Museum Pests–Cultural Heritage Pests

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Chapter 11
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Introduction

Many types of artefacts are vulnerable to deterioration from biological, physical and chemical sources. Artefacts that consist of organic materials, such as fur, hides, linen, plant material, wood, wool, etc., can be infested by a range of insects. Most heritage areas have collections which are at risk, including archaeology, prints and drawings, contemporary art installations, folk art, fine arts, ethnography, books and archives, industrial and technical heritage and natural sciences. The major factors causing deterioration are the agents of decay such as mould, insects and rodents and the environmental effects of humidity, temperature and light (Zycherman and Schrock 1988; Child 2001; Montanari et al. 2008; Pinniger 2009).

In the past, there was widespread use of many toxic or persistent materials, such as arsenic and mercuric chloride and DDT to prevent textiles and natural history specimens from being destroyed by pests. However, many treasures have been lost over the years to pests such as carpet beetle *Anthrenus* spp., webbing clothes moth *Tineola bisselliella*, and common furniture beetle, *Anobium punctatum* (Florian 1997; Carter and Walker 1999). In recent years, conservators and other museum staff have worked to develop alternative strategies for preventing and controlling pests. Integrated Pest Management (IPM) strategies have been developed and adopted with success. IPM strategies based on detection and prevention of pests have been successful in many small and large museums, museum stores, historic houses, galleries, libraries and archives worldwide (Rossol and Jessup 1996;

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Pinniger 2011a). There are many parallels with IPM in stored product protection and in the food industry. However, in the heritage sector, these methods have been modified to take account of the special needs of the historic collections and the buildings in which they are housed.

As a general concept, IPM emphasizes the integration of disciplines and control measures including biological enemies, cultural management, sanitation, proper temperature utilization and targeted pesticide use into a total management system aimed at preventing pests reaching damaging levels. For cultural heritage collections, prevention is better than cure, and any action which retards pest attacks is to be preferred to remedial treatments. Failing to prevent pest attacks will lead to the loss of objects, information and knowledge. Keeping optimal storage or exhibition conditions is part of the conservation approach known as 'preventive conservation', as defined by the European Confederation of Conservator-Restorers' Organisations (E.C.C.O. 2002): 'Preventive Conservation consists of indirect action to retard deterioration and prevent damage by creating conditions optimal for the preservation of cultural heritage as far as is compatible with its social use'.

The concept of IPM has been applied in museums and historic houses since the 1980s (see, for example, Story 1986; Linnie 1996; Albert and Albert 1988; Bennett et al. 1988). Strategies for museums and IPM concepts were described by Florian (1997), Kingsley et al. (2001), Pinniger (2001), Pinniger and Winsor (2004), Strang and Kigawa (2006), Querner and Morelli (2010) and Xavier-Rowe and Lauder 2011. Recent and complete works on IPM in museums were written by Brokerhof et al. (2007) and Pinniger (2009). The most important part of IPM is the prevention of pest attack. The control of the indoor environment plays a central role in preservation of cultural heritage collections. This is implemented by sealing the building, regulating the climate, periodical general cleaning, introducing quarantine and regular monitoring the collection with traps.

Beetles belonging to the families Anobiidae and Dermestidae and moths belonging to the family Tineidae are major pests of collections in art and natural history museums. Pests such as the webbing clothes moth, *T. bisselliella*, the case-bearing clothes moth *Tinea pellionella*, the drugstore beetle *Stegobium paniceum*, the common furniture beetle *A. punctatum*, different carpet beetles (*Attagenus* spp., or *Anthrenus* spp.) and silverfish *Lepisma saccharina* regularly cause problems in museums. Mice, pigeons and mould can also present a risk to collections in certain circumstances (Mound 1989; Strang and Dawson 1991; Pinniger 1994, 2009; Florian 1997; Ranacher 1998; Child 2001; Trematerra and Süss 2007). Also, there are many additional wood borers that can seriously damage the wooden artefacts or books, paper etc., such as termites and beetles such as Lyctidae, Bostrychidae and Cerambycidae.

This chapter will provide information on advanced and sustainable pest prevention and control strategies, to be used in worldwide cultural heritage institutions. The focus will be on alternative pest management strategies of insect pests.

Materials Most at Risk from Pest Attack

Materials most at risk from pest attack are animal skins, papers, dried food, dried plants and seeds, feathers, freeze-dried natural history specimens, fur, hair, insect specimens, materials rich in starch, parchment and vellum, sapwoods, silk, wool, and any damp organic material. Entire collections of books and entomological specimens have been lost; more common is damage such as holes or 'grazing' on the surface of textiles; an object's value for display can be lost and important decorative or aesthetic features destroyed. In general, dirty and neglected objects in dark places will be more at risk than those that are clean and in well-lit areas. The rate at which insect pest consume food is strongly affected by environmental conditions, the nature of the food materials themselves (e.g. age, nutritional value and specific composition). Furthermore, it seems that presence of organic dust is important for survival of some insect species. Improved knowledge about these factors may be an important tool for predicting the development of insect pest damage in various types of museum artefacts. Although moths (Lepidoptera) beetles (Coleoptera) and termite (Isoptera) species cause most insect pest problems, other insects, such as cluster flies (Calliphoridae), ants and cockroaches can also cause a great nuisance. Vertebrates (rodents and birds) can damage collections by eating them, shredding them for nesting material and staining from their urine and faeces.

Developing an IPM Strategy

In the past, chemical methods were used for control of pests in cultural heritage collections. However, this has proved problematic with regard to deposition of unwanted chemicals on the artefacts, and unwanted side effects on humans. In recent years most museums have turned to non-chemical methods as alternatives, these control methods include the use of high or low temperatures, or low oxygen atmospheres (Rossol and Jessup 1996; Florian 1997; Ranacher 1998; Pinniger 2001).

The key to avoiding pest infestations is to understand the conditions under which they thrive. The four principal needs for these pests are food, warmth, humidity and harbourage. These factors are often inter-linked. It is also important to develop procedures, such as quarantine of incoming material, so that a pest is not introduced as a result of normal collection activities. It is also important to identify degrees of risk from pests to collections on display and in store. The concept of 'Risk Zones' is based on the principle of assessing each area of a museum or historic house and assigning a Risk Zone, either Very High (red), High (orange), Low (yellow) or Very Low (green). Procedures for monitoring housekeeping and action plans are then based on the appropriate zone (Doyle et al. 2007). This Risk Zone approach is now being used successfully as the basis of IPM programmes in a number of museums in the UK (Pinniger 2011a).

Developing an IPM strategy:

- prevent entry of pests (insects, birds, and rodents) into buildings;
- develop good exterior building maintenance and appropriate landscaping;
- avoid practices and habits that attract pests;
- moderate interior high humidity and temperatures;
- develop good interior housekeeping practices;
- maintain appropriate food/trash removal practices;
- assess all display and storage areas for risk from pests and assign appropriate risk zones;
- set up and implement measures to detect and monitoring pests;
- inspect all incoming museum objects;
- inspect stored collections periodically for pest activity;
- take actions that reduce the source and spread of the pest infestation;
- isolate infested materials, and choose the most appropriate safe control method (s) for eradication.

Reviewing the IPM procedures, with periodic assessment of the effectiveness of the strategy and modifying in order to improve it.

Cleaning is probably the most important part of any IPM programme. The material that attracts insects is normally organic, such as leather and wool, paper, wood, though some insects can make do with dust and fluff derived from these. A close examination will usually show accumulations of organic dirt and debris in corners, wall/floor angles and behind fittings that will support and feed insect pests. Unused rooms and storage areas are often neglected and dirt and debris will provide food and an ideal harbourage for pests. Periodic deep cleaning of stores is recommended. All horizontal surfaces where dust and rubbish can accumulate should be cleaned, including the tops of storage and display units, light fittings and ledges, etc. Special care should be taken in less accessible areas.

Common sites where pests hide within buildings undisturbed by human activity include: unused or little frequented rooms and cupboards; cracks between floorboards; cavity walls and floors; gaps between walls and floors; dead spaces behind and under storage cabinets; heating and ventilation ducts; felt sealing strips on doors; old or discarded display material; deaccessioned material which has not been removed from the site, etc. Many of these sites are difficult to inspect.

