

RESEARCH ARTICLE

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Regularity in distribution, and control, of pests in the hall of mental cultivation, the Forbidden City, Beijing, China

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Abstract

Pests can seriously threaten the safety of organic relics and historic buildings. Every year, the Palace Museum spends a large of money and time preventing and controlling pests, but there is still no a better systematic and targeted method. The Hall of Mental Cultivation is a representative and essential building in the Forbidden City. Through three years of pest monitoring, the species, quantity, and occurrence regularity of the major pests were investigated. During this time, more than ten species of insects were trapped. These included carpet beetles (*Anthrenus picturatus* hintoni Mroczkowski, 1952 and *Thylodrias contractus* Motschulsky, 1839), silverfish (*Ctenolepisma longicaudata* Escherich, 1905), powder-post beetles (*Lyctus brunneus* Stephens, 1830), booklice (*Liposcelis bostrychophila* Badonnel, 1931), spider beetles (*Ptinus japonicus* Reitter, 1877 and *Gibbium aequinoctiale* Boieldieu, 1865) and the case bearing clothes moths (*Tinea pellionella* Linnaeus, 1758), among which the *Anthrenus picturatus* was the primary pests. Abundant resources of organic relics, suitable temperature, humidity, and light environment, and cypress existence are favorable factors for the occurrence of pests, and analysis of these factors is helpful for further integrated pest management (IPM). The period with the most significant number of active pests in the Hall of Mental Cultivation is July and August, and April and May are the rapid growth period. Carpet beetles are the key pests that can affect the overall change trend significantly. It should combine with their living habits, the ideal treatment time and methods, to give them a better control. Fumigation should be done in July and August, while chemical spray should be done referring to the florescence of outdoor trees (March to June), and used of pheromone is reasonable preventative measures.

Keywords: IPM, Preventive, Dominant pests, Optimal treatment, The Forbidden City

Introduction

Pests represent an essential risk in protecting cultural relics because of their large number, great damage, and difficulty in eradication. Some cultural relic workers have devoted substantial efforts to research and control of pests. For example, Querner surveyed the pests in central Europe [1, 2]; webbing clothes moths, drugstore beetles, carpet beetles, and silverfish were the main ones identified. Brimblecombe [3] surveyed 25 species of pests in the United Kingdom. Booklice,

silverfish, woodlice are the most abundant, followed by carpet beetles, clothes moths, spider beetles, etc. Since the 1980s, IPM (integrated pest management) was introduced to museums and has been widely adopted [4, 5]. Numerous pest control methods have been studied, both chemical methods: spraying with pesticides and fumigation [6], also physical methods: freezing [7], low oxygen [8], microwave [9], and others. Biological control methods such as parasitic wasps [10], insect pheromone traps have also been tried. In addition, scholars are also exploring the changes in insect damage to cultural relics caused by climate change [11, 12] to adopt more stable and effective methods to control the damage caused by pests. Thus, pest control has

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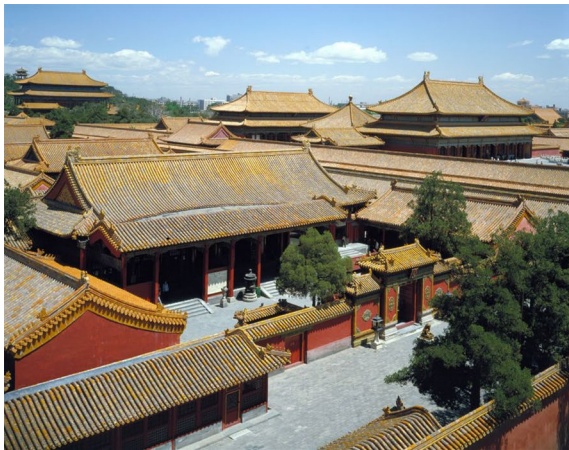
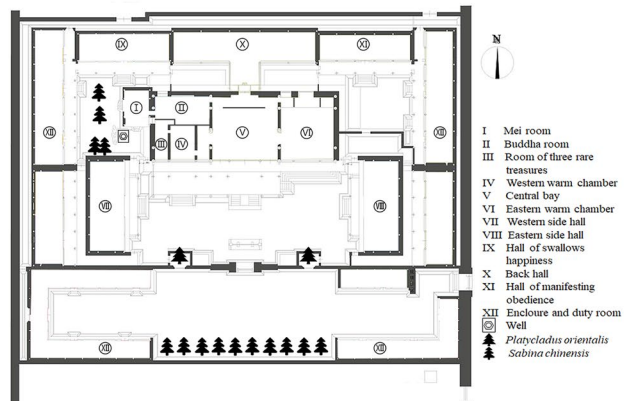


Fig. 1 Overall layout of the hall mental cultivation



begun to integrate various techniques rather than a single way. IPM was a late development in China, which began to wean itself off chemical pesticides in the 1980s [13]. In the 1990s, Chinese conservationists started to pay attention to the effects of the environment on pest control [14] while exploring methods such as nitrogen filling [15] and low temperature [16]. But the concept of IPM has only been reported in recent years [17], and comprehensive pests of relics control strategy studies are also rare.

The Palace Museum, the palace in Ming and Qing dynasties of China, is the largest ancient architectural complex existing in the world and a famous world cultural heritage site, which was called “the Forbidden City”. The Hall of Mental Cultivation was built during the reign of Emperor Jiajing of the Ming dynasty. It was a temporary resting place for the emperor at first. It was unique in the Forbidden City during the Qing dynasty, mainly because, from Emperor Yongzheng to the last Emperor Puyi abdicated, it became the country’s political center. Eight emperors lived and ruled the country here. Because of its special administrative status, there are many precious cultural relics in the Hall of Mental Cultivation. In the late Qing dynasty, there were more than 780 pieces of furnishings in the hall, including paintings, textiles, furniture, and other organic relics. This area was open to the public until the research repair project, but the hall’s interior was always closed to visitors. The abundant resources of organic relics and the quiet environment cause the breeding of pests and destruction. The species of major pests, distribution and occurrence regularity in the Hall of Mental Cultivation have been investigated and studied for nearly 3 years. Based on the investigation and analysis, we can provide comprehensive control measures for the

reference of cultural relic conservation workers. It can also let more scholars know about the pest population in historic Chinese buildings.

The layout of the hall of mental cultivation

The Hall of Mental Cultivation, covering an area of 5000 square meters, is located to the west of the central axis of the Forbidden City. This area includes several buildings, and all these buildings are partitioned by wooden doors or windows into many rooms. And these rooms in different locations have different roles (Fig. 1). The main hall is an I-shaped hall, and the front hall (36 m × 12 m) is partitioned into six rooms (I–VI), where the emperors govern, rest, and recreate. The famous queen mother Cixi “Holding Court Behind A Screen” also happened here in the late Qing dynasty. Comparatively, the western warm chamber (10 m × 12 m) is more complicated, because of it has more partitions. It divided into front and back room, and the west of the front room is the famous “Room of Three Rare Treasures” (III) (2.4 m × 6 m). The original was the place where the emperor read and rest. Emperor Qianlong named it because of three famous calligraphy and painting—“Bo Yuan Tie” by Wangxun, “Kuai Xue Shi Qing Tie” by Wang Xizhi, and “Mid-Autumn Tie” by Wang Xianzhi. The back room (II) is called the Buddha room (10 m × 6 m), and it stores many beautiful Thangka and Buddha statues. There is a Changchun book house and No Fatigue room on the first floor connected to Mei room (5 m × 4.7 m) (I).

