of insect pests within historic houses in the early twenty-first century. The reasons may include: warmer winters, widespread use of natural fibres, less potent insecticides, and occupation of new niches indoors. The interior climate, especially increasing warmth, offers the potential for greater insect growth and survivability. Modelling changes in the temperature and humidity within the Cartoon Gallery at Knole, southern England, for the period 1770–2100 suggests a dramatic increase in favourable temperature conditions through the current century.

Keywords: Biscuit beetle, Climate change, Furniture beetle, Indoor climate, Knole, Webbing clothes moth

Introduction

> she brushed her short hair with King James' silver brushes: she bounced up and down upon his bed…and pressed her cheek against the worn silver counterpane that lay upon it. But everywhere were little lavender bags to keep the moth out and printed notices, 'Please do not touch', which, though she had put them there herself, seemed to rebuke her.
>
> *Orlando*: *A Biography* (Virginia Woolf, 1928)

Climate change is frequently regarded as an outdoor process. This is understandable as the indoor environment seems protected from ambient conditions. This may be true of our domestic interiors and public spaces that are heated or air conditioned. However, it may be less true of historic properties where concerns over damage to the historic fabric means that there is typically a reluctance to install modern air-conditioning systems as such changes tend to contravene statutory limitations in the UK. There is also potential for air conditioning to be ineffective in older leakier buildings with open chimneys and casemate windows etc. Conservation heating can be important in maintaining satisfactory levels of relative humidity, but care is needed where walls are saturated, initially relative humidity can increase. Comfort heating can make interiors very dry (see Camuffo *et al*., 2012). Historic dwellings often benefit from a degree of passive control, but this often acts more as a buffer than differentiating the indoor climate from that outdoors. Climate change is likely to increase the average temperatures of Europe by a few degrees over the next century, although this change could be larger in the far northern parts of the continent (as in the multi-Atmosphere-Ocean General Circulation Models average projections shown in figure 3.2 of the Intergovernmental Panel on Climate Change Synthesis Report, *Climate Change* (IPCC, 2007)). Thus, it is also likely that the increases in temperatures will be experienced in unregulated indoor environments.

Climate change has emerged as a key concern for the twenty-first century. The socio-economic significance of climate change is widely recognized, although its potential to affect our cultural heritage was not explicit in IPCC 4. Despite this, there have been a number of European projects, such as *Noah's Ark* and *Climate for Culture,* which have funded major initiatives concerned with heritage and climate change, the latter being particularly relevant because of its focus on the indoor environment. Results from the investigation of the indoor environment at both European and national level (e.g. Camuffo *et al*.,

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2012; Lankester & Brimblecombe, 2012a, 2012b) give collection managers the opportunity to plan strategies to reduce impact of long-term climate change, putting strategic measures in place to prevent increased damage, and thus preserve our heritage for future generations.

The changes in temperature across the coming century, subtle though they may seem as a few degrees on average, can have profound effects such as increased thawing in Greenland (Brimblecombe, 2010). In the coming century insects may extend their northward limit and in warmer regimes existing insects may have longer periods of activity indoors (Child, 2007). This paper will explore how climate change may affect the insects found indoors and their potential to cause damage, with particular attention to Knole, an important historic property in southern England.

Knole was built by Thomas Bourchier, Archbishop of Canterbury, in the second half of the fifteenth century. The house passed to the Sackville family that has lived there since 1603. In the twentieth century, writer Vita Sackville-West lived there with Virginia Woolf, who represented both Vita and the house in the novel *Orlando: A Biography* (Woolf, 1928). Sackville-West wrote an elegant desiption of the property in *Knole and the Sackvilles* (Sackville-West, 1922) which provides a picture of the house almost a century ago. Since 1946 Knole has been owned by the National Trust and a significant proportion is open to the public. Items on display include three state beds, outstanding tapestries and textiles and an art collection that includes a copy from 1624 of the Raphael Cartoons, displayed in the Cartoon Gallery. This gallery at Knole is a key location for our modelling work. Parts of the house are heated and serve as a private residence, so these would represent a warmer habitat for insects.