Temperature

Cool conditions will discourage insects from breeding and any areas with temperatures of 20 °C and above will encourage insect breeding. Temperatures of 24–25 °C will allow insects to complete their development much more quickly. This may result in pests such as clothe moths completing two or more life cycles in a year. Although it may not be possible to lower temperatures in public areas, object stores should be at as low a temperature as is practical. However, ensure that the relative humidity levels are not permitted to rise to unacceptable levels. Direct sunlight can cause local hotspots even in cool areas, and preventive measures such as shading should be installed. Also, uneven temperatures can result in localized condensation on cool walls. Vertebrate pests are much more tolerant of high or low temperatures than insects. They have much better temperature regulatory systems and so have more potential nesting sites available to them.

Humidity

Many insect species can tolerate a wide range of relative humidity (r.h.) and some will survive for long periods in a dry environment, for example, the biscuit beetle, *S. paniceum,* but other species, such as furniture beetle *A. punctatum*, need a damper environment. Silverfish, *L. saccharina*, will only breed rapidly and cause serious problems in conditions of above 70% RH. Booklice (Psocoptera), also need a higher level of humidity, they are often found in damp basements or in localized damp areas. However, there are species that can survive at r.h. levels that are close to 60% (Opit and Throne 2008). Some other insects have a strong preference for environments with a higher r.h., this is because at these levels moulds and fungi have begun to attack their food sources making it easier to digest. Vertebrate pests need water to live, so it is important to eliminate potential sources of drinking water such as leaking pipes and taps, and cover all open drains with securely fitted wire mesh screens. By establishing appropriate environmental conditions, it is possible to limit the threat from a large number of potential insect pest species. This can be achieved by mechanical means but you also need to ensure that there are not localized areas of high humidity where some pests will thrive. These can be caused by condensation, poor damp proofing, broken or missing damp-proof courses, or leaks from gutters or water, sewage and heating pipes.

Inspection Area/Quarantine Area

An essential part of any pest prevention policy in a museum is to keep pests out of collections. Insects can be introduced from many sources, including new acquisitions, objects on loan from other collections and items returned from loan. A quarantine area must be established which is physically isolated from display areas and collection storage. Objects must be checked for infestation before being allowed into the main collection areas, whether storage or display. Inspection may reveal insect damage and clothes moth webbing, but insect eggs or small larvae are more difficult to see. Similarly, the emergence holes of wood boring insect may be obvious but any developing larvae will be hidden in the wood. If it is suspected that there may be an active infestation, the objects should be isolated and allowed to incubate over a period. If adult insects are seen to emerge, then remedial action can be taken. Pests may also be living in non-collections objects such as figures or other ‘props’ in displays. Packing materials may also be infested and will need to be checked and possibly treated or disposed of. Some museums have established procedures that treat all appropriate items, when they are acquired or on return from loan (Pinniger 2011b).

Keeping Pests Out

Good building construction practice and subsequent maintenance are essential if insects are to be kept out of a building. Excluding pests from older and historic buildings is often far more difficult. Most modern buildings successfully prevent the entry of pests by careful design and detailing of potential entry points such as doors, windows and vents (Scott 1991; Trematerra and Fleurat-Lessard 2015). All unnecessary openings should be blocked. Check brickwork for cracks and damaged pointing and initiate remedial work as soon as possible. Doors and windows can be fitted with unobtrusive sealing barrier strips. Windows and doors can be fitted with fly mesh screening; splits and holes in wooden doors and windows or their frames should be caulked. Cupboards, cabinets and drawers, which may appear to sound, should be inspected because they may have hidden cracks that can allow insect access. Particular attention needs ground, basement and roof areas. Where it is aesthetically acceptable, it is worthwhile cutting back vegetation for at least 3 m around the perimeter of buildings.

Specific measures to exclude rodents include wire mesh screens and grills fitted to ventilation louvre or other openings that cannot be sealed; sheet-metal cladding fixed to the base of wooden doors, windows or walls in high-risk areas or where there are signs of gnawing; insert steel mesh into gaps around pipes and in eaves to prevent access but without restricting ventilation; ensure that exterior drain covers and rodding caps are sound and close fitting; and fitting metal cones or screens around exterior pipework, cables and poles (Doyle et al. 2007). Measures to discourage birds from nesting or roosting include netting or wire screens fitted over balconies, alcoves, light wells and other openings. Steel mesh fitted into the gaps in eaves will prevent access, but without restricting ventilation. Prevent birds perching on ledges and sills by fitting sharp metal wire spikes and strip; anti-perching gel. Spikes (pins) and wires are more expensive but more durable. Cap chimneys to prevent birds getting inside and nesting.

Identifying Pests and Pest Activity

Although it is often the adult insects that are found, it is the larval stage that does the most serious damage. Adults will be more active and obvious during the warmer summer months but the larvae will feed and grow throughout the rest of the year. Signs of activity may include emergence holes and dead adults, but also silk webbing and cast skins of larvae and frass (Moud 1989; Pinniger 1994; Florian 1997; Chiappini et al. 2001; Trematerra and Süss 2007; Trematerra 2016). Some insect species are widespread and are a serious threat to cultural heritage items as they feed on a large range of organic materials.

Typical signs of a rodent problem are as follows: gnaw marks near the base of doors and cabinets. They can gnaw through wood, particleboard, plaster and asphalt, as well as soft metals such as zinc, lead and aluminium. Faecal droppings and urine stains may also be seen. Rats do not normally have a distinctive odour but mice have a musty smell reminiscent of stale biscuits. The house mouse, *Mus domesticus*, is the main cause of concern, although in many collections and historic houses the fear of infestation is often far greater than the real risk. Functions, cafes and restaurants which provide ample supplies of food for rodents are the main source of infestation problems. Brown or Norway rats, *Rattus norvegicus* and black rats, *Rattus rattus*, are rare in museums and usually only found associated with considerable and accessible sources of human or animal food (Strang and Dawson 1991).

The most common bird pests are pigeons (*Columba livia*). Roosting or nesting birds can be a nuisance on windowsills, ledges and other architectural features. Their droppings, which are mostly urine through which they excrete uric acid, cause unsightly stains and can damage the building fabric. These droppings pose a health hazard to humans as pigeons carry parasites and spread disease. The nests, feathers and other debris attract insect pests such as clothes moths and carpet beetles, and these can move into the building and cause damage to the collection. Birds can also become trapped in chimney flues, where they quickly die and become an attractive food supply for several insect pest species.

Museum Pests

Any insect pest with chewing mouthparts is a risk to museum specimens. Carpet beetles, clothes moths, powderpost beetles, cockroaches and others pose threats to specimens through feeding damage, frass, faeces and excretions. Some pests pose indirect risks such as fires (rodents gnawing on wires) and secondary infestations (dead cluster flies in attics can attract carpet beetles). Any insect pest that infests houses, restaurants or other buildings may at some time also become a pest in a museum. They can loosely be grouped into five categories: textile pests; wood pests; stored product pests; pests associated with mould and high humidity; general pests. The first step in solving any pest problem is to identify the pest and learn about its biology and habits. The identification of the insects present in heritage sites is essential in order to undertake preventive and curative measures. Frequently, the accurate identification of the insects requires complex keys often based on very specific morphological characters. This identification becomes even more difficult when considering the larval stages of insects. Therefore, accurate identification very often requires verification by entomologists.

Textile Pests

Most insect damage to textiles is caused by carpet beetles (family Dermestidae) or clothes moths (families Tineidae). The adults may be attracted to lights and windows, but this is not the stage that does the damage, as adults feed outside on pollen or not at all (Aitken 1975). It is the larva stage that feeds on fabric, fur, feathers or virtually anything made of animal fibres.

Carpet Beetles

Immature carpet beetles feed on dried animal products such as wool, silk, felt, hair, fur, feathers, dead animals, and taxidermy. The adults are often seen in spring crawling up walls and congregating on window ledges. Carpet beetle larvae are repelled by light and are usually found burrowed deeply into the infested material or in little-used drawers, cases and storage bins. Four species of carpet beetle are most likely to be found in museums (Fig. 11.1a).