There are five rooms in the Back Hall (26 m × 5.9 m), all with beds, where the emperor could live at will. Auricular chambers are on both the east and west sides of the back hall: the Hall of Swallows Happiness (17 m × 5 m), the Hall of Manifesting Obedience (17 m × 5 m), for the



Fig. 2 Sticky traps

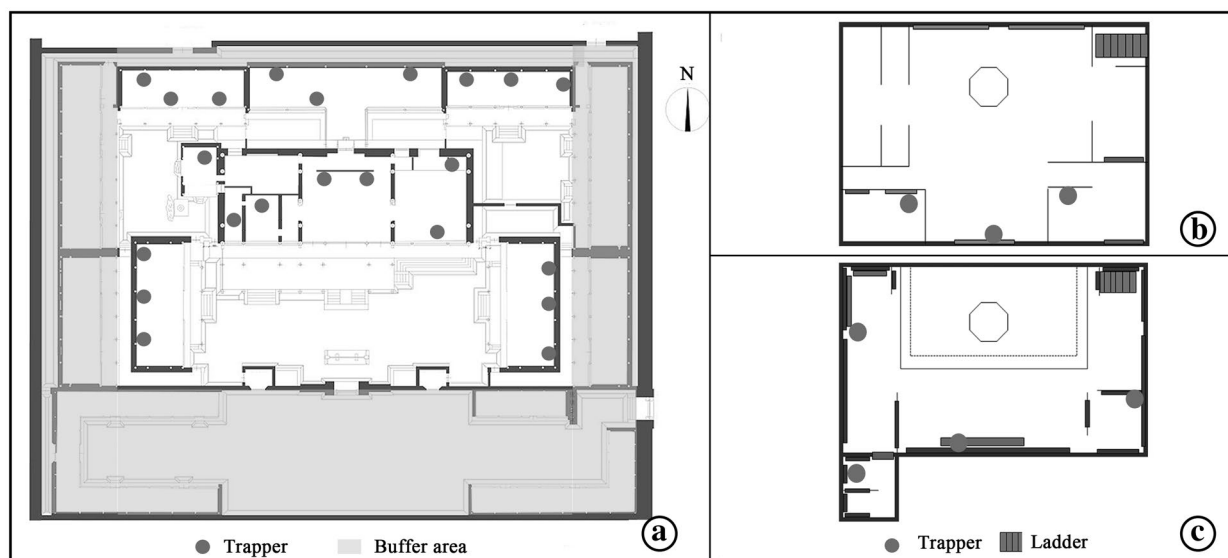


Fig. 3 Traps distribution. **a** Trap distribution of in the hall of mental cultivation except for Buddha room. **b** Trap distribution on the first floor. **c** Trap distribution on the second floor

Queen and Concubine. There are still some enclosure rooms for concubines to live temporarily.

Methods

Insect pests investigation

This investigation involved the quantity and species of pests. Traps without pheromones are passive and can only trap passing pests in their active area, so the effect is limited. Insect pheromones can actively attract pests and be more efficient. Even insect damage areas have migrated, it can also achieve trapping. Several studies have shown that insect pheromones can attract target

pests and significantly improve trap efficiency [18–20]. Therefore, we used British Russell IPM pheromones products, which can trap the black carpet beetles, the varied carpet beetles, the case bearing clothes moths, the webbing clothes moths, and silverfish. Pheromone products were stuck on the sticky trappers (Fig. 2). The monitoring area included the main hall and the eastern and western side halls. Enclosure rooms and duty rooms were set as a buffer area (Fig. 3).

Each trapper was counted every month and been cleaned or replaced every two months to ensure the effectiveness of all kinds of pheromones. Data were

evaluated by one-way analysis of variance (ANOVA) with the Duncan post-hoc test for comparisons between groups using SPSS Version 26. $P < 0.05$ was considered as statistically significant. Identify pest species according to books on storage pests in China [21]. Monitoring began in July 2017 and was completed in December 2019.

Fumigation

Before the investigation, serious pests had existed in the Hall of Mental Cultivation. To better explore the source, occurrence regularity, and suitable control time of pests, sulfuryl fluoride fumigation was conducted in the entire area from April 15 to 17, 2017, after pest investigation and sample collection. The concentration of sulfuryl fluoride used was 50 g/m^3 , which would increase by 10% wherewith more pests. The windows and doors were sealed with specific PVC film. After fumigation, the area was checked for active pests.

Material identification

The most severely damaged relics in the Hall of Mental Cultivation are carpets, felts, and rafters used as partitions. Because these materials are the source of attracting pests, identifying these materials can provide a basis for selecting alternatives. Fortunately, microscopic observation can identify these materials.

The wood samples were immersed in water for 24 h and then immersed in PEG 1500 solutions of 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, and 90% successively, at 60°C for 6 h. Use melted PEG1500 embedding samples. Sections ($10 \mu\text{m}$) of wood were obtained by Section Cutter along the three diagnostic directions (cross section, longitudinal radial, and longitudinal tangential sections). After stained with Safranin, the sections were observed by a light microscope (Olympus BX53).

Studies showed that high performance liquid chromatography/time-of-flight mass spectrometry (Waters H-Class UPLC G2-XS QTOF MS) could analyze dyes and other organic components [22]. Pre-treatment conditions for the test: put a few carpet samples in 1.5 mL liquid phase vials and add 1 mL mixed solvent of methanol/formic acid/10 mM EDTA Na_2 ($85 \cdot 5^{-1} \cdot 10^{-1}$, $\text{V V}^{-1} \text{ V}^{-1}$). After ultrasonic extraction at 75°C for 45 min, the samples were transferred to a 1.5 mL centrifuge tube and centrifuge at 12,000 r/min for 6 min. Pick up the supernatant, pass through a $0.22 \mu\text{m}$ filter, and blow-dry with nitrogen, then re-dissolved with 200 μL acetonitrile/water ($1 \cdot 1^{-1}$, V V^{-1}) mixed solvent for testing [23].

Since most dye components can obtain better ionization in the negative ion mode [24], we select the negative ion mode and utilize LE correction. The m/z is 554.2615. Specific parameters: Column BEH C18, column temperature 40°C , flow rate 0.3 mL/min , voltage 2.5 kV , injection

volume $1 \mu\text{L}$. Mobile phase: water in channel A, acetonitrile in channel B. Gradient elution procedure: the initial concentration of 90% of A, 10% of B, after 8 min, becomes 10% of A, 90% of B, keep for 2.5 min. Return to the initial state, which lasts 13 min.

Monitoring of temperature, RH, and light

Insects are poikilothermic animals, so they do not have any mechanism for regulating body temperature. Therefore, pests can complete development and reproduction only when the ambient temperature meets their conditions. Beijing is located in a warm temperate zone with semi-humid/semi-arid monsoon climate. The average annual temperature on the plain where the Forbidden City is located is $11\text{--}13^\circ\text{C}$, and the maximum yearly temperature is generally between 35°C and 40°C , which is suitable for many insects. Humidity is equally selective for the pests. For example, silverfish are considered a humidity indicator. Under high humidity conditions, dry pests are rarely found, and vice versa. Light is also very essential for insects, as most pests avoid light. Therefore, recording physical factors such as temperature, humidity, and light can help find pest prevention measures. HOBO UX100-011 was used to record temperature and humidity in the investigation, and the recording interval was half an hour. ELSEC 765 UV + logger was used to record light.

Results

Pests situation in the hall of mental cultivation

Species and distribution

Before the trapping, we investigated the pest hazards, recorded the degree of pest damage to cultural relics, and grasped the species of pests and their active areas. The previous investigation showed the distribution of pests was uneven (Fig. 4a). By and large, the damage to the west of the central axis was heavy, while the east side was relatively intact. Based on the damage of on-site woolen fabrics, silk fabrics, paper relics, and timber (Fig. 5), it was presumed that the species of pests in the hall were carpet beetles, silverfish, clothes moths, and powder-post beetles. Based on this, we worked out the trapping investigation plan. First, we carried out sulfuryl fluoride fumigation, and fumigation project acceptance was carried out after no live pests were checked, especially the buddha room with more carpet beetles.