Insect behaviour

Insects can pose a substantial threat to historic interiors. These include clothes moths, carpet beetles, the furniture beetle, and the death-watch beetle (both woodborers), silverfish, and more recently the brown carpet beetle (*Attagenus smirnovi*), more commonly referred to as the vodka beetle, (Pinniger, 2001; Xavier-Rowe & Lauder, 2011). At Knole there is both historic and modern evidence of insect attack as seen in the small holes in items of old furniture within the house. Vita Sackville-West writes of the galleries in the early twentieth century:

> There are other galleries, older and more austere….They have the old, musty smell – a mixture of woodwork, pot-pourri, leather, tapestry, and the little camphor bags which keep away the moth; the smell engendered by the shut windows of winter and the open windows of summer…
>
> Vita Sackville-West, 1922

This attests to a long history of insect pests. Even today evidence remains at Knole of the bags (Fig. 1) of natural insect repellents: 'by chance we were in the attics yesterday and spotted a small bag of it lying on the floor' (Barratt, 2012). Sadly, there are few records of the insect populations at the point that the National Trust took responsibility for the historic galleries within the house. James Lee-Milne, the architectural writer, as secretary of the Country House Committee of the National Trust, looked closely at the house. He knew the house well (his wife Alvilde had an affair with Vita Sackville-West) and described the great piles of dust that were found throughout the galleries, the result of wood boring insects (Sackville-West, 1998). When the Trust took on a management role in 1946 this problem may have been exacerbated by the war years as the house was closed to visitors because of a lack of staff (NT, 1977), following which the gesso furniture, picture labels, silver furniture, and window mullions needed attention (Sackville-West, 1998). There are few older documents available at Knole to help correlate observed damage

Figure 1 **Small bag of natural insecticide recently discovered in the attics at Knole (photograph courtesy of The National Trust).**

with the interior environment. Modern conservation records exist, from the 1990s onwards, but there is little useful information in these with respect to insect damage. There are a few hints of longer-term insect activity. Recently, a gilt table and a pair of candle stands, given by Louis XIV to the Sixth Earl around 1670–1671 (Sackville-West, 1998) were loaned to the Victoria and Albert Museum (Barratt, 2012). While in store there, increases in temperature meant that furniture beetles, dormant in the object in the colder storerooms of Knole, became active (see Fig. 2). This shows the possible impact of climate change on future insect activity at Knole, but fortunately once the items were returned to Knole, insect activity ceased.

It has been argued that damage from mould growth (Lankester & Brimblecombe, 2012a) and pests (Stengaard Hansen *et al.*, 2012) is likely to increase in the future because of changes to the indoor climate in historic houses without active climate control. Stengaard Hansen *et al.* (2012) recently calculated days-over-20°C in Scandinavian museums to predict the impact of climate change on the activity of the vodka beetle. Insects are affected by both temperature and relative humidity and the response varies from species to species. In agriculture, the potential for infestation by pests frequently uses the notion of accumulated warmth over time, which can be expressed in terms of the degree-days concept (e.g. Prasada Rao, 2008). Low temperatures can reduce insect movement, while higher temperatures are important in terms of insect development, feeding, egg-laying, and mobility. Low relative humidity can lead to desiccation, although some insects have developed mechanisms for coping with this; the webbing clothes moth can survive dry conditions by metabolizing food to provide water (Child, 2007; Cox & Pinniger, 2007; Plarre & Kruger-Carstensen, 2011).

Figure 2 Modern evidence of damage to the gilt table from wood boring insect pests (photograph courtesy of The National Trust).

Establishing indoor climate

The thermohygrometric conditions within the interior of Knole have been regularly monitored since 2000. However, such records cover a short timespan in comparison with the long history of the house and cannot tell us of the likely future climate. Recently, Lankester & Brimblecombe (2012a, 2012b) have used a simple transfer function to estimate from external conditions the indoor thermohygrometric environment of two galleries at Knole (the Cartoon and Leicester Galleries). The process (covered in detail in Lankester & Brimblecombe, 2012a, 2012b) correlated daily indoor temperature and relative humidity with that of a nearby weather station using a simple regression equation and establishes different coefficients for each month to allow for seasonal climate and changing patterns of room use. The transfer function adopted from the regression analysis can explain more than 90% of the variance and gives indoor predictions that show satisfying agreement with probable error at the 95% confidence interval of just under ±2°C (Lankester & Brimblecombe, 2012a).