Anthrenus (carpet beetles)

Adult *Anthrenus* are 2–3 mm long and covered with grey and gold scales; they fly in warm weather and may frequently be found on windowsills. The eggs hatch into short, fat, hairy larvae which are extremely small (less than 1 mm) and can get through very small cracks. As the larvae grow, they moult leaving empty hairy, cast skins which may be the first signs of attack. The larvae will wander widely and chew holes in textiles, bindings and mounts with animal glue. They eat other protein-rich material such as wool, fur, feathers, silk and skins. They will also feed on dead insects and are often found in birds' nests. One of the most common species worldwide is the varied carpet beetle, *Anthrenus verbasci*, a destructive pest of textiles and natural history specimens. There are a number of other species of *Anthrenus* including *Anthrenus flavipes, Anthrenus sarnicus* and *Anthrenus scrophulariae*.

Anthrenus verbasci (varied carpet beetle) is primarily a scavenger, and it is common in the nests of birds and on dead animals. It can damage woollens, carpets, wall hangings, hides, horns, taxidermy and bone artefacts, and insect collections. Small populations often go unnoticed behind furniture or along baseboards feeding on

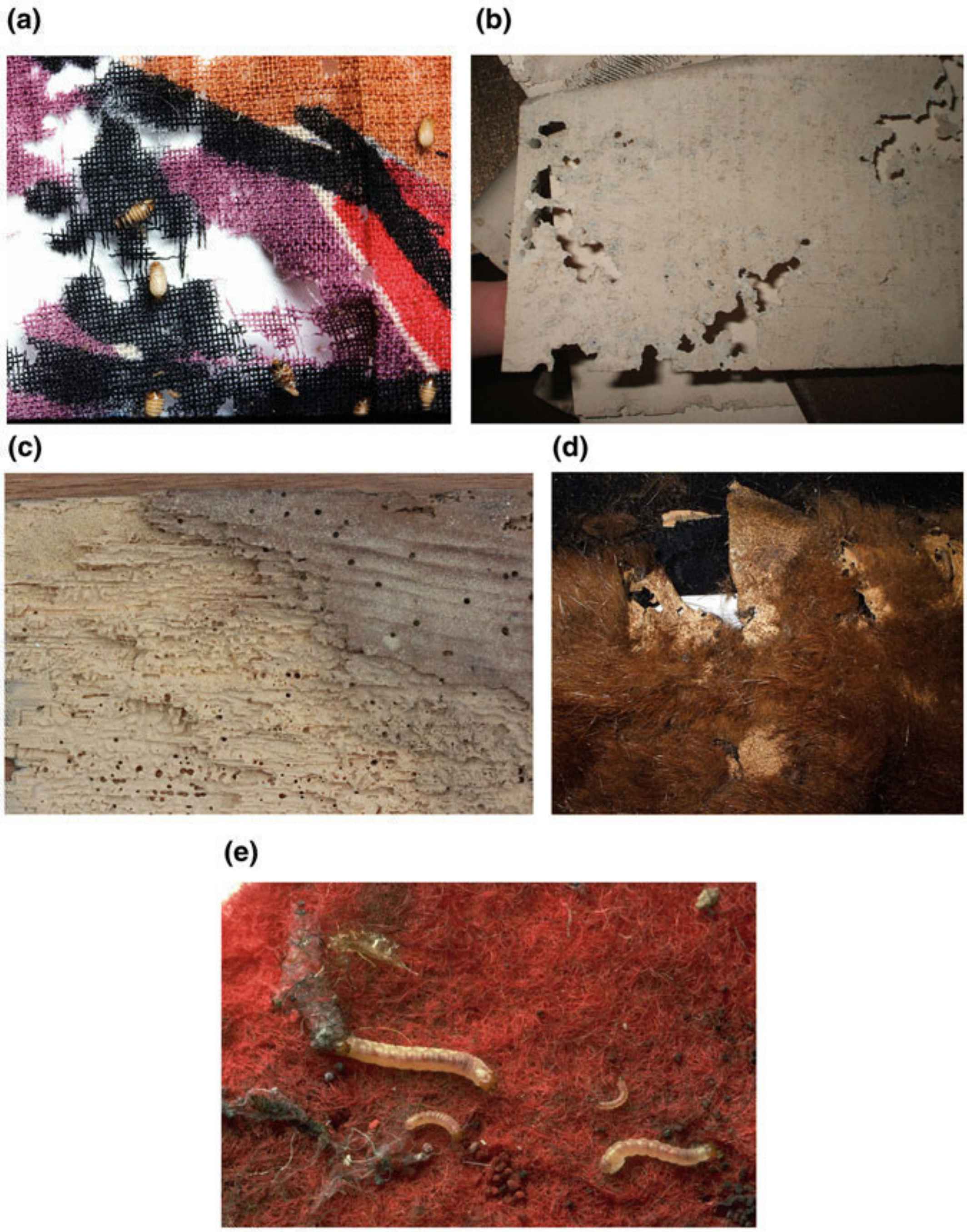

Fig. 11.1 **a** Infestation of *Anthrenus verbasci* carpet beetle larvae eating wool textile © DBP Entomology **b** Damage to paper documents by silverfish *Lepisma saccarhina* © DBP Entomology **c** Damage by furniture beetle *Anobium punctatum* to a wood floorboard from a historic house © DBP Entomology **d** Damage to a fur coat lining by webbing clothes moth *Tineola bisselliella* © DBP Entomology **e** Larvae of webbing clothes moth *Tineola bisselliella* eating wool felt textile © DBP Entomology

accumulated lint, hair, food crumbs, dead insects and other organic debris. The adult is 2–4 mm, oval to round, with patches of white, yellow and black scales on its back. The larva is teardrop-shaped and covered with rows of spiky brown hairs.

Anthrenus flavipes (furniture carpet beetle) attacks furniture (particularly old horsehair-stuffed furniture) and items made from wool, fur, feathers, silk, horns and tortoiseshell. It is commonly found in the USA and warmer parts of Europe. The adult is 2–4 mm and is rounded and blackish with variable mottling of yellow and white scales on the back and yellow scales on the legs. The larva is much darker and more hairy than the varied carpet beetle.

Anthrenus scrophulariae (common carpet beetle) attacks carpets, woollens and animal products such as feathers, furs, leather, silks, mounted museum specimens and pressed plants. It is mainly found in the USA. The adult is 2–4 mm with a band of orange scales down the middle of its back. The larva is reddish brown and covered with brown or black hairs.

Attagenus (fur and carpet beetles)

The genus *Attagenus* are mainly scavengers on the dried material of animal origin. Adults are oval, hairy beetles 3–5 mm long. Several species are uniform black in colour. Larvae are tapered, hairy and elongate, and when grown are about 10 mm long. Household infestations typically start from birds' nests and dead birds or rodents in roof spaces or wall cavities. They may also be found in the nests of bees and wasps. Adults can also be found feeding on nectar on flowers.

Attagenus unicolor (black carpet beetle) is the most abundant and destructive of these carpet beetles in the USA and some European countries. The adult is 3.5–5 mm long, a solid dark brown or dull black colour, and more elongate than *Anthrenus* carpet beetles. The larva is tapered from the front carrot-shaped. It is covered with bands of golden brown hairs and has a characteristic 'tail' of long hairs at the rear end.

Attagenus pellio (the two-spot carpet beetle) is found in the cooler parts of North America and Northern W Europe. The adult is 3.5–5 mm long, a dull black colour with two distinct white spots on each wing case. The larva is tapered carrot-shaped covered with bands of dark brown hairs and has a characteristic 'tail' of long hairs at the rear end.

Attagenus smirnovi (brown carpet beetle or vodka beetle) is a recently introduced pest to Europe, but has spread rapidly to many countries including Denmark, Sweden and the UK (Pinniger 2011a). The adult is 3.5–5 mm long, dark brown with a black thorax and head. The larva is tapered carrot-shaped covered with bands of brown hairs and has a characteristic 'tail' of long hairs at the rear end.

