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Effect of Indoor Climate and Habitat Change on Museum Insects during COVID-19 Closures

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Abstract: COVID-19 spread globally and, as there was little immunity, quarantine, isolation, and social distancing became widely practiced. As people were restricted to their homes in many countries, public venues, such as museums, galleries, and historic houses, were typically closed. This allowed insect abundance, under changed conditions, to be explored using traps from the Technical Museum, Schönbrunn Palace, Hofburg Museum, and Weltmuseum in Vienna. The trap contents reveal an increase in *Lepisma saccharinum*, the common silverfish, as well as in the Zygentoma *Ctenolepisma longicaudatum* and *C. calvum* at some museums. Other insects such as *Tineola bisselliella*, *Anthrenus verbasci*, and *Attagenus smirnovi*, though found in reasonable numbers, did not increase. Museum interiors were likely a little cooler and drier during lockdown, but this difference is too small to explain the increased silverfish activity. The larger rooms were certainly quieter, which allowed insects freedom to range more widely. Nevertheless, museums did not observe increased damage to collections from the larger numbers. The infestations during the closures suggest a need for low level cleaning and regular inspections, with an initial focus examining those areas frequented by insects in the past.

Keywords: silverfish; Technisches Museum Wien; Schönbrunn Palace; Hofburg Museum; Weltmuseum Wien; pheromone traps; blunder traps

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1. Introduction

Climate affects the life-cycles, habitats, and distribution of insects [1]. They represent a threat to heritage as they may be pests, attacking paper, furniture, or textiles, which form part of heritage collections [2], but can also cause major damage to structural elements of wooden buildings, e.g., [3]. Insects thus become relevant to the management of museums and historic buildings [4]. Relevant to heritage is the widening distribution of the brown carpet or vodka beetle (*Attagenus smirnovi*) [5]. Insects are sensitive to the effects of climate throughout their life cycles. Importantly, a warming world may enhance their activity as they can be sluggish at lower temperatures (<15 °C), so there is some interest in the way that a changed climate will alter their presence in the heritage environment [6]. Large surveys of historic properties show changes in insect populations are apparent, though not necessarily driven by climate [7]. Additionally, it is possible to find a relationship between outdoor temperatures and the catch of wooly bears (larval form of the carpet beetles, *Anthrenus* spp.) in historic properties in London, though many other factors will change insect populations in the heritage environment, such as food and habitat availability [8]. In particular, this work noted that, when trying to assess the impact of climate change on insect populations in the historic environment, there may be additional drivers, stating that, "Staffing levels, visitor numbers, the introduction of food and availability of habitat, such as dark undisturbed spaces and loans between collections may be important factors to investigate further". COVID-19 closures provided an opportunity for such investigations, as the restrictions imposed on museums allowed an assessment of the balance between climate and other factors potentially able to affect insect populations in museums.

In 2020, COVID-19 spread globally and, as a new disease, little immunity meant few effective treatments, so quarantine, isolation, and social distancing became widely practiced. As people were restricted to their homes in many countries, there was less use of the workplace and public venues. Museums, galleries, and historic houses were typically closed [9]. The lack of visitors imposed financial hardship on the heritage sector [10], while staff absence also meant a reduction in the care and maintenance of the collections, rooms, and buildings as a whole. In some cases, the period provided an opportunity for extra maintenance, renovation, and site investigations [11], but it is likely that a lack of the presence of conservators in many institutions created the potential for damage to proceed unobserved [12]. While museums were closed, some factors could have reduced insect numbers: loans of materials between collections were likely reduced and closure of museum cafes may have limited food availability. However, lowered levels of human activity, reduced noise, and a minimum of cleaning could mean that insects were able to range more widely in quiet and undisturbed environments, especially insects such as silverfish, which tend to thrive in unoccupied spaces [13].

Such novel environmental changes can provide an increased potential for insect infestations in museums, and thus need to be considered within integrated pest management (IPM). Since the 1980s, IPM has represented an important part of pest management within museums and historic houses. While minimising the use of pesticides and harsh remedies, it employs improved seals to buildings, regulating the indoor climate, periodic cleaning, quarantine of incoming material, and regular insect monitoring. The current study examines some insects (mostly the common silverfish, *Lepisma saccharinum*) caught on insect traps in some Viennese museums, with a special focus on the period during which they were closed because of COVID-19 restrictions. Silverfish are pests in heritage environments because they can cause extensive damage to organic materials (Figure 1). This work builds on an earlier study of the Zygentoma, an order of Insecta that includes silverfish and firebrats [13], and compares silverfish with other insects.