Daily temperature observations are available for central England from the late eighteenth century as the central England temperature record, HadCET (Parker *et al.*, 1992). These can also be used, with the appropriate coefficients in the transfer function to predict indoor conditions for the Cartoon Gallery. Tuning this transfer function with modelled high-resolution climate predictions, using nearby Gatwick as a site (as discussed in Lankester & Brimblecombe, 2012a), allows future indoor climate to be predicted. Our work has used output from the Hadley Model HadCM3 (Johns *et al.*, 2003) as expressed by the UKCP09 weather generator (Jones *et al.*, 2009) which can provide estimates of future daily climate, at 5 km × 5 km resolution. Different emission scenarios adopted within climate models make little difference to predictions of indoor climate for the near future, although beyond 2040 the highest predicted temperature is associated with scenario A1F1 (Lankester & Brimblecombe, 2012a). We adopt the scenario A1F1 in this work as it gives the largest changes and thus represents a type of worst case. The UKCP09 weather generator provides maximum and minimum temperatures and relative humidity on a daily basis for 30-year periods and output is available for 100 different evaluations, essentially providing 3000 estimates of the daily weather conditions in each period. These 30-year periods centre on 2025, 2035, 2045, 2055, 2065, 2075, and 2085 in addition to a baseline period centred on 1975. Daily average temperatures were calculated, as usual, by taking the mean of the maximum and minimum temperature each day.

Results

Previous calculations (Lankester & Brimblecombe, 2012a) suggest that indoor temperature is likely to increase in the Cartoon Gallery in the future. Fig. 3 shows a 300-year estimate for the median annual temperature and shorter span for relative humidity in the Cartoon Gallery. The HadCET data are for slightly overlapping 11-year periods centered at 1785, 1795…through to 2005. The UKCP09 derivations are for 30-year periods centered at various times from 1975 to 2085 with 100 values calculated for each year. The dispersion in the values is displayed as an error bar indicating the lower and upper quartiles. Medians and quartiles have been adopted in preference to means and standard deviation as they are more robust when the data are not normally distributed. The statistical dispersion is displayed as such error bars in the figures, but the reader needs to be cautious and regard this as accounting for the mathematical uncertainty that arises from multiple runs with the climate data and not representing error that might arise in the estimate of insect growth parameters. There are few measurements of the growth rates of individual insect species so it is not possible to estimate the error. This means that it is best to think of the results shown in the figures as illustrating relative rather than absolute change.

In the gallery the historic indoor temperatures have been about 12.5°C, which is about two degrees higher than outdoors. This is commonly found even in unheated rooms, much of which is probably the result of solar gain by the building. There is a satisfying overlap between the values derived from the HadCET which is essentially measured and those from the UKCP09 output. Relative humidity is predicted to remain largely unaltered (note the scale which shows spans of just a few percent), but Lankester & Brimblecombe (2012a) show that there will be changes in seasonal variation with slightly higher future values in winter and rather lower values in the summer months.

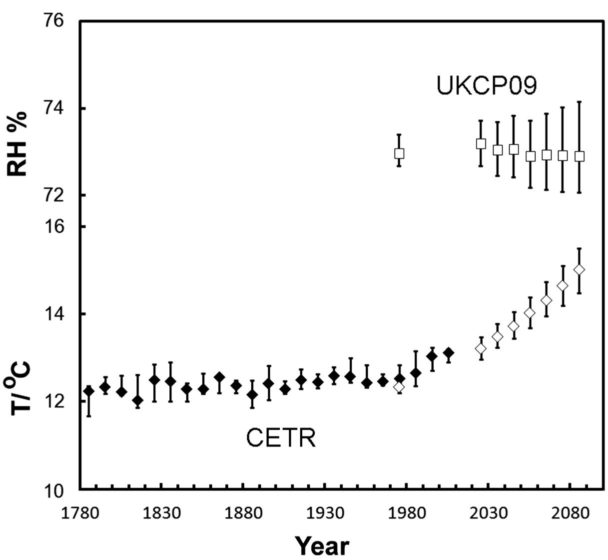

Figure 3 Median annual temperature (diamonds) and relative humidity (squares) in the Cartoon Gallery derived from the HadCET (closed diamonds) and UKCP09 (open symbols). The error bars show the upper and lower quartiles.

Insects require warmer conditions to become active, so below 10°C movement virtually ceases, while pesticides are ineffective at low temperatures (Child, 2007). The number of days with low temperatures are shown in Fig. 4A. Thus, the days of sluggish behaviour are displayed for both external conditions and in the Cartoon Gallery. The calculations used the historical values of temperature HadCET and UKCP09 and again are displayed as the median values and quartiles using the ranges and number of values in the same way as Fig. 3. The Cartoon Gallery is buffered against the outdoor cold, even though it is unheated, so experiences substantially fewer cold days than occur outdoors. The historical record shows some hint of a slight decrease in the number of cooler days, externally in particular, from the mid-twentieth century, with a much more pronounced decrease through the present century.