Dermestes

Dermestids are 2–12 mm long oval or elongate oval beetles with short, clubbed antennae. They usually have a distinct colour pattern, and many are covered with fine setae or scales. Larvae and adults of *Dermestes* species feed on many dry substances of animal origin such as bones, dried meats, feathers, fur, glue, leather and skins; they may also attack food products of vegetable origin. Some museums use cultures of *Dermestes* for cleaning animal carcasses to prepare skeletons and as they can cause havoc if they are allowed to spread into other areas, they should never be used on the museum site.

Dermestes maculatus and ***D. peruvianus*** (hide and leather beetles). The hide or leather beetles, as the name suggests, will attack leather and skins but they will not feed on tanned leather in good condition. The larvae can be found on dead animals, and they also attack book bindings with animal glue. The adults are black or dark brown and larger (6–10 mm) than carpet beetles. The larvae are also dark brown and large and very hairy and they have two distinctive spikes at the back end. The larvae have a very destructive habit of tunnelling into objects to pupate and they make big holes.

Clothes Moths

These are small, silvery-gold moths with a wingspan of 10–15 mm. They have narrow wings fringed with long hairs. They avoid light and are rarely seen flying, they prefer dark corners, closets, and storage areas, and usually remain out of sight. A number of species of moth will attack and cause serious damage, the larval stage causes damage to woollen clothes and objects such a feather hats, dolls and toys, bristle brushes, weavings, and wall hangings, they very rarely damage books and papers (Fig. 11.1d, e).

Tineola bisselliella, the webbing clothes moth, and ***Tinea pellionella***, the case-making clothes moth, are the two most common clothes moths found in museums both have a wide distribution. The larvae feed on the surface of the material infested. The webbing clothes moth larvae produce feeding tunnels of silk and patches of silken webbing on the fabric's surface. The case-making clothes moth larva is rarely seen since it constructs a cylindrical case of fabric, which it carries around to hide and feed in. The grain moth ***Tinea granella*** was found on dried plants, corks dried animals and fungus (Trematerra and Süss 2007; Trematerra 2016). Other moth species such as the white-shouldered house moth, ***Endrosis sarcitrella***, and the brown clothes moth, ***Hofmannophila pseudospretella***, are very common in old houses where they can be often found in bird nests in blocked chimneys. The larvae will occasionally tunnel into bindings of books but very rarely cause damage to clean, dry materials. Larvae of Indian meal moth ***Plodia interpunctella*** live on foods, dried herbs and spices and may be found in food areas.

Wood Pests

Materials made of wood are susceptible to attack by a number of wood infesting pests. The culprits in museums in cooler countries are furniture beetles and in hotter climates, it is usually powderpost beetles or drywood termites, but often other termite categories, such as the subterranean termites. All can severely damage valuable artefacts because the larvae are hidden away in the wood.

Powderpost Beetles

The term powderpost beetle applies to any of two related families: Lyctidae (true powder pest beetles that cannot digest cellulose and usually attack the sapwood of hardwood), and Bostrychidae (false powderpost beetles that attack both softwood and hardwood). The term ‘powderpost’ comes from the very fine, powder-like frass (excrement and bits of wood) produced by the feeding process. Powderpost beetles infest wooden artefacts and materials such as frames, books, toys, furniture, tool handles, gunstocks, bamboo, lumber, panelling, and crating, as well as girders, studs, flooring, and other wooden building components. Look for exit holes where the talc-like beetle frass will be found.

Adult powderpost beetles, ***Lyctus brunneus, L. linearis*** and often ***L. africanus***, leave exit holes which are circular 0.8–1.6 mm diameter, the frass is loose and has a very fine powdery consistency. There are many species of Bostrychid beetle ranging from the very small bamboo borers ***Dinoderus minutus*** or ***D. brevis*** to the large ***Heterobostrychus***. The adults leave exit holes which are circular 1.5–7 mm in diameter. The frass has a tendency to stick together in clumps, feeling more gritty to the touch powderpost beetle spend most of their lives unseen as larvae tunnelling within wood, so their frass and the exit holes they make in the wood’s surface as they emerge as adult beetles are the primary signs of their presence. In warm conditions, the life cycle can be completed in a year. The adult beetles are short-lived and seldom seen.

Furniture Beetles

The common furniture beetle or woodworm, ***Anobium punctatum***, is widespread in most temperate countries where it infests buildings, furniture and wooden objects and may also attack books. The larvae make tunnels in compressed paper and take 2–5 years to complete development depending upon the food and the conditions of temperature and moisture content. Adults emerge in spring leaving small 1.5–2 mm exit holes with a pile of gritty frass below the hole. *Anobium* infestations will survive in cool, damp conditions but do not thrive in hot, dry conditions with humidities below 65%. Outbreaks of woodworm activity are usually confined to collections which have been brought in from damper storage in cellars, outbuildings or areas where there are leaks, condensation and poor air circulation. *Anobium* larvae will attack wooden shelving and wooden boards in books, preferring starchy hardwood and softwood, they will not attack sound heartwood. Plywood or bindings with animal glue are particularly susceptible, because of the added protein, and can be severely damaged (Fig. 11.1c).

Other Anobiidae beetle species which have recorded as attacking timber and books are ***Xestobium rufovillosum*** (death watch beetle), ***Catorama herbarium*** (the Mexican book beetle), ***Nicobium castaneum***, ***Ptilinus pectinicornis***, ***Ernobius mollis***, ***Oligomerus ptilinoides*** and ***Gastrallus imarginatus***.

Termites

Termites are the world's most serious and destructive pests of structural timber. In many museums, libraries and archives, termite infestation of the buildings has spread to display and storage furniture, archives and book collections, which are then seriously damaged. There are many different species of termites and they are generally divided into two pest types with distinctly different lifestyles—drywood and subterranean. Termites are not a serious problem in cool temperate countries and the most severe problems are encountered in countries with warm temperate and tropical climates (Daniel 2001).

Cryptotermes and ***Kalotermes*** (drywood termites). Drywood termites, which include the genera *Cryptotermes* and *Kalotermes*, bore tunnels and galleries in wood in many directions, and also live in compacted paper and books. Although some faecal pellets are scattered in the passages, large quantities are often stored in chambers or thrown out of the wood through 'toilet holes'. Drywood termites attack wooden items of all kinds and establish colonies in dry, sound wood with low levels of moisture and do not require contact with the soil. Most infestations are in building structures but they may spread into furniture and wooden objects in museum collections which are then attacked. The excavated galleries or tunnels feel sandpaper-smooth. Dry and loose, their distinct six-side faecal pellets are found in piles where they have been kicked out of the chambers. Other than the pellets, there is very little external evidence of drywood termite attack in wood as they tend to work just under the surface of the wood. Swarming winged adults may also be a sign of an infestation. Winged termites have four wings of equal length and when the wings, are shed after swarming they may be visible. However, given that usually swarming occurs only once per year, termites usually remain unseen during most of the time.

Reticulitermes, ***Coptotermes*** and ***Macrotermes*** (subterranean termites). Subterranean termite colonies need to live in contact with soil and some species, including *Reticulitermes*, *Coptotermes* and *Macrotermes*, will spread from the natural environment of soil and trees to the woodwork of buildings. Many species require fungi in their diet, which is produced on decaying wood or paper within the nest. They need to maintain high levels of moisture in the colony for the development of fungi and to prevent the desiccation of the nymphs and workers. This leads to the characteristic tube-building habitat of subterranean termites. These tubes, which may be some metres in length, are constructed of soil and faecal material which protect the termites as they pass between nests in the soil to the food sources of wood or paper. Subterranean termites are found near or below ground level and seldom spread above the lower floors, this means that collections in basement areas are particularly at risk. They may invade libraries and archive stores and completely destroy the inner parts of books and bound archives, just leaving an outer skin of bindings or packaging. The eradication of termites and their subsequent exclusion can be extremely difficult and often requires specialist expertise.

Pests of Dried Food

Many museums include items made in part of seeds, nuts, grains, spices, dried fruits and vegetables, and other foods. A long list of pests, traditionally called stored product pests, can infest items containing these foods. Probably the most common of such pests in museums are the cigarette beetle and the drugstore beetle.