Figure 1. Typical example of damage by silverfish, where they have eaten curved patterns into bindings. Photograph by P.Q.

2. Materials and Methods

2.1. Insects

This study especially focusses on the common silverfish, but will compare it to other museum insect pests commonly found in Austria. The insects of particular relevance to this study are as follows:

- *Lepisma saccharinum*—common silverfish. This is a frequent pest in museums and an important indicator of high relative humidity. Normally, only low numbers are captured, but in basements, bathrooms, or kitchens, higher numbers can be found, indicating higher moisture on the floor, often from wet cleaning, condensation, or leaky water pipes.
- *Ctenolepisma longicaudatum*—gray or long-tailed silverfish. It is increasingly abundant in Austrian museums, with high numbers present per room or trap, even at a lower humidity than that preferred by the common silverfish. Nymphs need high humidity, but adolescents and adults can wander long distances and access new areas with favorable microclimates. Females lay up to 80 eggs per year and can live for 6–7 years (maturity ~2 years), so the population increases exponentially 3–4 years after new infestations have occurred.
- *Ctenolepisma calvum*—ghost silverfish. Little is known about the biology of this introduced pest, but it also prefers higher temperatures and humidity for survival and reproduction; it is probably similar to the grey silverfish.
- *Ctenolepisma lineatum*—four-lined silverfish. Little is known about the biology of this introduced pest, which is now spreading in Austrian museums. Unlike the other two species of *Ctenolepisma*, it can also live outside, so wider distribution and further infestation from outdoors is possible.
- *Tineola bisselliella*—webbing clothes moth. One of the most abundant and common pests, and a serious problem in historic properties and museums throughout Europe. The larvae attack fur, feathers, and woolen textiles, but can also survive on detritus (dust) and dead animals.
- *Anthrenus verbasci*—varied carpet beetle. Larvae feed on keratin and chitin and, while inside buildings, feed mainly on dead insects such as flies and spiders. Dust from natural fibers (fur, feathers, and woolen textiles) is also a potential food source. It is very common in Austrian museums, but usually present only in low numbers.
- *Attagenus smirnovi*—brown carpet beetle or vodka beetle. Larvae feed on keratin and chitin; while inside buildings, they feed mainly on dead insects. Natural fibers (fur, feathers, and woolen textiles) are also a potential food source. Common in Austrian museums, sometimes, populations live below historic wooden floors, where dust has accumulated over centuries.
- *Stegobium paniceum*—bread or biscuit beetle. A common food pest that can also attack a variety of museum objects, especially those made with starch glue: old books in historic libraries, paintings, and modern art objects.
- *Ptinus fur*—whitemarked spider beetle of family Ptinidae. However, some other species of spider beetles were also found (*Gibbium psylloides*) and counted separately. They usually live below historic wooden floors, where they feed on straw that was used for insulation under floorboards.

More details about Zygentoma in museums can be found in Brimblecombe and Querner [13]. The studies presented here did not involve endangered or protected species, and thus required no ethical approval; additionally, animal welfare regulations typically exclude insects and most small invertebrates.

2.2. Sites

The trapping that formed the basis of this study is undertaken as part of IPM; it allows the extent of the insect problem to be assessed and reveals the presence of infested objects. The museums were selected for the current analysis as there were hints of a higher number of silverfish on individual traps during the months of COVID-19 lockdown (Figure 2). Traps examined come from the following museums:

- Technisches Museum Wien is in a building that was specially constructed in 1909 and has become a technical museum with a diverse collection from science, communication, and industry, with specific displays representing nature, heavy industry, energy, and musical instruments.
- Schönbrunn Palace was once the main summer residence of the Habsburg rulers. Areas sampled in this study include the childrens' museum, the Crown Prince's Room, Berglzimmer, and the Weißgoldzimmer.
- Hofburg Museum has insect traps in the Silberkammer, an exhibition area of Hofburg palace, which houses the Imperial Silver Collection.
- Weltmuseum Wien houses a substantial ethnographic collection expressing the cultural diversity of humanity. There are 14 display rooms and more than three thousand objects.

Figure 2. Heavily laden trap with a large number of silverfish caught during the museum closures. Photograph by P.Q.