The reverse situation is shown in terms of heat. Fig. 4B displays the annual degree-days as a representation of accumulated warmth from 1780 to the end of

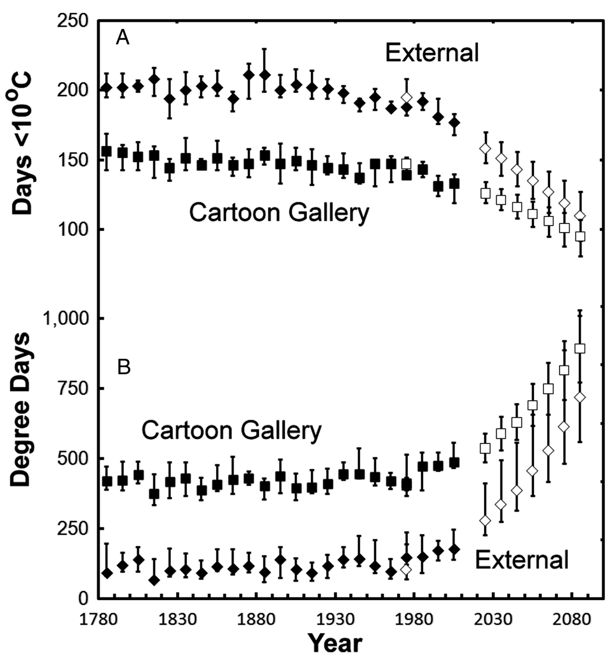

Figure 4 (A) Median number of days each year when the average temperature is less than 10°C, both externally (diamonds) and within the Cartoon Gallery (squares) derived from the HadCET (closed symbols) and UKCP09 (open symbols). The error bars show the upper and lower quartiles. (B) Median annual growing degree days, with a threshold of 15°C, both externally (diamonds) and within the Cartoon Gallery (squares) derived from the HadCET (closed symbols) and UKCP09 (open symbols). The error bars show the upper and lower quartiles.

the twentieth century. This degree-day concept is widely used in agriculture to estimate the development of insect pests where they can be referred to as growing degree-days (GDD). The concept considers that insect growth will depend on the number of heat units received. These units are calculated by summing the number of degrees each above a certain temperature threshold for the period of interest. There are extensive tables of the number of GDD required for many insects, although these are largely for pests of agricultural interest (e.g. CCE, 2010). We have attempted to apply the concept of GDD in a general way to Knole, by determining the number of degree-days over a threshold of 15°C that accumulate over a calendar year, so it is these that are displayed for both external conditions and in the Cartoon Gallery in Fig. 4B. We choose 15°C as it is the lowest temperature at which there is insect activity because below this temperature movement is sluggish (Pinniger, 2001; Child, 2007).

The historical record shows a relatively constant value of 115 degree-days outdoors. Only in the late twentieth century does this appear to change, but subsequently it climbs through the twenty-first century to more than six times this value, a very substantial although hardly unexpected change, given the increasing number of hot days. Within the Cartoon Gallery there is a similar picture of change through the present century, although the cumulative warmth in terms of insect growth only doubles. This means that the GDD indoors and out converges over the century. Warmer conditions indoors, even in the unheated room, indicate a potentially favourable environment for insect development, although this might not necessarily lead to a six-fold increase in infestation indoors as issues such as habitat or food availability would likely intervene.

The GDD approach neglects humidity and this can be important as very low humidity can harm insects as they lose water despite their waxy external cuticle. Dehydration can be particularly significant through respiration and defecation. The eggs and young larvae are especially sensitive. In the case of the furniture beetle (*Anobium punctatum*) they require the relative humidity to be about 65% or above (Child, 2007).

Measurements of the development time of male *Stegobium paniceum* (the bread or biscuit beetle) are available over a range of temperature and relative humidity from Lefkovitch (1967). Such measurements allow us to estimate the time it would take for the male insects to develop in any given year. Under warmer conditions it is possible for growth to occur quite rapidly perhaps in just a couple of months, so by the end of the twenty-first century it would be theoretically possible, though perhaps entomologically unlikely, to have almost two growth cycles in a year (see Fig. 5). The idea of the number of growth cycles is used here as a way of illustrating the increasing rate of insect development as warmer conditions emerge through the twenty-first century. As with the changes in GDD the indoor and outdoor estimates converge as the century passes.