Stegobium paniceum (Biscuit beetles or drugstore beetles). *Stegobium* belongs to the Anobiidae, the same family as the common furniture beetle or woodworm, *A. punctatum,* although it will not attack wood. When it is warm (above 22 °C), the adults are very active and will fly to light sources. *Stegobium paniceum* is a major pest of dried plant specimens, and it is also a serious pest of books and manuscripts where it usually lives in the starchy bindings. It has also been found living in dried animal specimens and mummies larvae feed by tunnelling through a wide variety of foods and spices (particularly paprika or red pepper and has been known to chew through tin foil and lead sheeting). The adult drugstore beetle is rounded, reddish brown and hairy it has a three-segmented antennal club.

Lasioderma serricorne, cigarette beetle, is named for the fact that it is a pest of stored tobacco, but is also a serious pest of flax, spices, crude drugs, seeds, and, most importantly for museums, books and dried plants. This beetle has been called the 'herbarium beetle' in hotter countries because of the damage it can cause to dried herbarium specimens. It has also been found infesting rodent baits. The adult beetle is very similar to the cigarette beetle but smaller and much shinier antennae with 14 elements.

Pests Associated with Mould and High Humidity

Moulds are fungi that can cause damage or disintegration of organic matter. When moisture and other environmental conditions are right, mould spores can germinate and develop and cause significant damage to wood, textiles, books, fabrics, insect specimens, and many other items in a collection.

Psocids or Booklice

They feed on microscopic mould growing on paper and in the starchy glue in the binding. Psocids also infest such items as dried plants in herbaria, insect collections, manuscripts, cardboard boxes, and furniture stuffed with flax, hemp, jute or Spanish moss. Psocids are so small they rarely cause serious damage. However, their presence often indicates a moisture problem and the likely presence of damaging moulds. They are tiny insects, less than 1–2 mm, and range in colour from clear to light grey or black. Most indoor psocids are wingless.

Liposcelis bostrychophila and other species of *Liposcelis* (booklice). There are a number of different species of booklice which have very different habits and needs. *Liposcelis bostrychophila* is the most common species in heated buildings (Florian 1997). The adult is wingless and very small (less than 1 mm). They develop through a series of nymphal stages which feed on microscopic moulds on a range of substrates including flour, paper and cardboard, dried plants, herbaria, insect collections, manuscripts, cardboard boxes, furniture stuffed with flax, hemp, jute or moss. Populations of *Liposcelis* can increase very rapidly if temperatures rise above 25 °C (Opit and Throne 2009), and this gives rise to apparent population explosions. Although damaged by a few booklice may be negligible, large numbers of booklice will graze the surface of books and papers. In addition, squashed bodies will stain materials and may encourage moulds.

Adistemia spp., ***Cryptophagus*** spp. and ***Mycetophagus*** spp. (plaster beetles and fungus beetles). There are many species of these small brown beetles, 1–2 mm long, including ***Adistemia watsoni***, ***Cryptophagus nitidulus***, ***Mycetophagus quadriguttatus***. They feed on microscopic moulds and are often found in large numbers when papers and books are stored in damp areas. As they graze, they may cause some superficial damage to the surface of the paper.

Crustacea (Woodlice)

Woodlices are not insects but belong to the Crustacea, which also includes shrimps and crabs. There are a number of species that come into buildings, most are greyish-brown and range in size from a few millimetres to 15 mm. Woodlice live in damp, rotting vegetation and wood and may graze on damp paper and cardboard. They are often found in basements or near doors and windows where they have wandered in from damper outdoor environments. As they cannot survive for long in dry conditions, most soon die of desiccation without causing any damage. If there is a persistent problem of live woodlice, the area should be investigated as there is probably local high humidity and rotting wood.

General Pests

Any household pest may become a pest if it gets into a museum. Cockroaches, silverfish, ants, rodents and other common pests can invade and cause problems in museums.

Cockroaches

Cockroaches are omnivorous and feed on leather, paper, glues, animal skins, hair and wool fabrics, especially if the item is stained with food and sweat. German cockroaches ***Blattella germanica*** (10–16 mm) are found indoors in warm, humid areas, preferring crevices near food and water in bathrooms and kitchens. The brown-banded cockroach ***Supella longipalpa*** (11–14 mm) is also found indoors and requires less moisture. The German and brown-banded cockroaches are the only known domestic cockroach species that depend on human activities for survival. The oriental cockroach ***Blatta orientalis*** (18–28 mm) prefers decaying food, is cold tolerant and prefers damp areas with temperatures below 29 °C. In warmer countries, it can be found in bark mulch around the perimeter of buildings. The American cockroach ***Periplaneta americana*** (28–53 mm) requires a water source and prefers fermented foods. It can be found in sewers and basements, particularly around drains and pipes. Cockroach faecal pellets can resemble small mouse droppings without pointed ends. All species lay their eggs in egg cases (oothecae), and then these hatch into tiny nymphs which develop rapidly in the right conditions. Identification of the insect adults, nymphs and egg cases and an understanding of its life cycle are critical to determine what are the risks and assess the most appropriate control measures. ***Blaptica dubia*** was reported by Montanari et al. (2008) as pest of photographs.

Lepisma and ***Ctenolepisma*** (Silverfish). Silverfish are always associated with damp conditions and they require localized humidity above 70–80% to breed and multiply. They are primitive, scaly, wingless insects (10–15 mm) with three bristles (cerci) at the tail end. Silverfish feed on starch, glue, ink and microscopic moulds paper, paper products and textiles (cotton or artificial silk), they will also eat organic glue on wallpaper. There are a number of silverfish species including ***Lepisma*** and the larger ***Ctenolepisma***. Silverfish damage can be recognized by the ragged, scraped surface areas and irregular holes in paper. They are serious pests in humid countries, but in temperate climates, they are usually confined to damp rooms and basements (Fig. 11.1b).

The related firebrat ***Thermobia*** will also damage paper, photographs and bindings but needs hotter and drier conditions.

Ptinus tectus and ***Niptus hololeucus*** (spider beetles). Spider beetles are common in birds' nests and general debris in attics, basements and stores where they will feed on a wide range of vegetable and animal detritus. The adults are 3–5 mm, hairy and superficially spider-like. The brown, hairy Australian spider beetle, ***P. tectus***, and the golden spider beetle, ***N. hololeucus***, are common in many temperate countries. The larvae are similar in appearance to those of the biscuit beetle and they will also boreholes and cavities in paper and wood before pupating in a globular silk cocoon.

Rodents and Birds

Rodents and particularly mice, *M. domesticus*, will seriously damage paper when the female mice collect and shred paper to make nests. They will also damage books by their habit of gnawing hard objects to keep their teeth sharp. Additionally, mouse urine and droppings can stain paper and also present a disease hazard.

Birds (like pigeons) will rarely directly damage books but droppings can be unsightly and corrosive.

Monitoring

Regular checking is needed to look for live adults and larvae and the presence of shed larval skins or faeces. The presence of fresh feeding debris or frass around or below specimens is an indication of an active infestation. Exit holes, feeding holes, hair falling from fur or pelts, mats of fibres, silken feeding tubes or cases, or moth or beetle pupae are also signs of activity. Windowsills and the inside of ceiling light fixtures should be checked on a regular basis as many pests fly or crawl to light. Pests may be found behind baseboards, under furniture, behind mouldings, in cracks in floors, behind radiators, or in air ducts.

The Use of Insect Traps

Traps are used to detect the presence of insects and rarely to control them. Trap catches can show an increase in insect numbers in a specific area; the spread of a pest from one area to another; an invasion of the adult insects in summer; or the failure of a control treatment. Traps should be used as a supplement to visual inspection but not as a replacement. The information they provide can then be used to identify what preventive and remedial measures are required and to establish priorities.

A range of sticky traps is available that work on the principle of the wandering insect blundering into the trap and becoming stuck on the non-toxic adhesive surface (Pinniger 2009; Child 2011). The traps for Coleoptera are designed to be placed on the floor and are most effective when placed in corners and wall/floor angles, traps for Lepidoptera are designed to be suspended (at about 2.50 m from the floor) in the environments. In historic houses, place a trap in fireplaces to check for pests in blocked and disused flues.