So far, our investigation results showed pests could also appear after fumigation, even in the presence of buffer zones. There were over ten species of insects, such as carpet beetles, booklice, silverfish, ground beetles, woodlice, scutigera, spiders, spider beetles, katydids, powder-post beetles, and clothes moths. Among them, carpet beetles, booklice, silverfish, spider beetles, powder-post beetles,

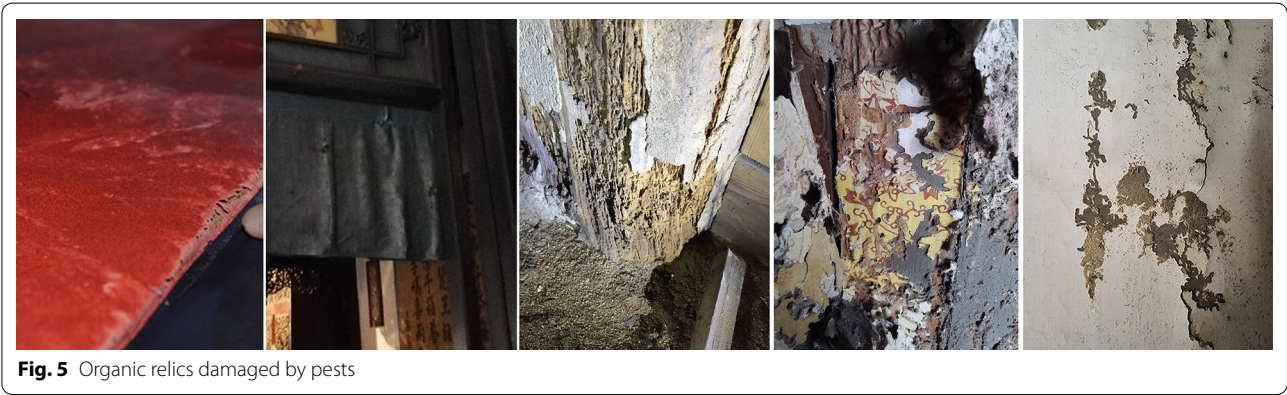
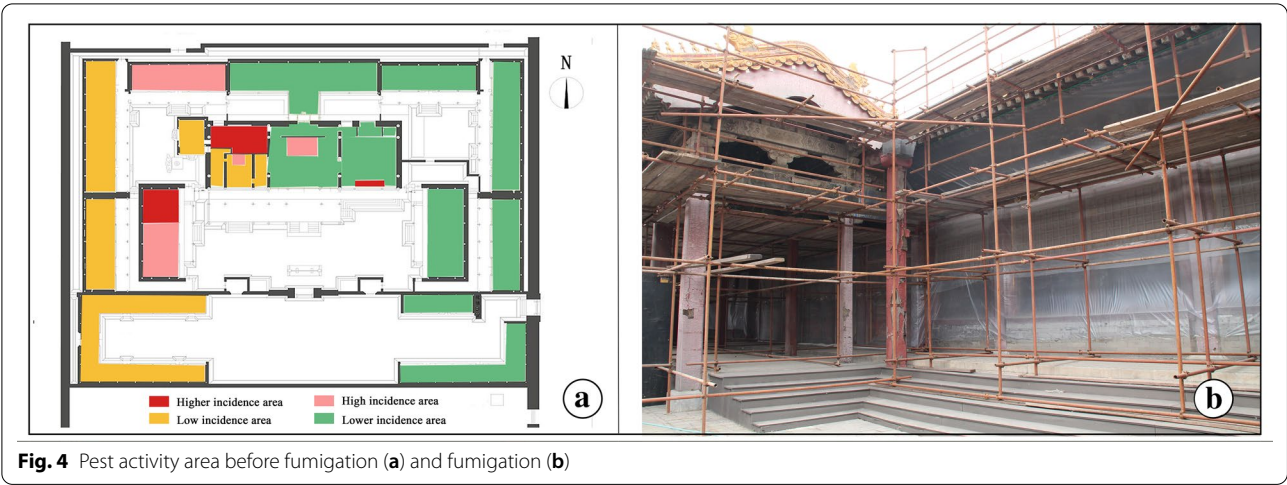


Table 1 Yearly distribution of major pests in different regions

	Total insect			Carpet beetles			Booklice		
Buddha room	378.33 ± 271.35	A		376.67 ± 275.97	A		3.67 ± 6.35	A	
Front hall	184.33 ± 28.50	B		99.33 ± 68.97	B		68.00 ± 99.69	A	
Back hall	46.00 ± 18.25	B		12.00 ± 10.58	B		13.33 ± 3.21	A	
Western side hall	60.33 ± 42.72	B		6.00 ± 6.00	B		6.33 ± 5.03	A	
Eastern side hall	21.67 ± 6.66	B		2.67 ± 3.78	B		2.67 ± 3.78	A	
Hall of swallows happiness	16.67 ± 9.02	B		1.33 ± 2.31	B		7.00 ± 11.27	A	
Hall of manifesting obedience	16.00 ± 4.36	B		1.33 ± 2.31	B		2.33 ± 3.21	A	

Data are shown as means ± standard deviations of annual numbers in different regions

and clothes moths were pests that damage relics. The other insects and arthropods were “visitors” because they feed on dead plant material or insects and do not directly harm cultural relics. However, their carcasses will attract carpet beetles, increasing the security risk to cultural relics. Among the pests, the quantity of carpet beetles was the highest, with over 1,300 trapped in two-and-a-half years. This was followed by the booklouse, two of them

make up 79% of the total. Silverfish, powder-post beetles, spider beetles, clothes moths appear rarely, and the quantity was still less than ten (Fig. 5). It is especially noteworthy that the captured carpet beetles were mainly larvae, and adults seldom appeared.

The distribution of pests was highly uneven, the number of pests in the buddha room was the largest, and carpet beetles accounted for a large proportion