2.3. Traps

The insects were collected in traps, set out at ground floor locations in the early part of the year, usually in February (Weltmuseum) or March, and were examined five to six times each year through to October, when the traps were renewed and left unchecked over the winter. Both sticky blunder and pheromone traps [14–16] were used at the sites, and cover a period starting, in many cases, from 2015. Once retrieved, the insects could later be identified and counted on the traps (Figure 2). The catch rate of insects in pheromone traps is, as would be expected, higher than that in blunder traps at most sites [13].

2.4. Climate and Mobility Data

Daily values for ambient temperature and relative humidity are available from the airport in Vienna at Fischamend on the Danube to the south east of Vienna. These were from https://www.wunderground.com/history/monthly/at/fischamend, accessed on 15 August 2021.

2.5. Statistical Analysis

Insect traps necessarily catch an integer number of animals and, frequently, traps have no silverfish at all, so care over the non-parametric nature of observations becomes very important in the statistical analysis of the catch [17]. Mean values were compared using both the *t*-test and its non-parametric equivalent, the Mann–Whitney test (http://www.vassarstats.net/, accessed on 21 August 2021). Grubb's test, which is convenient for finding a single outlier, used the online calculator at *GraphPad* (www.graphpad.com/quickcalcs/Grubbs1.cfm, accessed on 21 August 2021). Catch rate is a common measure in insect studies, though the rate may become deflated if large numbers of traps are set out. The Kendall rank correlation coefficient (τ) was used in preference to the common Pearson correlation coefficient (r), as it is likely to be more resistant to bias from the ordinal nature of catch data.

3. Results

The changes in the overall catch of silverfish from three museums are shown in Figure 3a, and reveal the dramatic increase in catch rate while museums were closed in Austria, from 11 March 2020 to 15 May 2020. Collections of insects made in April or May often show the highest numbers of silverfish, and those of 2020 are always higher. The post-lockdown catches are significant outliers for the three museums ($p_2 < 0.01$ using Grubb's test). The Weltmusem showed the same pattern, though it was omitted from the figure as its record did not begin until 2018. The increased insect catch occurred at the same time that the visitor numbers declined, as shown for the Kronprinzenzimmer of Schönbrunn Palace in Figure 3b. The lockdown imposed to reduce the spread of COVID-19 infections caused a dramatic change in visitor numbers, which fell to zero on Thursday, 12 March. There was a modest recovery in the summer of 2020, but tourism, especially international tourism, remained affected by the ongoing pandemic. There were no substantial differences in spring temperature and relative humidity at Vienna airport in 2020, compared with previous years (Figure 3c). The outdoor temperatures into May are generally less than 15 °C, a temperature low enough to discourage insect activity. In this regard, 2020 was not especially warm, and by mid-May, only 18.5 degree-days over 15 °C had accumulated, compared with 2018, a year with much early warmth, when there were 92 degree-days by the middle of May. Thus, the outdoor climate of 2020 was not remarkably warm in Vienna. Nevertheless, there were changes in the indoor climate at the Technisches Museum Wien (Figure 3d,e). Indoors, the temperature—for example, in the Schwerindustrie exhibition room—was cooler across the period of closure in 2020 (22.1 ± 0.10 °C) compared with the same period in the years 2015–2019 (25.0 ± 0.39 °C), and relative humidity was lower (2020: 28.2 ± 0.2%; 2015–2019: 31.3 ± 1.2%). These differences are significant at $p < 0.0001$ from both the *t*-test and the Mann–Whitney test. The humidity in the Schwerindustrie exhibition room is very low, but a dry environment is beneficial for metallic items [18]. Daily cycles of temperature and humidity appeared to have smaller amplitudes during the period the museum was closed.