The method used to estimate the number of growth cycles is worth exploring further because it reveals some interesting features of the two approaches to estimating insect growth. Measurements from Lefkovitch (1967) were used to construct a trend surface (classically as in Unwin, 1975) by least-squares regression using the online software at *Online Curve Fitting and Surface Fitting* website (ZunZun.com). The cubic surface which describes the development time in days could be expressed by the equation:

$$z = a + bx + cy + dx^2 + fy^2 + gx^3 + hy^3 + ixy + jx^2y + kxy^2$$

where z is the development time in days, x is the daily temperature (°C), and y is percentage of relative humidity. The constants a–k, obtained from a least squares fit, are given in Table 1. The trend surface was a non-linear two-dimensional fit to the data that would conveniently represent the variation for daily growth. The growth isopleths for *S. paniceum* which correspond to this trend surface are shown in the inset within Fig. 5. The fit to the trend surface was weighted so that it agreed best at conditions where growth was rapid. Except in the warmer months,

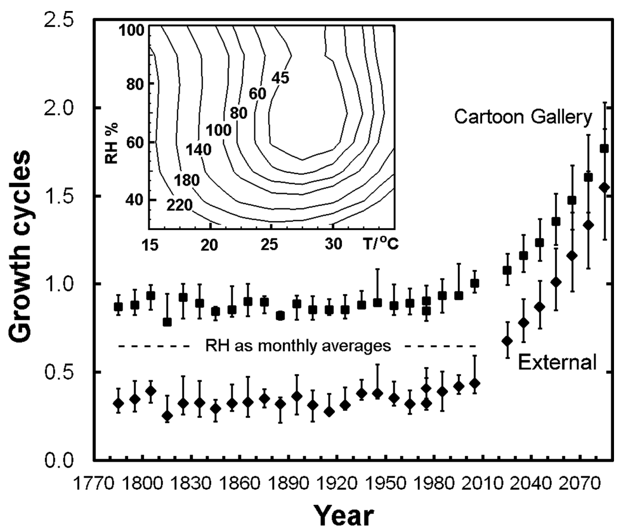

Figure 5 Median number of potential growth cycles each year for male *S. paniceum* externally (diamonds) and within the Cartoon Gallery (squares). Data for the period 1795–2005 derived from the HadCET used estimated monthly average relative humidity. Inset: cubic trend surface for the development time of male *S. paniceum* in days adopted to predict the annual medians.

Table 1 Constants *a–k* obtained from a weighted least squares fit to a cubic polynomial surface. It was weighted in terms of the reciprocal of the days required for development

$a = 8.2346450E + 02$
$b = 9.8308568E + 00$
$c = -1.6689165E + 01$
$d = -1.4082108E + 00$
$f = 2.9694187E - 01$
$g = 4.0364162E - 02$
$h = -1.7565039E - 03$
$i = -4.9109698E - 01$
$j = -3.7164286E - 03$
$k = 4.5684251E - 03$

daily temperatures would lie beyond the left axis of the inset of Fig. 5, but this is to be expected as insect growth becomes important only when the temperatures are above 15°C.

The number of growth cycles for a year was then calculated by taking the daily mean temperature and relative humidity and determining the development time for that day, and from this the fraction of development which would occur. At no point in the calculation was the incremental growth time allowed to be shorter than an effective 40 days. These small amounts of development were summed for each day of the year to give the growth cycles plotted in Fig. 5.

It was not possible to calculate the growth cycles from the HadCET because this has temperature alone and does not give daily values for relative humidity. However, as the inset to Fig. 5 shows, at ambient temperatures typical at Knole (15–25°C) the isolines are almost vertical, except at the relative humidity values less than 60%. This suggests that the growth rate for *S. paniceum* is not especially sensitive to humidity (Rumball & Pinniger, 2003), so it would be reasonable to take the average monthly relative humidity for the current period and use that each day to determine the values for the decades that stretch from 1785 to 2005. Although for much of the twentieth century observed daily values would be available from nearby sites, these have not been used in order to retain a consistent methodology across the period.

The low sensitivity of the growth rate of *S. paniceum* to relative humidity also suggests why the GDD concept has been so widely adopted as an approach to predict the threat from pests to agriculture. Fig. 6 shows the relationship between GDD and the growth rate of *S. paniceum* as lifecycle number in the ambient air for the 30-year period centred on 1975. A least-squares regression suggests a reasonable linear fit as:

$$N_{\mathrm{GC}} = 0.0015T_{\mathrm{GDD}} + 0.272$$

where N_{GC} is the number of growth cycles each year and $0.0015T_{\mathrm{GDD}}$ is the cumulative temperature as degree-days from a baseline of 15°C. The best-fit line has a correlation coefficient, r^2, of 0.84, which reflects a reasonable agreement. However, it is important to note that the intercept is not especially close to zero, which hints that although this agreement seems to work well in contemporary south-east England it may not be especially robust. As an example the graphical data of Lefkovitch (1967) indicate that for *S. paniceum* one life cycle is the equivalent of 490 degree-days.