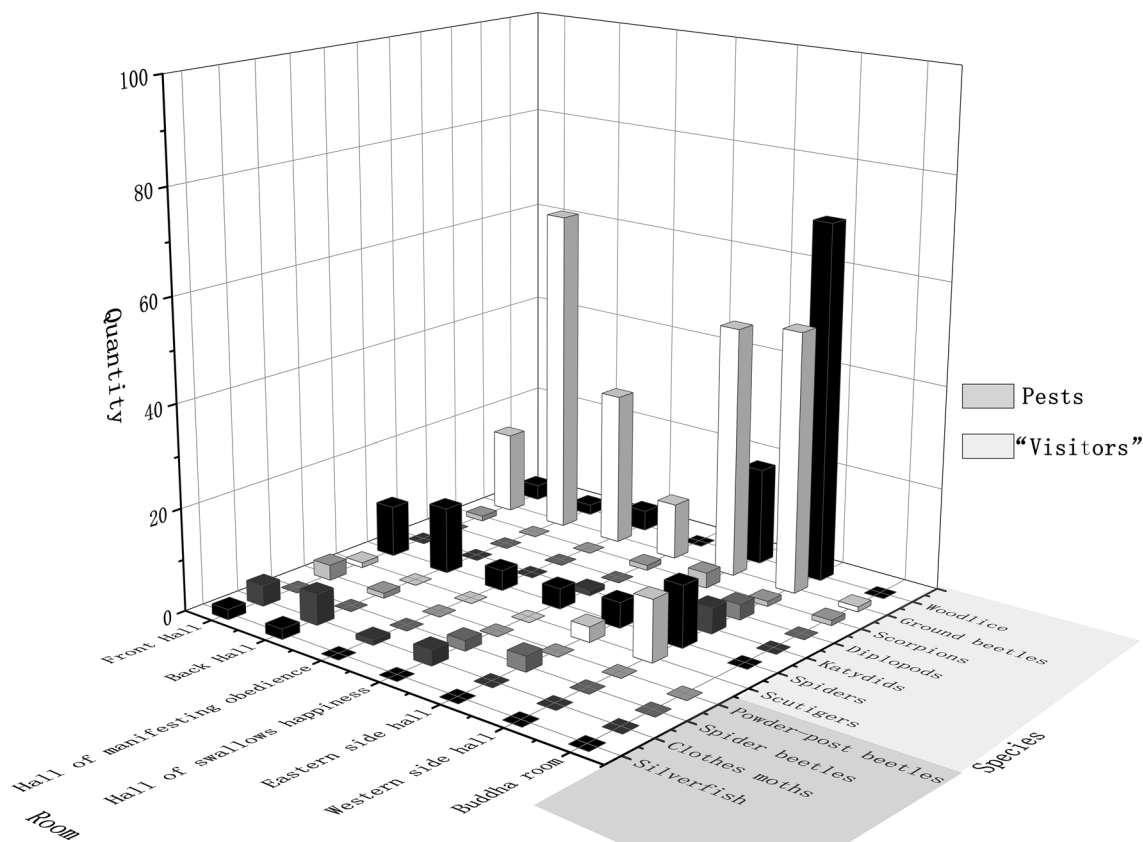


Fig. 6 Quantity and distribution of other pests and "visitors"

($P < 0.05$) (Table 1). Over 1000 carpet beetles were found in the buddha room, and the remaining 300 carpet beetles were distributed in the other halls. The central bay had the second most pests, with the most common pests: carpet beetles and booklice. Although the eastern and western side halls have similar architectural structures, there were more insects, such as ground beetles, in the western side hall. There were many insects and other arthropods in the back hall, the Hall of Swallows Happiness and the Hall of Manifesting Obedience, but the quantity is small (Fig. 6).

We found that there are mainly six kinds of pests that damage cultural relics, and their species were identified:

There were two species of carpet beetle trapped. The first is *Anthrenus picturatus* (Fig. 7a), which is distributed in most provinces of China and mainly damages woolens, feather products, animal materials, specimens, and silk [25]. *Anthrenus picturatus* accounted for most of the pests, and it was the dominant pest in the Hall of Mental Cultivation. The second is *Thylodrias contractus* (Fig. 7e), also distributed in most provinces of China. Its larvae can damage various animal products and animal specimens.

The trapped booklouse was *Liposcelis bostrychophila* (Fig. 7b), widely present in many kinds of storage. Booklice are small and can reproduce at an amazing rate, making them difficult to treat. Molds that grow on starch paste, paper, and wallpaper are attractive to booklice; however, they can scratch and erode the surface of these materials [26].

Lyctus brunneus is a powder-post beetle (Fig. 7c) that is widely distributed in China. It feeds on dry, high-starch, wood furniture, bamboo, traditional Chinese medicinal herb, etc. Their larvae live in wood. And adults need to leave the wood when they mate, and most live indoors [27].

Tinea pellionella (Fig. 7d) is mainly distributed in central China, Beijing, Tibet, and other places. It damages textiles and causes regular holes. It also damages articles containing keratin such as rabbit hair, wool, and plumage [28].

Two species of spider beetle were trapped in the investigation, one was *Gibbium aequinoctiale* (Fig. 7f), and the other was *Ptinus japonicus* (Fig. 7g). Both distribute throughout most provinces of China and feed on dried or rotting animal and plant materials, including flour, grain,

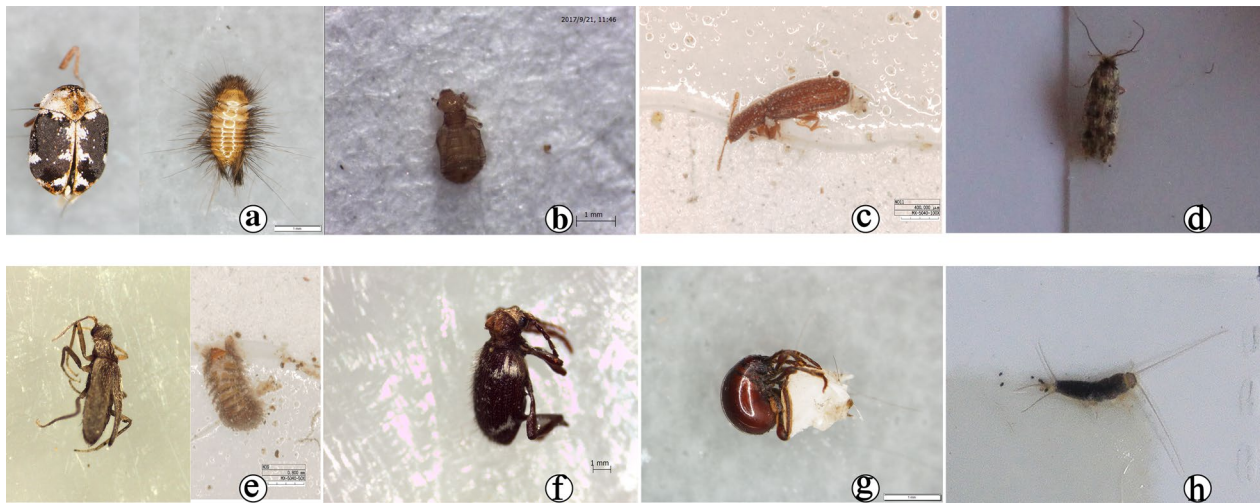


Fig. 7 Major pests of cultural relics

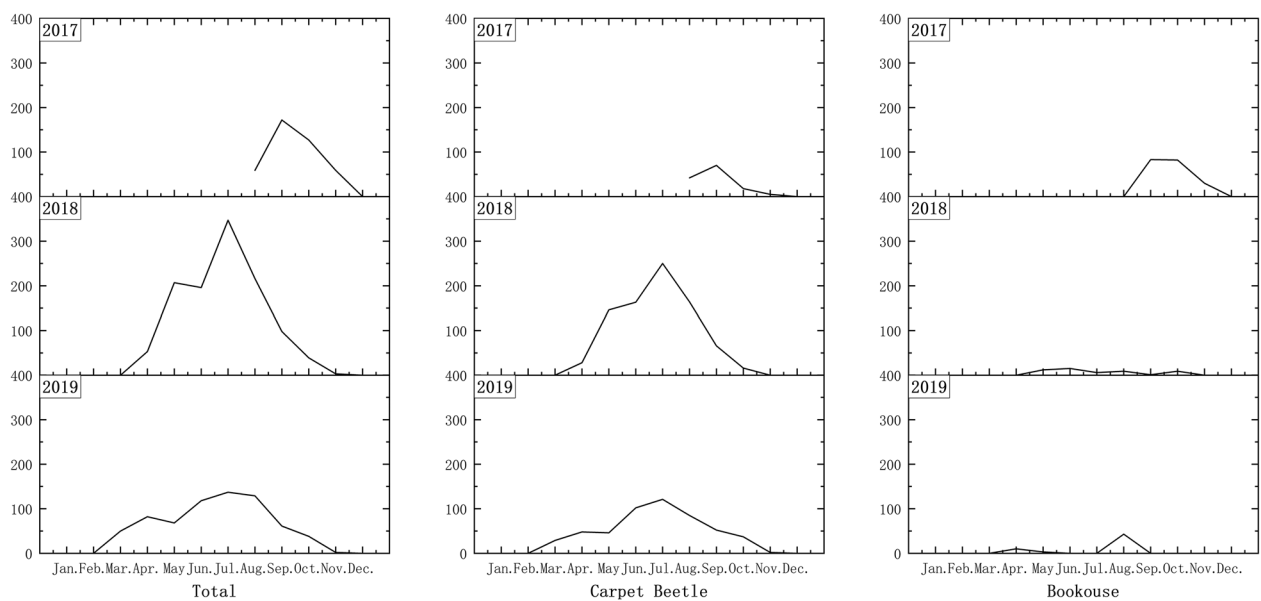


Fig. 8 Monthly catch quantity of major pests: 08. 2017–12. 2019

seeds, fur, wool, Chinese medicinal herbs, and animal specimens [21].