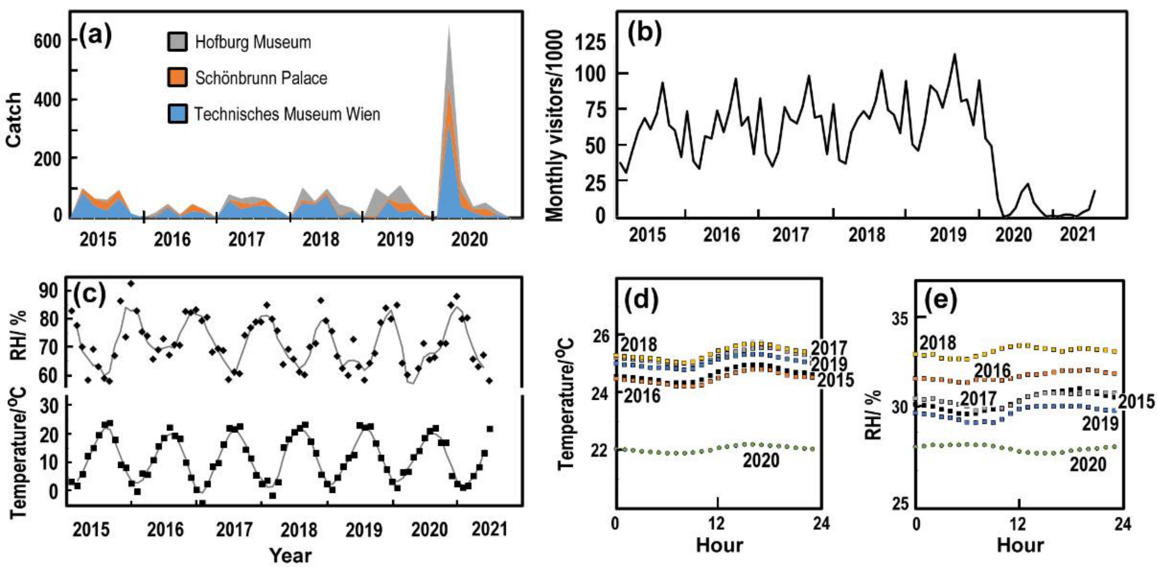

Figure 3. (**a**) Silverfish (*L. saccharinum*) catch from three museums; (**b**) Monthly visitor flow at the Kronprinzenzimmer of Schönbrunn Palace; (**c**) Monthly temperature and relative humidity at Vienna Airport from 2015 to 2020. The curves are three-point running means; (**d**) Diurnal cycle of temperature; (**e**) relative humidity in the Schwerindustrie exhibition room at the Technisches Museum Wien over the closure period of each year from 2015 to 2020.

The overall change in silverfish (*L. saccharinum*) catch is shown in Figure 3, but the numbers conceal the distribution of these changes. Nevertheless, the trapping regimes at the Technisches Museum Wien can be divided into discrete sub-units: Natur, Bewegung, Schwerindustrie, Energie, Musik, and Archiv. At Schönbrunn Palace, the spaces are as follows: Kindermuseum, Berglzimmer, Weißgoldzimmer, and Kronprinzenzimmer. The changes in catch rate in these areas over time are shown in Figure 4a. In the case of the Technisches Museum Wien under closure, the average catch rate for silverfish (i.e., insects/traps) was 2.7, almost all deriving from the Bewegung and Schwerindustrie areas. Both had seen catches of silverfish in previous years, most notably the Schwerindustrie sites, though Musik and Archiv had outbreaks in 2015. However, these were not repeated during the 2015 closures, so the problems in those areas seem to have been eradicated. On the face of it, the increase in *L. saccharinum* (common silverfish) is not as striking as in the Technisches Museum (Figure 4b), but other Zygentoma, *C. longicaudatum* and *C. calvum*, especially the latter, make significant contributions at Schönbrunn Palace (Figure 4c). To some extent, these infestations appear in a number of earlier years, but what is clear under closure is that both *L. saccharinum* and *C. calvum* increase. The Kindermuseum seems to show continued high catch rates across the period including the closures and dominates the catches of both insects.