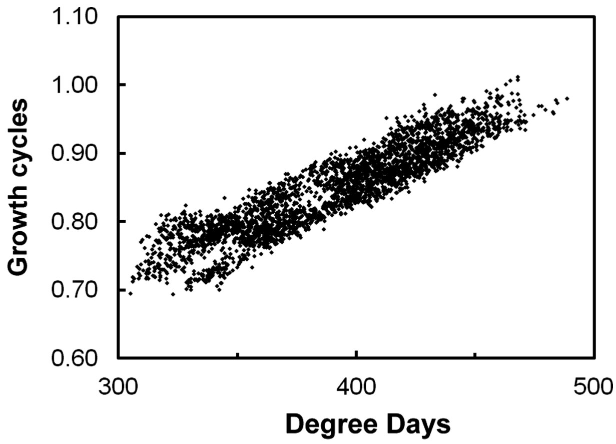

Figure 6 The relationship between annual growing degree-days, with a threshold of 15°C, and the growth rate of *S. paniceum* as lifecycle number for external conditions. The points show 3000 estimates derived from the UKCP09 output for a 30-year period centred on 1975.

So far this analysis has used average daily values. The HadCET has both maximum and minimum values extending back to the late nineteenth century and the output of UKCP09 contains both maximum and minimum values for each day. The maximum temperature has been used to assess whether insects might fly or disperse, because this tends to require quite warm conditions. The furniture beetle (*A. punctatum*), for example, does not readily fly at temperatures below 25°C (Child, 2007). However, a temperature of 20°C has also been suggested (White & Birch, 1988). The actual temperature has little impact; it is the general principle that is important. Additionally, a temperature of 25°C is said to lead to rapid development of insects (Pinniger, 2001). We have determined the average number of these *flying days* (>25°C) each month where the maximum temperature was likely to exceed this value for four 30-year periods centred on 1895, 1975, 2025, and 2085. These are shown in the bar chart in Fig. 7. As might be expected, the number of days experiencing such high temperatures increases substantially over the coming century. Furthermore, the peak of these days where the furniture beetle is likely to fly shifts slightly earlier in the year, reaching a peak of almost 24 days in the month of July at the end of the current century. This occurs because July tends to be

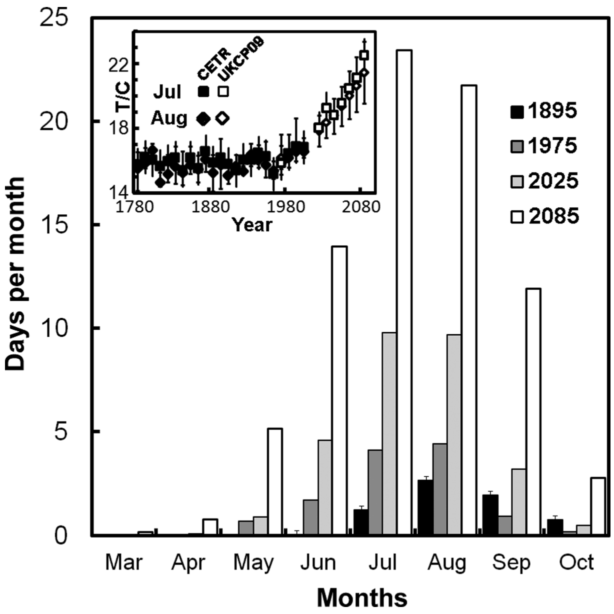

Figure 7 The number of days each month where the maximum temperature externally exceeded 25°C such that the furniture beetle would be likely to fly. These are shown for the 30-year periods centred on 1895, 1975, 2025, and 2085. Inset: median annual July (squares) and August (diamonds) external temperatures derived from the HadCET (closed symbols) and UKCP09 (open symbols). The error bars (uncapped for July, capped for August) show the upper and lower quartiles.

substantially warmer than August by the end of the twenty-first century as shown in the inset to Fig. 7. We should also note that the high-temperature days are spread more widely through the year and increases such that 'shoulder months' previously considered of little importance can now be periods of insect activity.