The trapped silverfish was *Ctenolepisma longicaudatum*, and its distribution range is constantly expanding [29, 30]. Silverfish have a vast food range, including grains rich in protein, sugar, trace elements, Chinese medicinal herbs, photos, paper, paste, cotton, animal fur, silk fibers, and even organic matter in indoor dust [31]. They like dark and humid environments, primarily hide in the host's gap during the day and come out at night.

Occurrence regularity of major pests

Except for the carpet beetles and the booklice, the number of pests trapped was small. Therefore, this paper focuses on the changes in the quantity of carpet beetles and booklice (Fig. 8).

After the fumigation, many carpet beetles were trapped in August of that year. Depending on the investigation data in 2018 and 2019, it was clear that the carpet beetles first appeared during February, and the number increased rapidly from March to June. In July and

Table 2 Classification and quantity of paper and textile cultural relics (unit: pieces)

	Paper cultural relics		Textile cultural relics					
	Calligraphies and Paintings	Books	Felts	Curtains	Lazybacks	Quilts	Bed sheets	Thangkas
Western warm chamber	0	0	0	0	0	0	0	0
Central bay	6	35	3	43	1	0	0	0
Eastern warm chamber	24	0	11	13	15	1	1	0
Back hall	33	0	20	17	8	7	0	0
Hall of swallows happiness	6	0	8	1	8	2	1	0
Hall of Manifesting obedience	17	0	11	4	0	2	1	0
Buddha room	6	0	2	1	6	1	1	17

August, the number of carpet beetles was the largest, and the peak was reached in July. After August, the number of carpet beetles had dropped significantly. The change in the number of carpet beetles almost determined the changing trend of the total pests.

After fumigation, a considerable number of booklice appeared. The number of booklice decreased significantly in 2018 and 2019 compared to 2017. As can be seen from the trapped in 2018 and 2019, booklice generally appear between April and October. But the quantity fluctuations throughout the year are not significant. But we cannot infer more information of booklice occurrence regularity mainly because there are no pheromone substances of booklice in this investigation.

Infested materials

Organic relics

It is well-known that carpet beetles like woolen fabrics, while clothes moths prefer silk fabrics. Silverfish and booklice are pests of books and archives. Powder-post beetles, long-horned beetles, and anobiid beetles can cause severe damage to wooden buildings. Hundreds of woolen fabrics, silk fabrics, books, calligraphy, painting, and other cultural relics displayed in the Hall of Mental Cultivation are a strong temptation to the pests. Table 2 summarizes all kinds of organic antiques inside the Hall of Mental Cultivation (Table 2).

The investigation result showed that numerous carpet beetles gathered in the buddha room; the quantity of which was three times higher than in other areas. Unlike other regions, the entire second floor is covered with carpet and is badly infested. The carpets in the buddha room include two styles: red and yellow. Microscopic observation showed the carpet fibers of the two colors have apparent scales and a black medullary cavity in the middle, consistent with the typical characteristics of wool [32] (Fig. 9).

In the court, Chinese herbal medicines, such as *Phellodendron chinense* Schneid, 1907, *Zanthoxylum bungeanum* Maxim, 1871. were usually employed as an insect repellent to treat paper or fabric.¹ So, we also assessed whether the carpets had been treated with Chinese herbal medicines when we analyzed the dyes. Through liquid chromatography analysis, we know Chinese traditional plant dyes dyed the two carpets. Brazilian hematoxylin and protosappanin B, typical components of sappan dyestuff, were detected in the red carpet. Safflower yellow A, a unique component of safflower yellow, was detected in the yellow carpet. That is to say, the yellow carpet was dyed by safflower yellow (Fig. 10). No insect repellent component was detected in the two carpets.

Besides the woolen carpets, the most seriously infested parts were the wood grates employed as partitions. The buddha room and the western side hall were more serious. Because of management reasons, this investigation failed to collect samples of the grates from the buddha room. Still, from the historical archives, we found the probability of its use was cypress wood.² This investigation identified the timber samples from the western side hall. The wood samples have the following characteristics: growth ring boundaries are distinct, and the transition from earlywood to latewood is abrupt. Earlywood tracheid is polygonal, square, and latewood tracheid cells are rectangular, square. Axial thin-walled tissues are scarce and scattered; wood rays have two types: uniseriate ray and fusiform ray. The former is 2–15 cells high, and the latter has a radial resin canal; axial tracheid with bordered pit 1–2 column; the cross-field pits are

¹ Archives of the interior affairs office of the Qing palace, 45 volume, 1783 A.D.

² Archives of the interior affairs office of the Qing palace, 7 volume, 1736 A.D.



Fig. 9 Carpet and microstructure of carpet fibers 200 × (a red carpet; b yellow carpet)

fenestriform (“Window-like”), and one or two pits in each cross-field (Fig. 11). Synthesizing all characteristics, the grates were made of *Pinus massoniana* Lamb, 1803 [33], which is a species of pine widely distributed in China.

Except wool felt and wood, we found some pests also prefer the dead “visitor”. For example, the carcass of ground beetles infested by dermestid beetles are often seen on the traps (Fig. 12).

Temperature, relative humidity, and light

Winter in Beijing is cold, but the interior temperature is higher than outside in the Forbidden City because it's sheltered and buffered by buildings. According to the recording, the lowest temperature of the year is no < − 5 °C (Fig. 13). The warm room contributes to pests' ability to survive the winter. On the other hand, the summer highs are consistently above 25 °C, conducive to the rapid reproduction of pests.

The distribution of pests is also intimately related to light. By comparing, we can find that the quantity of carpet beetles in the darkroom is more; there were more than 1000 carpet beetles in the buddha room. Because of the compact layout, the overall light is dim in the buddha room; most of the partitioned room is

entirely black. There is plenty of light in the western warm chamber and eastern warm chamber, thanks to the large windows, so the number of carpet beetles in these two rooms is much fewer (Table 3).

Trees or nectar source

There are 16 cypress trees in the Hall of Mental Cultivation, of which ten are *Sabina chinensis* (L.) Ant, 1857, located near the duty room, and two are *Platycladus orientalis* (L.) Franco, 1949, located on both sides of the Gate of Mental Cultivation. Most importantly, four *Sabina chinensis* were planted in front of the Hall of Swallows Happiness, next to the buddha room (Fig. 14). Not only that, but there are also two *Pinus bungeana* Zucc. ex End, 1847 in the Palace of Eternal Longevity courtyard behind the Hall of Mental Cultivation. And to the west, there are five cypress trees in the yard of the Hall of Supreme Principle.