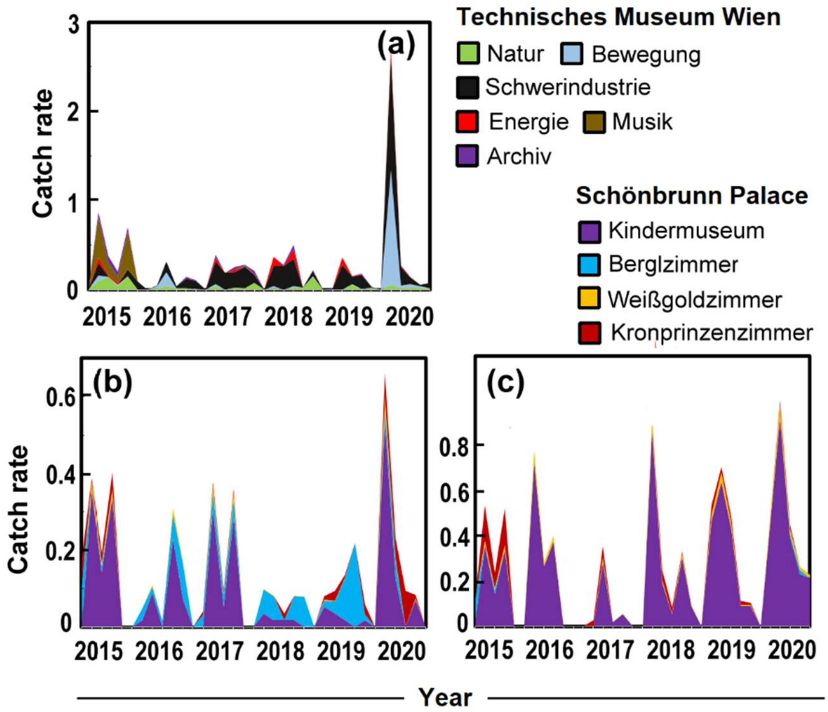

Figure 4. (**a**) Silverfish (*L. saccharinum*) catch from areas of the Technisches Museum Wien and (**b**) Schönbrunn Palace, along with (**c**) *C. calvum* from the Palace.

If the catch is analysed on a trap by trap basis, there is a loose relationship between the total catch of *L. saccharinum* summed from earlier years on a trap and that found immediately after the closures. As many of the traps reveal no catch at all, the Kendall rank correlation coefficient was used: Technisches Museum Wien: $\tau = 0.14$, $p_2 < 0.07$; Schönbrunn Palace: $\tau = 0.35$, $p_2 < 0.001$; Hofburg Museum; $\tau = 0.01$, p_2 ~0.95; and Weltmuseum Wien: $\tau = 0.42$, $p_2 < 0.002$. These correlations suggest that traps that had insects in the past were likely to reveal an elevated catch when the museum was closed. Although the correlation is absent from the analysis of traps at Hofburg Museum, the very highest catches during the closures there typically came from sites that had shown larger catches in earlier years. At Schönbrunn Palace, the Kendall τ correlation was very significant ($\tau = 0.63$, $p_2 < 0.0001$) for the catch of *C. calvum*, which is caught at a high rate in this museum. It should be noted that it is rare for two silverfish species to be found on a single trap, which may suggest that they maintain slightly different ranges.

Some locations in the museums that recorded large numbers of insects are shown in Figure 5, which illustrates that these were in places frequented by the public when the museum was open as normal. These were often in large exhibition rooms and public spaces. At Schönbrunn Palace, silverfish were frequently found beneath the Blue Stairs and in the Audioguide, but, generally, it was the Kindermuseum that revealed high catches, while in the Silberkammer of the Hofburg Museum, catches were also high. High catches were found in areas that would normally be frequented by visitors, so it is of little surprise that, at the Weltmuseum Wien, silverfish were abundant in the vestibule. Areas of museums that had higher abundance in lockdown were often the same areas that revealed the presence of silverfish during more normal times.

Figure 5. Locations with notably high catches during closure: (**a**) Schwerindustrie exhibition room; (**b**) public space at the Technisches Museum Wien; (**c**) staircase; (**d**) entry hall at the Schönbrunn Palace. Photographs by P.Q.

Although silverfish were captured most frequently during the lockdown closures, most notably *L. saccharinum* and *C. calvum*, other species were also observed on traps, as seen in Figure 6. This figure sums the catch from the Technisches Museum Wien, Schönbrunn Palace, and Hofburg Museum. Moths and beetles were frequently counted in the traps, but these do not change notably in 2020. The clothes moth (*T. bisselliella*) is common and varies from year to year, yet, while 2020 shows high numbers, it is not distinctively so. The 2021 trap collection was only conducted up to June, but this year is likely to show a substantial decrease over the previous year.

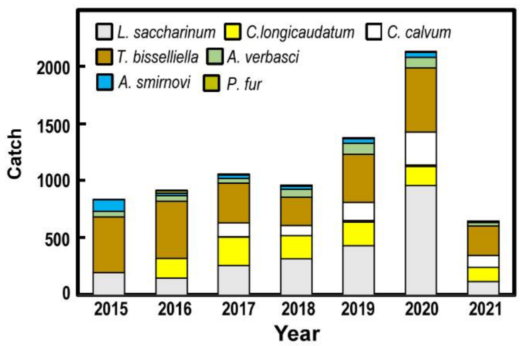

Figure 6. Total annual catch of various insects summed from the Technisches Museum Wien, Schönbrunn Palace, and Hofburg Museum. *C. lineatum*, *S. paniceum*, and other Ptinidae (spider beetles not uniquely identified) displayed numbers so small that they are not visible in the histogram bars. The year 2021 includes only those from traps from spring (collected up to June 2021) and, as catches from the early part of the year are usually the largest (Figure 4), it appears as if silverfish will have lower catches in 2021.