Most traps will remain effective for at least a year and need to be checked at regular intervals. It is better to check regularly every two months than to start by checking every week and then finding that the workload is too great. A minimum regime would be to check traps four times a year, in March, June, September and December. It is also important to check the stickiness of the trap at the same time as you check for pests. Dust can build up on the adhesive which renders it useless. The greater the number of traps used, the greater is the chance of finding insects. However, the workload should not be underestimated and trapping programmes should be designed to be manageable. Traps should be placed in a regular grid pattern and all traps date labelled and their position marked on a plan.

Insects caught in traps should be identified and the information recorded in a log. Record whether the insects caught are larvae or adults as an adult beetle may simply have wandered in from outside. If it is a larva then it is almost certain that the species is breeding within the building. Over a period of time, careful monitoring of the traps enables a picture to be built up of insect distribution. Additional traps can be placed in areas where pests need to be more accurately pinpointed.

Large numbers of non-pest insects may be caught on traps, especially if they are near an outside door. When this happens, the traps should be replaced as the trapped insects can act as a food source for pest species. Moreover, even in pheromone traps, the capture of non-target species is very common, hence, it is essential that the insects captured should be identified, at least up to the group of species level noted above (wood borers, psocids, etc.).

Pheromones

Pheromone traps are one of the most valuable new tools for pest management in museums. Traps useful in museum settings include those for cigarette beetles, drugstore beetles, Indian meal moths, and warehouse beetles (*Trogoderma*). Trapping procedures vary depending on whether the objective is monitoring or control. Pheromone traps are generally effective when pest numbers are very low and they can be qualitatively used to provide an early warning of pest incidence. They are useful in defining areas of pest infestation, particularly in cases when the overall distribution and life cycle are poorly understood. Simple mathematical models are needed to interpret pheromone trap catches and to provide predictions of pest population dynamics and distributions (Hagstrum and Subramanyam 2006).

Multiple pheromones for different species can be employed in single traps where no interspecific influence of the semiochemical attractants has been shown. Pheromone traps are currently available for *T. bisselliella*, *T. pellionella, Trogoderma* spp., *L. serricorne*, *S. paniceum*, *B. germanica*, *A. verbasci* and *Attagenus* spp. The lures are extremely effective, but will only attract the males of the target species and have no effect on other insect species. Some species, such as *S. paniceum*, are only attracted to pheromones when there is a light source and are not effective in the dark.

Various studies have reported success in the mass trapping and attracticide method in the control of *L. serricorne* and *P. interpunctella*. Against *Trogoderma glabrum* attracticide method utilized pheromones in an inoculation device contaminated with some kind of pathogen (*Mattesia* spp.), or in the control of *P. interpunctella* with granulosis virus. In mating disruption, several successful experiments have been reported, such as for *A. unicolor* (*megatoma*), *L. serricorne, P. interpunctella*, *S. paniceum* and *Trogoderma inclusum* (Trematerra 2012). Trial evaluation of the Exosex CL tab™ pheromone disruption system for *T. bisselliella* has shown that populations of moths can be suppressed when it is used as part of an IPM programme (Lauder 2011). A preliminary field study in the USA suggests that release of the synthetic sex pheromone serricornin can significantly inhibit proper orientation of male cigarette beetles *L. serricorne* to females and result in reduced reproduction (Trematerra 2012).

Ultraviolet light traps can be useful for detecting and controlling some flying insects, particularly flies and some moths. These traps must be checked and emptied periodically or the dead insects will themselves attract dermestid beetles and other scavengers. For these traps, there are designs that are very discreet, in order not to be visible from the visitors.

For most pests in the immediate museum area, the action level will be one live specimen. Presence of live adults or larvae indicates ongoing infestations, which should be investigated immediately and treated as a priority. Shed larval skins and feeding damage may have resulted from old infestations, but in regularly monitored and cleaned collections, these should be regarded as an indication of an active infestation.

Control Methods

If a serious insect infestation occurs, or if insect problems do not respond to the preventive techniques, direct treatment for insect infestation may be necessary. This strategy should be used as a last resort.

Chemical Treatments

Pesticides used in museum pest control are generally similar products used for household or other structural pest control (Pinniger and Child 1996). Insecticides should only be used as a targeted treatment and not as a routine. They should not normally be applied directly to objects unless this is approved by a conservator. Museums are potentially good sites in which to use non-conventional pesticides such as repellents and insect growth regulators (IGRs) for controlling cockroaches, cigarette beetles, and certain other stored product pests.

Common chemical treatments used to control insects include the following:

- aerosol sprays;
- baits and pellets (which are eaten by the insects);
- contact and residual sprays (normally sprayed into cracks and crevices, these kill on contact and/or by absorption of the pesticide when the insect walks through the residue);
- cold fogging concentrates (these use equipment that suspends a pesticide and oil formulation in the air);
- fumigants (these expose infested material to a lethal gas);
- residual and vapor pest strips (the insect absorbs pesticide by walking across residual pest strips, while pesticide evaporates from vapor pest strips to become a fumigant);

- dusts (e.g. boric acid or silica dust, which dehydrates insects or interferes with internal water regulation);
- attractants (which lure insects into traps, sometimes killing them);
- repellents are also sometimes used; these are meant to discourage rather than kill insects.

Repellents

Paradichlorobenzene and naphthalene have been commonly used as repellents in museum cases. These materials do not eliminate infestations, but may be useful in preventing them. Paradichlorobenzene and naphthalene may cause damage to certain plastics (bakelite, for example), and may soften and shrink resins, adhesives, and paints. They are now banned in some countries.

Cedar wood chests are often recommended to protect fabrics from clothes moths and carpet beetles. However, only freshly cut cedar wood is toxic or repellent to fabric pests, and then only in an airtight container. By the time the wood is two years old, there is no toxic effect left. Lavender and lavender oil has been shown to have a repellent effect on adult clothes moths but has little effect on larvae (Pinniger pers. com.).

The knowledge of these substances and their potential to repel or attract insects could be utilized in pest management by either using them by masking attractive artefacts or in attractive traps (Shaaya and Kostyukovsky 2006). Some of these compounds have been identified, especially pheromones of relevant pest species like cigarette beetles, drug-store beetles, Indian meal moths and warehouse beetles (*Trogoderma*).

Fumigants

If non-chemical treatment of infested materials is not practical, some materials can be treated with standard insecticides. However, in most situations, infested museum specimens should be fumigated. Fumigation is hazardous and it requires professional training to do it safely and effectively. Fumigation of museum specimens is normally conducted in special fumigation chambers, vaults or ‘bubbles’. Some fumigation is done under tarpaulins. In severe and extensive infestations, an entire building may have to be ‘tented’ and fumigated.

There are a number of different fumigants to choose from. The choice will depend mostly on the objects and materials to be fumigated, since different fumigants are best suited for certain uses. Some fumigants cannot be used on certain materials because they may react with them. The most commonly used fumigants for museum specimens in the past were methyl bromide and ethylene oxide. More recently, sulfuryl fluoride and carbon dioxide have been introduced as replacements. Fumigation treatments do not provide a residual effect that will prevent reinfestation.

Methyl bromide was a very effective fumigant for pests. However, it has been identified as an ozone-depleting chemical and is no longer available in many countries. It has also been used in the past for fumigation of commercial aircraft.

Objects are sometimes fumigated using phosphine. This is done either in a special chamber or under gas-proof sheeting. The temperature must be above 20 °C to avoid over long exposure to the chemical. At high relative humidity, phosphine can corrode metal objects (gold, silver, copper and brass) and it is therefore only suitable for treatment of wood, some textiles or natural history specimens. On painted plasters, this gas induces the highest colour alterations after treatment, especially on gold gildings. It should not be recommended for the disinfestation of heritage premises in the presence of metal artefacts in silver, copper (or alloy containing copper), tin or lead.

Sulfuryl fluoride is one of the most suitable substitute gases for methyl bromide. It is very effective for termite control and wood borers but its cost remains very high as the required active substance has to be at least double the concentration, to achieve the same effect against other pest species as with methyl bromide. Sulfuryl fluoride fumigations have been used to control wood infesting beetles in structures, in museums and churches without damaging materials. However, eggs are less susceptible to sulfuryl fluoride.

Ethylene oxide (ETO) was commonly used in libraries and archives until the 1980s, and many libraries had their own ETO chambers. ETO is effective against insect adults, larvae and eggs. There is evidence that ETO can change the physical and chemical properties of paper, parchment and leather. Because of health issues, it has now been banned in many countries.