These predictions relate to outdoor conditions because the maximum temperature indoors was not easy to calculate because of the likely thermal buffering and slow air exchange in the Cartoon Gallery. The bar chart shows averages of the numbers of days because expressed as a median can often mean that they get lost as zero. Furthermore, it was not obvious how to express statistical dispersion in this data set, but on the assumption that the *flying days* took a Poisson distribution gave error bars small enough to be almost invisible when plotted on the bar chart.

The webbing clothes moth (*Tineola bisselliella*) has been prevalent at Knole for a long time as noted earlier in the quotation from Vita Sackville-West (1922). It is also frequently found in insect traps at the property today (Barratt, 2012). These moths can be especially damaging as they are often concealed, and infestations on textiles and upholstery can remain unnoticed until the damage is very apparent. The eggs are attached to threads of fabric and the larvae spin webbing as they feed. The excrement of the clothes moth may be the same colour as dyed cloth fibres that have been a food source (CCE, 2010). In general, the webbing clothes moth has been a problem for thousands of years, and is currently the most important and widespread clothes moth throughout the world (Cox & Pinniger, 2007).

The number of eggs laid by clothes moths depends on temperature, 80 at 25°C, but perhaps 100 at 30°C. These are laid over two to three weeks, with few eggs laid at 15°C and none by the time temperatures reach 10°C (Child, 2007; Cox & Pinniger, 2007). The potential for future egg production has been estimated using a simple model as shown in Fig. 8, which suggests that this might increase threefold in the Cartoon Gallery by the end of the present century. Unfortunately, a realistic model would require a detailed analysis of the moth's life-cycle, but to gain a preliminary idea of the likely change we determined the likely production of eggs from females in a given month, according to the temperature and then summed over the year. This does not account for multiple life cycles each year, which are increasingly common (Child, 2007; Pinniger, 2011). The calculation proceeded by estimating the number of eggs laid (E) as a function of monthly temperature °C (T_m) described by the equation:

$$E = \text{int}(130\ \exp(-((T_m^2/30 - 30)/12)^2))$$

This was simply a convenient representation of the egg production that suggests three eggs at 15°C, 18 at 20°C, 34 at 22°C, 57 at 24°C, and 88 at 26°C, although it has no biological reality. At the end of the century there is considerable variance in the data, because of some hot months where there is the potential for a large number of eggs to be laid.

The results here illustrate that there are two different factors affecting the life cycle of insect pests: the development time and egg production. These factors are

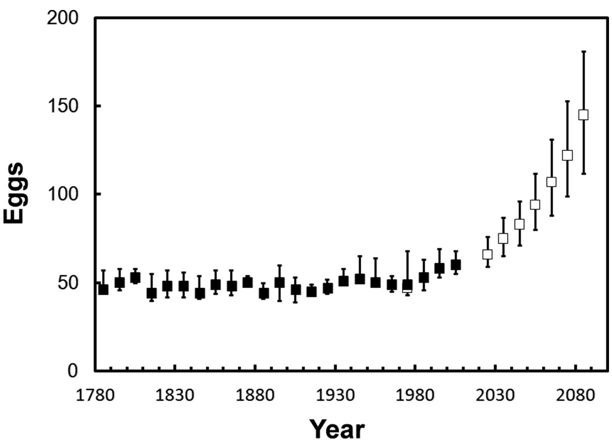

Figure 8 Median annual egg-yield estimated for the Cartoon Gallery with temperatures derived from the HadCET (closed squares) and UKCP09 (open squares). The error bars show the upper and lower quartiles.

likely to change in the future with each leading to an increased pest population. Essentially, these two factors can compound the problem, with potentially more lifecycles per year and each with increased numbers of eggs. In the absence of effective integrated pest management (IPM) this would lead to larger populations and thus greater damage to historic collections.

Discussion

The webbing moth has long been a problem in historic houses. Lady Evelyn Cavendish (c. 1945) wrote in her notes on the long prior experience of housekeeping at Hardwick that she was in favour of cedar dust, apple, and lavender, believing wisely that DDT had not stood the test of time. At Knole, Vita Sackville-West (1922) describes how '… lavender and dried rose-leaves stand on the window-sills ….'. The pot-pourri at Knole was always made from a recipe that derived from Lady 'Betty' Germaine who lived at Knole for many years in the eighteenth century. Her recipe survives, and includes: double violets, rose leaves, lavender, myrtle flowers, verbena, bay leaves, rosemary, balm, musk, and geranium in addition to cinnamon, mace, nutmeg, pepper, lemon peel, and other ingredients (Jekyll, 1900). Lavender oil is effective at repelling moths (Landolt *et al.*, 1999) including clothes moths (Plarre *et al.*, 1997) because of the presence of linalool, or 2,6-dimethyl-2,7-octadien-6-ol (Moon *et al.*, 2006).