The florescence of *Pinus bungeana* and *Platycladus orientalis* is from April to May every year, and *Sabina chinensis*'s is earlier, from March to April, in Beijing. Moreover, both cypress and pine are rich in pollen. Compared with the development trend of carpet beetles, this is somewhat surprising since these plants' florescence matches the rapid growth period of the trapped number. Coincidentally, the *Anthrenus picturatus* overwinter as

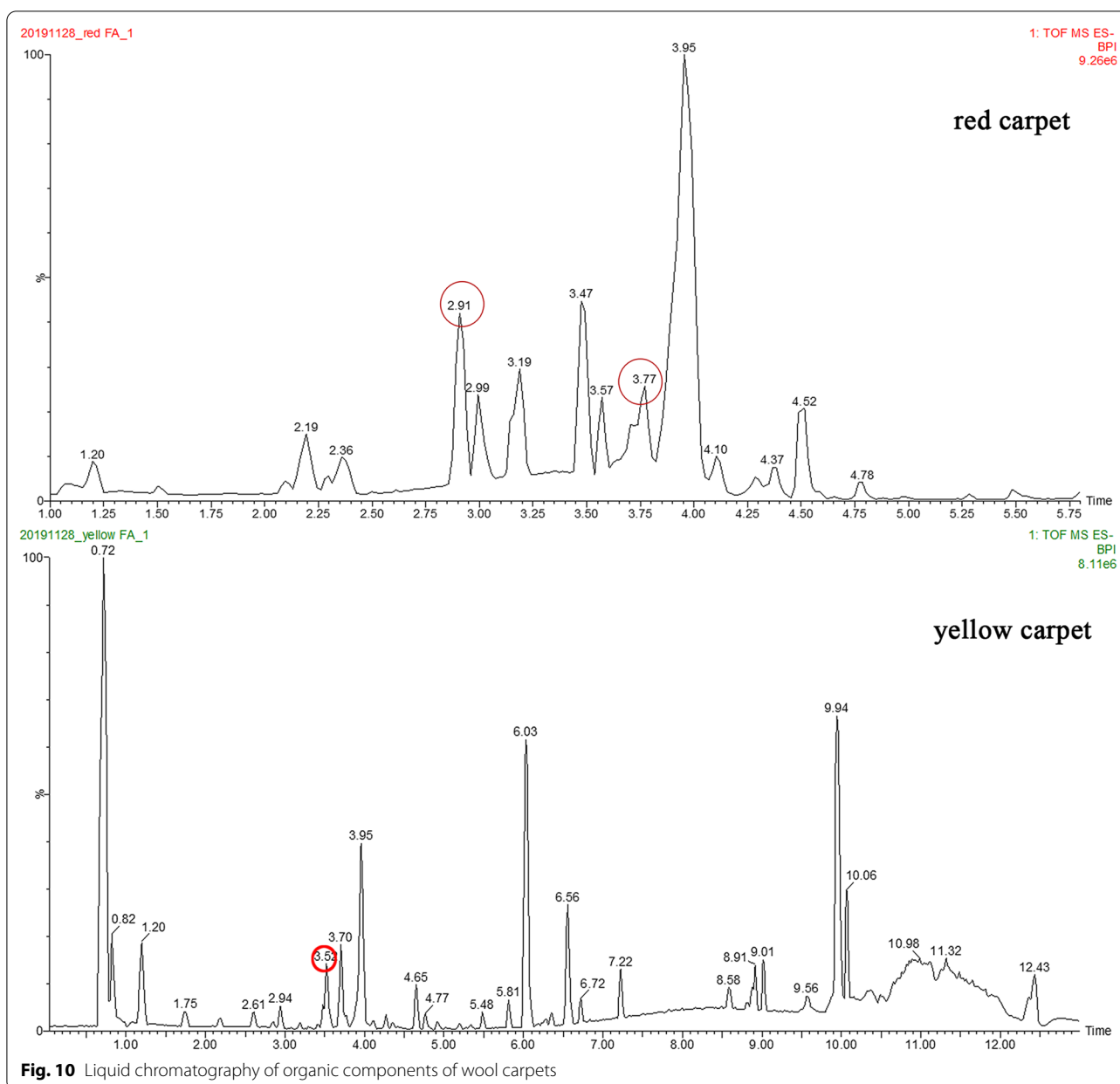


Fig. 10 Liquid chromatography of organic components of wool carpets

mature larvae. And the adults go out to gather honey to mate [34] when spring comes. Then return to the indoor to lay eggs where food is abundant. Thus, we can infer the pine and cypress flowers around the Hall of Mental Cultivation provided a rich source of nectar for the *Anthrenus picturatus*, and that it's helpful for them to mate and reproduce.

Discussion

Risk assessment

The Hall of Mental Cultivation is an independent courtyard in the Forbidden City. This hall remains the display

and architectural form since the Qing dynasty emperor Puyi abdicated. The out-of-repair doors and windows cannot prevent outside pollutants from entering the room, nor can they prevent pests from invading. Because of so many rooms and complex furnishings in the Forbidden City, it is difficult for the limited number of professional staff to clean regularly. Although the courtyard was open to visitors, all the visitors will not be allowed to enter indoor. Thus, tourists' negative impact on the interiors is more limited, but the quiet environment also provides a convenient place for pests to develop.

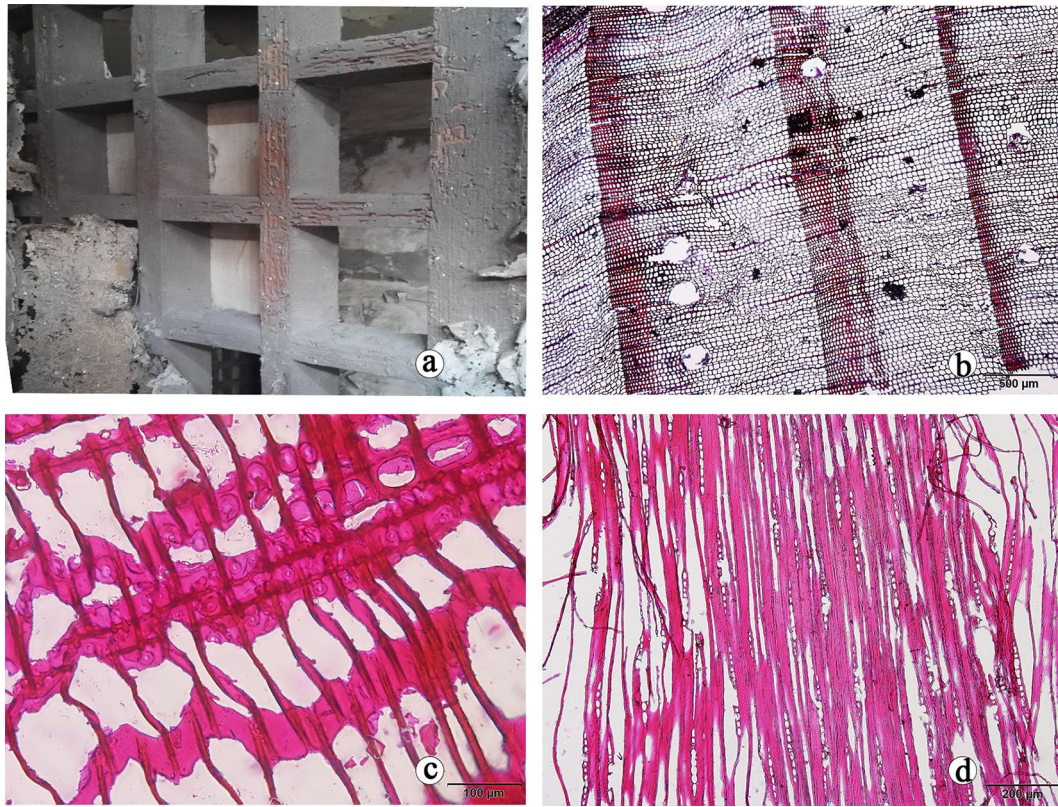


Fig. 11 Sections of wood grate (**a** sample, **b** lateral section 40 ×; **c** radial section 200 ×; **d** tangential section 100 ×).

Pests in an area are not determined by a single factor



Fig. 12 Carpet beetles fed carcass of ground beetle on the trap

but by the combined action of food, vegetation, temperature, humidity, light, and other environmental factors [35]. For example, there are many organic relics in the Hall of Mental Cultivation, suitable temperature and humidity conditions, many dark rooms, limited open areas, and several trees in and around the courtyard. All

these factors jointly decide the diversity and quantity of pests.