In general, fumigants and other pesticides can cause long- and short-term health problems, ranging from nausea and headaches to respiratory problems to cancer. Many chemical treatments will leave residues and may be absorbed into the body to cause health problems years later.

Non-chemical Treatments

Non-chemical management includes cultural controls (temperature and humidity control, sanitation and lighting), pest-proofing (pest-proof containers or display cases, screening and caulking, etc.), trapping (mechanical, sticky, pheromone and light traps) and vacuuming. Treatment of objects can be by freezing or heating, and, in rare cases, 'radiation' such as microwave ovens and gamma irradiators.

Cultural Control

Many heritage buildings have an endemic population of insects living in voids and dead spaces. Poor sanitation encourages pests, food debris, grease, loose hairs and other organic debris in and around specimens, storage areas, and in cracks and crevices in floors and furniture attracts and feeds pests. Good sanitation, particularly regular vacuuming, of display and storage areas removes potential food and newly arrived foraging pests.

Light shields, curtains and closed doors can reduce the numbers of flying insects attracted to the museum. Windows in areas where specimens are kept should be tightly screened or kept closed at all times to prevent pest entry. Caulk or otherwise seal cracks and holes in walls and floors, holes around pipes and other utility lines, and other points of pest entry. Install door sweeps where necessary. Air vents and hot air registers can be equipped with filters to trap potential incoming pests. Filters should be changed on a regular basis.

Lowered humidity and temperatures reduce the chance of infestation and slow down the growth of existing pest populations. For some pests, such as psocids and silverfish, reducing humidity can eliminate a pest problem.

The most effective way to prevent damage from dermestid beetles, clothes moths, and many other museum pests is to prevent the establishment of infestations in the first place. All incoming specimens should be examined carefully for damage and live insects and any showing signs of infestation should be isolated and disinfested. All actions should be recorded.

Adult dermestid beetles and other museum pests feed on pollen and nectar, so decorative cut flowers should be kept out of specimen areas to reduce the chance of accidental infestation. Those specimens at high risk of insect damage should be kept in insect-proof cases and examined on a regular basis.

Low Temperature

Strang (1992) reports on the efficacy of cold treatments against cultural heritage pests and with correct procedures, this method will kill all stages of an insect's life cycle. Low-temperature treatments are used routinely by many museums and are sometimes used for large-scale programmes of disinfestation, particularly when moving collections from one building to another (Berkouwer 1994). Low-temperature treatments are generally used for new objects and specimens coming into the museum to prevent pests being introduced on incoming collections.

Many types of infested museum collections can be disinfested by freezing them in a chest freezer or a large commercial freezer (Bergh et al. 2006). Textiles, furniture, herbarium specimens, books, mammal and bird collections, as well as various ethnographic materials, have been successfully frozen for insect control. Low-temperature treatment schedules should be clearly documented and recorded. The objects must be sealed in polythene (other plastic films such as polyester can be used) and exposed to temperatures of −30 °C for three days or −18 °C for at least 14 days. Objects should not be removed from the bag until they have returned to room temperature and there is no risk of condensation. Freezing is most often conducted at temperatures that are lower, e.g. −35 °C, or at more moderate temperatures but for very long time, e.g. more than 2 weeks. Materials can be treated in household or commercial freezers, blast freezers, or controlled-temperature and humidity freezers.

Freezing provides no residual protection from attack. If collections are not returned to a well-maintained storage area, reinfestation will almost certainly occur. Very fragile objects, those made from a combination of materials, and artefacts with friable media should probably not be frozen. Note that freezing poses a significant risk of damage to certain wood veneers, bone, lacquers, some painted surfaces and leather. Generally, low temperature is not advisable for canvas and wood-panel paintings, painted or inlaid wooden objects, finished furniture, lacquered wooden objects, objects under tension (e.g. drums, strung parchments), composite objects containing ivory or teeth and inorganic materials, such as glass, high-fired ceramics and metal.

Low, but above-freezing temperatures, usually 5 °C, will stop insects feeding and reproducing and can be used to protect items in storage. The best example is low-temperature storage of valuable furs, skins and costumes.

Elevated Temperature

Heat can effectively exterminate insects and it has been used widely in food processing (Xavier-Rowe et al. 2000; Hagstrum and Subramanyam 2006). The risk of damage to objects is greatest at higher temperatures, but studies have shown that heating can be successful at more moderate temperatures (around 50–52 °C) (Ackery et al. 2004). With any heat treatment of vulnerable collections, it is essential to maintain a constant humidity so that the objects do not dry out and shrink or crack. Safe treatments can be carried out in a controlled humidity heat chamber such as Thermo Lignum (Nicholson and von Rottberg 1996). Objects are placed in the chamber and the temperature is gradually raised to 52 °C and then lowered back down to ambient over a cycle of 18–20 h. The control system keeps the RH at a set level of, for example, 50% for the whole cycle. Some less sensitive objects can be treated in an oven at 52 °C if they are bagged to keep the RH around the object stable. Large objects can be treated in a simple hot box (Xavier-Rowe et al. 2000) or by using solar heating (Daniel 2001; Brokerhof 2002). Studies must be conducted to determine whether repeated treatment with low or high temperatures make the artefacts more attractive to insects and thus more vulnerable to infestation (Strang 2001).

Modified Atmospheres

Modified atmospheres have been used widely in the agricultural and food industries to control insect infestation and are now being used by some museums. The term refers to several processes: increased carbon dioxide, decreased oxygen (anoxia), by the use of inert gases (primarily nitrogen) and use of oxygen scavengers to decrease oxygen levels. Both nitrogen anoxia and carbon dioxide fumigation can be very effective in killing insects in objects. The technique is particularly useful for fragile and very vulnerable objects, which might be damaged by low- or high-temperature treatments (Selwitz and Maekawa 1998; Pinniger 2001).

Modified atmospheres can be applied (1) in a traditional fumigation chamber or a portable fumigation bubble or (2) in low-permeability plastic bags. With a chamber or a bubble, materials are prepared for treatment, air is evacuated from the chamber and carbon dioxide (generally about 60% concentration) or nitrogen (to achieve an atmosphere of less than 0.1% oxygen) is introduced. Long exposures of three weeks or more may be needed to kill all pests. Once treatment is finished, the vacuum is released, the carbon dioxide or nitrogen is removed and the chamber is aerated. The process for treating materials in low-permeability plastic bags is similar, except that materials are sealed in bags with an oxygen scavenger that will reduce the oxygen level in the enclosure to less than what is needed for insect respiration. In some cases, the bags are purged with nitrogen before sealing.

Different species of insects, as well as different stages, differ in their tolerance to low oxygen atmospheres. As with carbon dioxide, exposure times need to be longer at lower temperatures and treatments may not be effective below 20 °C. The larvae of some wood boring beetles are particularly tolerant of low oxygen and may survive for many weeks.

Use of controlled atmospheres against pests in museums has received an increasing amount of interest during the last twenty years (Maekawa and Elert 2003; Pinniger 2011b). At moment, the recommended protocol validated for *Anthrenus vorax, L. serricorne*, *S. paniceum* and *T. bisselliella* suggests an oxygen percentage below 0.1% for at least three weeks at above 20 °C. The most common problems are the long treatment time that, together with difficulty in achieving and maintaining such low oxygen concentrations.

Modified atmospheres show great promise, but additional research is needed to determine optimum exposure times and methods for particular types of insects (Rust et al. 1996; Selwitz and Maekawa 1998; Binker 2001; Warren 2001). The use of carbon dioxide as fumigant gas is very effective and is used by a number of museums in North America (Selwitz and Maekawa 1998; Warren 2001).