4. Discussion

The traps reveal a sharp increase in the catch of silverfish from collections made as the museum closures drew to an end. Some traps captured more than a hundred individual insects during the two-month exposure. Closed museums meant no visitors and limited staff movement, so animals living within the building experienced less disturbance. As silverfish prefer dark and quiet spaces, a wider range of peaceful habitats were likely available during lockdown. Light levels changed during the closures. Normally, at night, lights are off in all the museums, with only emergency exit lights providing illumination. The lights are almost always off in the Kronprinzenappartements as these rooms are rarely used. During the COVID-19 lockdown, lights were typically also off during the day, but the traps with high numbers of silverfish are in places that are reasonably well lit by daylight, so the insects were not in continuous darkness. There were other modest changes in the indoor climate during the COVID-19 closures. The rooms were generally colder by about 3 °C, i.e., 22 °C rather than 25 °C at the Technisches Museum Wien; both relative humidity (3–4%) and absolute humidity were lower (1 g m^{-3}) during closure. This pattern was repeated over a number of rooms. Ventilation in the museums was largely reduced during closure, meaning ideal micro-environments, small cracks, and restricted spaces along the wall may have had more stable climates, so suitable habitats may have become more numerous. Such special museum microenvironments have not been well studied, but will be investigated as part of a new project, which began July 2021 [19]. In this research, the microclimates in twenty Austrian heritage institutions will be monitored over the next two years to establish the statistical relationship between outdoor climate, indoor climate, and pest abundance and fungal activity.

Any changes during the lockdown closures were likely to have occurred across all the rooms. There may have been more distinct changes related to features such as stone floors, but these were not obvious in the present study. A lack of cleaning meant that more dust accumulated, but the nutritional value of this material is uncertain, and dust shed by visitors [20] would have decreased. The rooms with a notably increased presence of silverfish during the closures tend to be large, such as that housing the Schwerindustrie displays in the Technisches Museum (Figure 5a). In general, traps at the museums, which have revealed high numbers of silverfish in the past, also tended to have increased catch during the COVID-19 closures.

The life cycle of *L. saccharinum* is rather longer than the closure period. Nymph development to a sexually reproductive adult, mating, and eggs requires a minimum of 3–4 months, but most often a year. Even under ideal climatic conditions with sufficient food, the short two-month lockdown would be insufficient for the populations to grow in substantial numbers. The increased numbers found on the traps are probably the result of higher activity and insects ranging more widely during a period of stable microclimate and limited disturbance. Some museums and historic properties in England cited in [13] have also shown an increased presence of silverfish and other pests during the lockdown, pointing to this organism as being sensitive to subtle changes in its habitat during closures.

5. Conclusions

Silverfish were trapped in greater numbers when the Viennese museums were closed during the COVID-19 lockdown. This seems likely to have arisen from greater activity and a wider range during a time when the museum environment was largely undisturbed by human activity in the exhibition rooms. The museums did not observe increased damage to collections from the greater numbers of insects. However, it seems probable that only the silverfish range and foraging behaviour widened, with little increase in the catch rate of moths and beetles, which suggests that the fact that silverfish are so shy makes them a very good indicator of the types of change that occurred. There is clearly the need for further research on the factors that control insect populations in museums and to understand relative importance, such as food availability, habitat, disturbance, and ease of ingress. During the recent closures, it is evident that, even when museums are shut, it remains necessary to continue IPM procedures, especially at sites where infestations have been apparent in the past. Although the interior climate was cooler and drier while the museums were closed to visitors, this does not seem to have been a factor in increasing the catch of silverfish. It reminds us that, although climate change is likely to alter the geographic range and activity of insects in the future, it is not the only factor that alters insect abundance. Changes in insect behavior may be sensitive to factors other than climate.

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Informed Consent Statement: No specific ethical approval was required for the invertebrate trapping and care was taken not to trap mammals where they were likely to wander onto traps. These studies did not involve endangered or protected species.

Data Availability Statement: Details regarding data supporting the reported results are available in the text. Some additional trapping data can be obtained from the author (P.Q.).

Conflicts of Interest: The authors declare no conflict of interest.

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