Because of the complex environment, sulfuryl fluoride fumigation has become the main pest control method in ancient buildings in the Forbidden City. However, as we have investigated, pests will still appear quickly after fumigation. Therefore, we need to integrate various methods to implement preventive protection.

Pest distribution and occurrence regularity

There were over ten species of insects in the Hall of Mental Cultivation. As the dominant species, carpet beetles are an important pest for cultural relics. Other pests were booklice, silverfish, clothes moths, powder-post beetles, spider beetles, but in limited quantities. In addition, there were few “visitors”: ground beetles, woodlice, katydids, scutigera, scorpions, and so on.

The environment of the investigated area is complex, resulting in an uneven distribution of pests. The Buddha room is a partition on the north side of the western warm chamber. There is only one window on the north side, and also, because of the Hall of Swallows Happiness and the back hall, the interior is very dark. In addition, there were four cypress trees on the west side adjacent

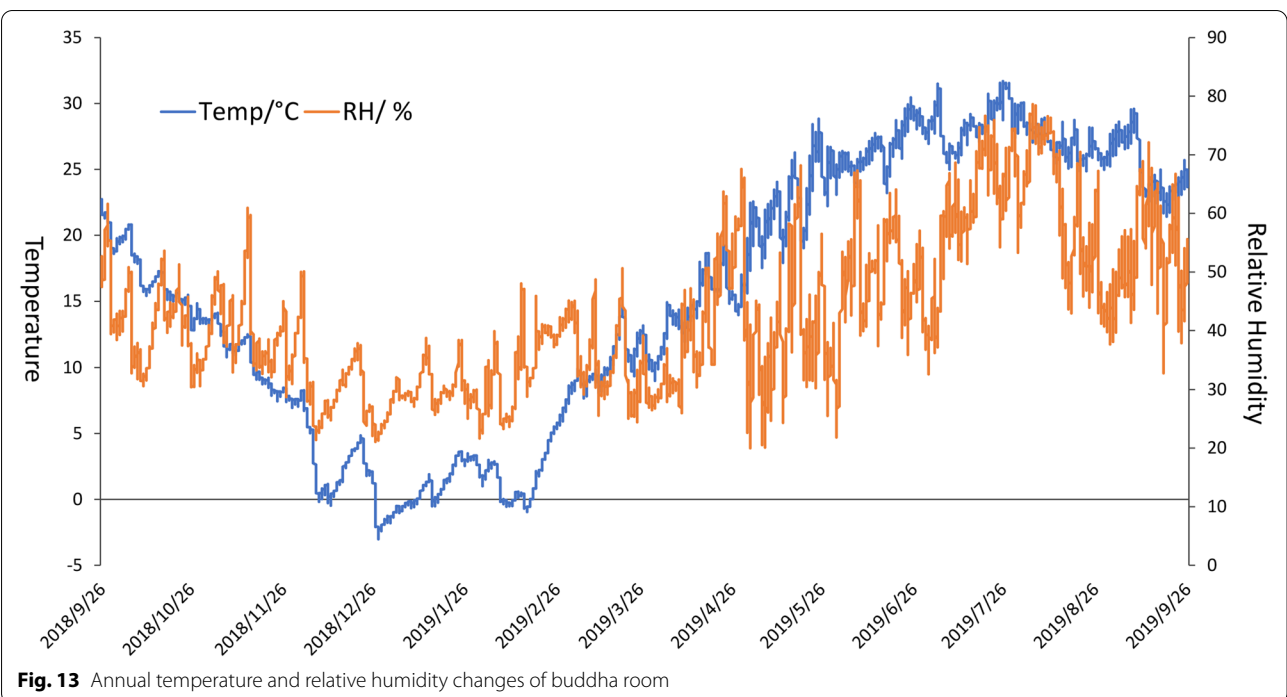


Table 3 Environmental factor and the number of carpet beetles in the main hall

		Temp/°C			RH/%			Light/lux	Quantity of carpet beetle
		Max.	Min.	Avg.	Max.	Min.	Avg.		
Central bay	1	33.3	− 3.8	15.2	91.9	12.8	45.3	0.8	166
	2	32.8	− 4.9	15.1	90.1	14.2	45.2		
Western warm chamber	1	30.8	− 1.8	15.4	86.4	18.4	45.6	6.4	8
	2	29.2	− 0.6	15.3	87.2	19.6	47.3		
Eastern warm chamber	1	29.9	− 3.8	15.1	86.3	18.4	45.4	2.6	26
	2	30.3	− 2.0	9.1	86.0	15.7	45.2		
	3	29.9	− 1.5	15.4	85.1	16.4	45.1		
Buddha room	1	30.0	− 3.1	15.1	86.4	15.9	45.6	0	1009
	2	31.7	− 3.0	15.7	78.6	20.0	43.8		
	3	33.2	− 3.5	15.6	82.4	18.2	43.7		

to the house, and no person entered the house for a long time, leading to many carpet beetles. There are both trees and wells on the west side, making the western side more humid than the eastern side, so more woodlice and ground beetles in the Western Side Hall. On the east side, especially in the Hall of Manifesting Obedience and its enclosure, pests were rarely found.

After fumigation, many carpet beetles and booklice were trapped in August of that year. Thus, we consider the possibility: the foremost reason is that the Hall of Mental Cultivation is not isolated, communicates with the surrounding environment. Without pest control

measures, pests can still enter and forage. So, pest control should consider isolating specific areas and assess the impact of the surrounding environment. Secondly, fumigation time was not well chosen. Sulphuryl fluoride is an excellent fumigating insecticide, but several studies have demonstrated that sulphuryl fluoride does not work well on eggs [36, 37]. The fumigation time was in the middle of April, during the florescence of cypress trees outside the hall; the adult of *Anthrenus picturatus* was still looking for honey and mate. Moreover, April to June was a rapid increase in trapped carpet beetles, which is the peak of egg hatching. So, the surviving eggs



Fig. 14 Cypress trees in the Hall of Mental Cultivation (b: *Sabina chinensis*, c: *Platycladus orientalis*)

were the source of active carpet beetles after fumigating. Besides, the higher the temperature, the more influential the fumigant is [38]. The temperature in April was only about 20 °C, which was also a limiting factor. Therefore, failing to kill the eggs may cause the short-term occurrence of pests.

The cypress and pines in and around the Hall of Mental Cultivation are rich in pollen, allowing *Anthrenus picturatus* to reproduce successfully. Therefore, in this region, *Anthrenus picturatus* becomes the dominant pest. Booklice were active from April to October of the year. However, after 2017, the number of booklice had decreased, possibly because of the cleanliness of indoor hygiene. This investigation did not use pheromone substances for booklice, but was still trapped. There are two main reasons: one is that their nymphs are only two instars, the growth cycle is short, and the other one is they can undergo parthenogenesis, thus reproducing quickly [39].

Other pests were found sporadically, so it is impossible to grasp their occurrence regularities. Mainly because corresponding pheromone products could not be purchased at that time, and the efficiency of the sticky board without targeted pheromone was low. So, these pests need further investigation.

Pheromone

Although most pests prefer the dark, some nocturnal insects like radial light sources, so light can also lure pests [40]. Due to fire prevention considerations, the power is cut off at night in the Forbidden City, so the trap lamp cannot function. Pheromones have been a useful biological weapon for monitoring pests in the museum in

recent years. But it is not yet widespread in China, where few museums use it.