A Museum example

The Kunsthistorisches Museum in Wien is one of the largest museums in Europe with numerous exhibitions and storage rooms housed mainly in historic buildings and with a large variety of object types. Formerly, all kinds of chemicals were applied in the collections against insect pests or fungi, for example, DDT, naphthalene, methyl bromide, lindane (up to 1982), pyrethroids (until 1998) or ethylene oxide. Eulan was sprayed or objects submerged with until 1990, thymol applied to remove mould or xylamon was used to combat wood destroying insects. In addition, natural crystalline camphor, patschuli, lavander flowers, essential oils like clover in alcohol or lemongrass were used to prevent infestation. From 1996, fumigations with nitrogen were tested in the Picture Gallery collection (Ranacher 1998) and the construction of the walk-in nitrogen chamber initiated for the whole museum. In 1998, this 32 m^3 chamber was built and since then, all infested objects from the museum, but also from other museums, institutions and private collections are successfully treated in 5-week cycle.

Future Developments

Because of the effects of some chemicals on staff, objects and the environment, there has been pressure to move away from persistent and toxic insecticides. Some alternatives could be found in the use of semiochemicals, radiation, essential oils, biological control.

Semiochemicals. The development of semiochemical-based systems for population suppression is exciting, but success will depend upon the understanding of pest behaviour and the availability of economically priced lures. In the management of museums, insect pheromones can be used to monitor and to suppress and control the pest populations by means of mass trapping, attracticides and mating disruption methods, as well as acting as repellents and as specific behavioural stimulants or deterrents (Phillips and Throne 2010; Trematerra 2012). During recent years, computer-assisted decision support systems have also been developed that estimate insect population growth and the spatial distribution of insects as a function of environmental factors (Brenner et al. 1998; Trematerra and Sciarretta 2004; Baslé et al. 2011).

Radiation. Microwaves are used successfully in the food, agricultural and textile industries to control insects. Their effectiveness depends on the type of insect and the intensity and frequency of the radiation. The average infested book is microwaved for 20–30 s. According to Chmielewska et al. (2011), this method is safe for most hardback books printed after 1950 and high-quality soft-cover books with sewn bindings. Method on valuable old editions, older books with metallic dyes, inexpensive soft covers (it will melt the glue) or books bound in leather. X-rays, gamma rays and electron beams could be applied for disinfestation of cultural heritage objects. A dose as low as 0.3 kGy of gamma radiation completely inhibits the development of immature stages and sterilizes adults of *L. serricorne* and *S. paniceum* (Chmielewska et al. 2011). When it is needed, the effectiveness of gamma irradiation can be increased by application of additional treatment that would predispose insects to become easily damaged: high temperature, chemical treatment and infrared or microwave radiation could be additional applied.

Essential oils. Certain plant essential oils and their active constituents, mainly terpenoids, have potentially high bioactivity against a range of insect and mites. They are also highly selective to insects, since they are probably targeted to the insect receptor, a non-mammalian target (Shaaya and Kostyukovsky 2006). The ultimate goal is the introduction of these phytochemicals with low toxicity as alternatives to methyl bromide and phosphine fumigations. The use of bioactive compounds, for example, essential oils with CO_2, or isothiocyanates, especially methylthio-butyl ITC can be used as fumigants.

Biological control. While little information is available on natural enemies of the more specific cultural heritage pests, and almost none on biological control, a lot of information is available on natural enemies and biological control of stored product pests. There are parasitoid species that are associated with human-based habitats and their stored product insect hosts and also parasitoid species that accept stored product insects as hosts, but were transferred from agricultural ecosystems to indoor habitats. Natural enemies are known from many cultural heritage pests, but evaluation of their potential for biological control has been limited to, for example, biological control of *T. bisselliella* with *Trichogramma* spp.; *T. bisselliella* and *T. pellionella* with *Apanteles carpatus*; *S. paniceum* and *L. serricorne* with *Lariophagus distinguendus*; *A. punctatum* with *Spathius exarator*. Use of parasitoid wasps *L. distinguendus* and *Trichogramma evanescens* as part of an IPM concept in museums against *S. paniceum* and *T. bisselliella* in Austria and in Germany is reported by Schöller and Prozell (2011).

Conclusions

There are new developments that are now becoming available for the detection, prevention and control of museum pests.

Application of pesticides to control insect pests in museums has been shown to be accompanied by unwanted side effects on humans as well as on the items themselves. Regulations are continually being revised to restrict or ban the use of many chemicals. Certain alternative strategies (e.g. freezing and anoxia) have therefore been developed and used for a number of years (Bergh et al. 2003, 2006; Child and Pinniger 2008). Low-temperature treatments are now used for quarantine prevention and infestation control in many museums worldwide. The use of high temperatures is less common at the moment, but offers a rapid and safe alternative for many objects. The ability to use solar heating is of particular interest and value for developing countries with limited access to expensive equipment and technology. The further development and adoption of treatment regimes based on anoxia and low and high temperatures should ensure that historic collections will be safely preserved for the future.

An important part of using various methods for control of museum pests is an analysis of potential unwanted side effects. The exact effects of each treatment method need to be known to allow an informed decision balancing the effect of the treatment against the continued attack by insect pests (Kigawa and Strang 2011). Modern conservation ethics determine that where possible, any effect on artefacts must be minimal or reversible (Caple 2000). Methods in use must also be safe for persons using them, for persons handling the artefacts after treatment and for museum visitors (Carter and Walker 1999).

Changes in the distribution of a number of animal species in the northern hemisphere have been documented during the last decades. This includes insect pests in agriculture and forestry general and it has implications for urban and museum pests as well. There is evidence of the spreading of museum pests to new sites and the likelihood of this increase in the future must be considered (Hansen et al. 2011). Evaluation of the future risks and the distribution of the insect pests will also have to include global climate change predictions.

Pests of Museum—Cultural Heritage Pests

Wood pests		Distribution	
		North America	Europe
Coleoptera			
Anobium punctatum	Furniture beetle/woodworm	+	+
Callidium violaceum	Longhorned beetle		+
Dinoderus minutus	Bamboo powderpost beetle	+	
Hylotrupes bajulus	Old house borer/house longhorn	+	+
Lyctus brunneus	Powderpost beetle	+	+
Lyctus linearis	Powderpost beetle	+	+
Nicobium castaneum	Library beetle		+
Pentarthrum huttoni	Wood boring weevil	+	+
Xestobium rufovillosum	Death watch beetle	+	+
Isoptera			
Cryptotermes brevis	Drywood termite	+	
Kalotermes flavicollis	Yellow-necked drywood termite	+	
Reticulitermes lucifugus	Subterranean termite/destructive European termite	+	+

General pests		Distribution	
		North America	Europe
Dictyoptera			
Blattella germanica	German cockroach	+	+
Blatta orientalis	Oriental cockroach	+	+
Periplaneta americana	American cockroach	+	+

(continued)

(continued)

General pests		Distribution	
		North America	Europe
Coleoptera			
Lasioderma serricorne	Cigarette beetle	+	+
Niptus hololeucus	Golden spider beetle	+	+
Ptinus tectus	Australian spider beetle	+	+
Stegobium paniceum	Drugstore beetle/biscuit beetle	+	+
Lepidoptera			
Hofmannophila pseudospretella	Brown house moth	+	+
Endrosis sarcitrella	White-shouldered house moth	+	+
Thysanura			
Lepisma saccharina	Silverfish	+	+
Thermobia domestica	Firebrat	+	+
Psocoptera			
Liposcelis bostrychophila	Common booklouse	+	+
Trogium pulsatorium	Deathwatch booklouse	+	+

Pests of textiles and natural history		Distribution	
		North America	Europe
Coleoptera			
Anthrenus flavipes	Furniture carpet beetle	+	+
Anthrenus verbasci	Varied carpet beetle	+	+
Anthrenus museorum	Museum beetle		+
Anthrenus sarnicus	Guernsey carpet beetle		+
Attagenus pellio	Two-spotted carpet beetle		+
Attagenus smirnovi	Brown carpet beetle/vodka beetle		+
Attagenus unicolor	Black carpet beetle	+	+
Dermestes lardarius	Larder beetle		+
Dermestes peruvianus	Peruvian hide beetle	+	+
Dermestes maculatus	Leather beetle	+	+
Reesa vespulae	Museum nuisance	+	+
Thylodrias contractus	Odd beetle	+	
Trogoderma angustum	Berlin beetle		+
Lepidoptera			
Tineola bisselliella	Webbing clothes moth	+	+
Tineola pellionella	Case-making clothes moth	+	+
Trichophaga tapetzella	Carpet moth/tapestry moth	+	+

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