In recent years there has been a spectacular increase in the presence of webbing clothes moths in museums and historic properties in England (e.g. Pinniger, 2011; Xavier-Rowe & Lauder, 2011). In 2001, clothes moths were absent or found in very small numbers in most of the major museums in London, and at historic houses managed by English Heritage (Lauder D, personal comunications). It is hard to explain this increase in webbing clothes moths, but Pinniger (2011) suggests a range of reasons including warmer winters, more widespread use of natural fibres (including wool insulation material), and loss of potent insecticides such as DDVP/dichlorvos/Vapona. However, he believes it likely that we are witnessing that the species has the ability to live in and exploit organic debris in dead spaces and voids of buildings. Modern integrated pest management approaches stress the importance of building maintenance. Moths inhabit debris-laden voids, with adult moths, which originate from populations living behind displays and under floorboards, free to fly around and put collections at risk. Moth catches in voids are at their highest in the summer months (e.g. Higgs & Bridal, 2011) and there may be up to three cycles a year; at Knole, the furniture beetle, absent in recent decades, is now increasingly found (Barratt, 2012).

This work follows that of Stengaard Hansen *et al.* (2012) in recognizing that the outdoor climate is not the only variable controlling the prevalence of insects such as *A. smirnovii* (brown carpet beetle). These beetles are found more widely distributed in museum interiors than would be expected on the basis of the outdoor climate. They are likely to be spread among heritage environments, benefiting from favourable niches indoors, which could well be more prevalent in the future. In the present work we have been able to explore the long-term indoor climate at a specific location and demonstrate that conditions can indeed become more favourable over the coming century. Although the calculations here were restricted to a single unheated room there is evidence that such conditions are not atypical (e.g. Lankester & Brimblecombe, 2012b).

Conservation heating is used in historic properties primarily to reduce relative humidity rather than heating the interior. At Knole conservation heating is being trialled in one room, with the view to extend its use throughout the areas directly managed by the National Trust. If this policy were adopted in the future, when more humid winters are predicted (Lankester & Brimblecombe, 2012a), the temperature would rise, more than that predicted here. In turn, this could potentially increase the rate of damage caused by insect pests during the winter months. Previous work (Lankester & Brimblecombe, 2012a) indicates that in the Cartoon Gallery, in the future September and October will be warmer. Relative humidity increase is predicted to start in October, so the application of conservation heating would increase the number of degree days further during October and November. Effective IPM, as currently practised by the National Trust and other organisations, such as English Heritage and Historic Royal Palaces, should help prevent any future insect damage and inform decisions about the sustainable management of collections.

Conclusion

The increasing warmth expected for the climate of central England through the current century is likely to be propagated indoors and make interiors more favourable to insect pests. Despite the fact that the temperature increases are relatively modest (just a few degrees) the changes have the potential to alter insect lifecycles and numbers. There may be increases in number of eggs, insect growth rate, and days of flying (that could enhance dispersal). Indoor changes in relative humidity seem to have a less dramatic impact as these are small and the insects examined here not very sensitive to relative humidity. This is partly because, in the Cartoon Gallery, the relative humidity is almost unchanged over time when expressed as an annual median. However, additionally the growth of webbing clothes moths is not especially sensitive to humidity, although the survival of eggs may be more susceptible.

The enhanced availability of suitable habitats in historic houses means that greater insect activity is already evident. The webbing clothes moth, long a problem, seems to be one of the insect pests increasingly found. In addition to the rising numbers and activity, insects appear active through more of the months each year, especially if conservation heating was to be applied in the autumn. The widening threat posed by insects makes robust integrated pest management of continued relevance to historic properties. Such programmes may require increased resources in the future, especially in buildings which are vulnerable to a changing climate, such as historic houses, where climate control can be difficult.

If we are to understand how to estimate future insect populations in historic houses, further research will need to take a more robust approach to modelling the entire lifecycle and incorporate factors such as food and available habitats. This work is currently underway and is developing a model that accounts for each stage in the insect lifecycle and lays this out in terms of environmental parameters. The model will also need to incorporate issues of food availability and the size of the ecological niche provided by places such as under-floor voids, within historic properties. It will also require more detailed quantitative data on the lifecycle of relevant species, such as the webbing clothes moth and the brown carpet beetle. There is a further need to validate such models against the environmental conditions within historic houses and the numbers and types of insects trapped, so we have started to collect detailed records from a number of historic properties.

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