Insect pheromones are information substances secreted by insects and act on the same species of insects or other species of insects. Commercialized pheromones are mainly sex pheromones, aggregation pheromones, and alarm pheromones. Sex pheromones and aggregation pheromones have a luring effect, while alarm pheromones have a repellent effect. Using trap pheromones can monitor the situation of insects and have the effect of trapping and killing to control the pest. It should be noted that the use of pheromones to control the pest population is a long-term process, often showing effects in the second or third generation, and the longer breeding, the slower the period. Because of pheromone trapping, the population density of carpet beetles in 2019 was significantly lower than in 2018. So, pheromones have a control effect on carpet beetles. In the future, pheromones will be used to monitor and control pests in the Hall of Mental Cultivation for a long time.

As mentioned above, the trapped carpet beetles were mainly larvae. Because sexually mature individuals secrete sex pheromone, they act on heterosexually mature individuals and do not affect larvae. So, it suggests the potential the pheromone of carpet beetles should be aggregation pheromone. Compared with the sex pheromone that only affects single-sex and sexually mature individuals, the aggregation pheromone can gather both adults and larvae for food and labor. Thus, it can trap more pests and do better protection of cultural relics.

The following points should be paid attention to in the use of pheromone to trap pests. First, prevent and control

the mildew of pheromone substances or traps. Second, the effect will decrease if significant amounts of dust fall on the trap, so the trap should be replaced in time in this environment. One more to note, sanitary pests have no direct damage to the cultural relics. Still, their carcass can become an important food source for the carpet beetles [41], indirectly damaging the cultural relics. Therefore, timely replacement of the trap is essential.

Infested materials

The Hall of Mental Cultivation is rich in organic materials, an important food source for pests. First, the felts and carpets under the bed were infested by pests. The main reason being that these protein fibers are attractive to pests. Studies have shown that stained fabric is more attractive to pests [42]. Dyeing was also a form of stain of wool. So, these wool products dyed by sappan dyestuff or safflower yellow are more attractive to pests. Besides, no anti-insect compounds were detected.

Second, the wood grates were also seriously damaged by pests inside the hall. After identification, the grates in the western side hall were made of pinewood. Pinewood is an important coniferous material, as it is a softwood that furniture beetles [43], termites, and long-horned beetles prefer [44]. Fortunately, there were no termites in the Hall of Mental Cultivation area (termites were found inside the Forbidden City in 2006 and 2010 and were eventually brought under control). There was also much frass with a coarse, gritty feeling, the characteristic of furniture beetles infesting [45] in the buddha room and western side hall. However, no furniture beetles were trapped, which suggested that fumigation had a beneficial effect on killing furniture beetles.

To reduce the attraction to pests, we should try our best to put the silk relics, wool felts, and carpets into storage and replace them with synthetic fiber fabrics. It is also possible to use pheromones that are more attractive than food, decrease the contact chance between pests and cultural relics, and give a regular check to avoid damage. When repairing, the seriously damaged grates should be treated by pest control measures or replaced with hardwood that the furniture beetles dislike. However, it should also be noted that the powder-post beetles were also trapped, which like hardwood with high starch content [46], so wood with low starch content should be used or treated with reduced starch content [47].

Environmental factor

First, insect activity is closely related to temperature. The temperature in the Hall of Mental Cultivation is conducive to the safe overwintering of pests and satisfies their

rapid reproduction in summer. In addition, we have to face this reality, the greater consumption of pests, the greater threatening to cultural relics, under high-temperature conditions [12].

Second, wells increase the moisture in some houses, providing water needs for wet-loving pests, such as booklice, silverfish, and furniture beetles.

Third, the existence of cypress trees not only provides a source of nectar for carpet beetles but is also an intermediate host for long-horned beetles. Besides, the cypress can also shade the light and inhibiting the loss of water.

But beyond all that, the buddha room and other areas are not open to the public for a long time, and the quiet and dark environment is also conducive for pests to gather.

The emphasis on these environmental inducements can help us eliminate the reasons that make pests amass, destroy the environment where pests live, and find reasonable comprehensive ways to prevent pests. For example, by dehumidification, we can control the damage of silverfish, booklice, and furniture beetles. And the relationship between light and population raised an intriguing possibility because the larva of the carpet beetles is fond of dark environments; minimizing this dark space may also be an effective method to control the population of carpet beetles.

Chemical measures and control time

Various technical methods are available for killing pests in ancient buildings. Based on the principles of safe and efficiency, sulfuryl fluoride fumigation is still the primary choice for pest control in China. Through the investigation and research, it was found that, even in the severe areas where the sulfuryl fluoride dosage was increased in order to ensure the active pests had been killed, the carpet beetles and booklice still appeared in a short time. Therefore, the appropriate fumigating time is critical. First, the number of adults that go out should be as few as possible. Second, we must make sure that the spawning and egg hatching periods are staggered. Third, we must do regional control to reduce the spread of surrounding pests. The analysis of occurrence regularity in a year has important guiding significance for the control opportunity. In the Hall of Mental Cultivation, the number of active individuals (dominant pest: *Anthrenus picturatus*) increased rapidly from March to June, and in July and August was the biggest. Thus, summer is the best time for fumigation. During this period, the eggs have hatched, larvae are the main stage, the number of activity individuals is the largest, and the temperature is high; thus, the best fumigation effect can be achieved.

Except for the carpet beetles, silverfish, powder-post beetles, and spider beetles were equally trapped. The

quantity of these pests was not large, but only sporadic. This result was closely linked to their living habits. The above pests live indoors almost all their lives and rarely go out. Therefore, fumigation killed these pests relatively thoroughly. Under the effect of the buffer area, a few external individuals spread to the detection area. It also explained why furniture beetles seriously damaged the timber structures, but they were not trapped.

As mentioned above, the adult stage of the *Anthrenus picturatus* needs to fly outdoors and collect pollen and nectar. Therefore, we can also reasonably utilize this period to spray chemicals on the flowering plants from March to June, except for fumigation. While harsh the chemicals are used, they don't damage cultural relics because they are sprayed outdoors, not in contact with the interior cultural relics, this is also a preventive measure that is easily overlooked. It's safer than using pest repellent [48]. It is necessary to pay attention to select pesticides that are not sensitive to bees to not kill bees by mistake and cause ecological damage.

Conclusion

In the Hall of Mental Cultivation, there are side halls, back halls, enclosed rooms, wells, and trees, which have a superior architectural layout and enrich the ecological environment, which is a good representative for studying the pest occurrence regularity in the Forbidden City. It also has definite reference value to the investigation, analysis, and control of pests in Beijing and even the ancient buildings in north China. After fumigation, pests can still appear quickly. So, we must adhere to the principle of integrated pest management and adopt various technical means to control pests. Controlling temperature and humidity, reducing dark spaces and infested materials, and using pheromones are reasonable preventative measures. Using pheromones helps to explore the habits of pests, which is essential for their extermination. Because the optimal time for fumigation and chemical spray can be found according to the habits. It is of great practical significance to protect ancient buildings and cultural relics inside the Forbidden City.

Abbreviations

IPM: Integrated pest management; ANOVA: One-way analysis of variance; SPSS: Statistical product and service solutions; PVC: Polyvinyl chloride; PEG: Polyethylene glycol; UPLC: High performance liquid chromatography; QTOF: Hybrid quadrupole time-of-flight mass spectrometer; MS: Mass spectrometer; LE: Leucine encephalin; Temp: Temperature; RH: Relative humidity.

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Authors' contributions

ZG: the main person in charge of the investigation and analysis, responsible for the design and implementation of the investigation, the statistical analysis of data, and the identification of cultural relics. WL: participated in the organic component analysis of wool carpet. GA: participated in the design and guidance of the investigation. All authors read and approved the final manuscript.

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Availability of data and materials

All data generated during this study are included in this published article or are available from the corresponding author upon reasonable request.

Declarations

Competing interests

The authors declare that they have no competing interests.

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