Integrated Pest Management (IPM) in Museums, Archives and Historic Houses - Proceedings of the International Conference in Vienna, Austria 2013

Edited by: Pascal Querner, David Pinniger and Astrid Hammer

Section I: IPM in Museums

- Contents -

Section I

IPM in museums

Museum Integrated Pest Management: a timeline

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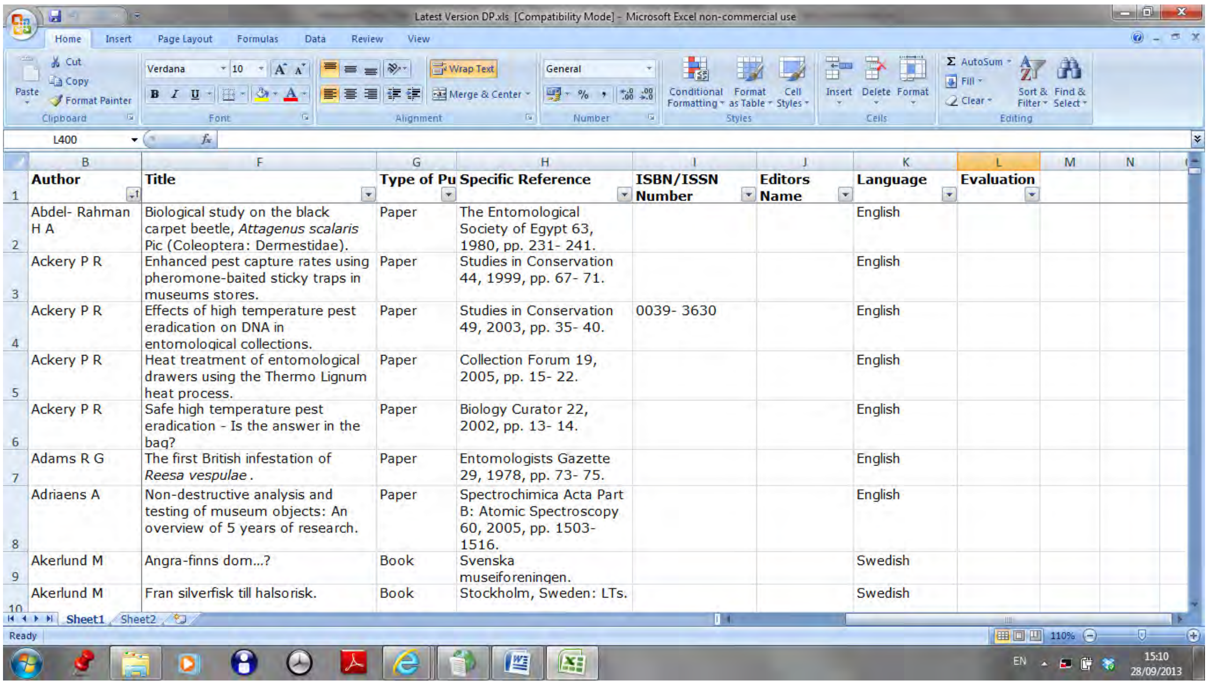
Abstract
There is a very large number of references relevant to Integrated Pest Management (IPM) which has been quoted in books and literature over the last 20 years. They are in a wide variety of publications, some of which may not be easily discovered or tracked down. A comprehensive and readily accessible database system which includes as many relevant sources as possible has been put together in an Excel spreadsheet with each reference arranged according to the Harvard system. There are additional categories of subject, type of publication and language. It is intended that the database will be freely available on a website in the near future. Initially the references were abstracted from some of the key recent IPM publications, such as Florian (1997) and Pinniger (2001). There are currently 399 references on the database system, dating from as early as the 17th century. Categorisation of the references, according to the main subject area has taken place, eight categories of Collections/Environment, Conservation, Strategies, Biology, Treatment/Physical, Treatment/Chemical, Monitoring/Trapping and General have been chosen. Analysis focuses on the 1970's onwards, since the majority of references (381) date from this period. The categories receiving the lowest amount are references is Collections/Environment (5%) and Conservation (7%). Conversely, the categories receiving the highest volume of publications are Treatment/Physical (27%), Strategies (17%) and Biology (16%). This paper presents only decade by decade analysis, revealing that the 1990's was a rich decade for research into IPM, with nearly all categories following similar trends, with the exception of Conservation which peaks later in the 2000's. There is a definite shift in focus from background research in areas such as Biology and Treatment/Physical to more specific cultural heritage related topics, including Conservation and Collections/Environment. This may be in response to external factors, such as the current economic situation and changes in legislation, causing IPM workers to rethink their practices. It is also demonstrative of the time lag specialist knowledge takes to filter into our professional sphere.

Key words: IPM database; IPM references; IPM literature review

1. Introduction

The objective of this paper is to provide an initial analysis of the database system of IPM publications, identifying relationships within and between categories of subject, type of publication and language. The basis of the work was outlined in Crossman and Pinniger (2011) (Fig. 1). Preliminary investigation of the database has shown correlations within chronology of references. Key dates tie in with advances in technology and scientific understanding, as well as increased awareness and collaboration with other professions, in addition to identifying areas of hot topics in reaction to external social and economic factors and changes in legislation.



Author	Title	Type of Pu	Specific Reference	ISBN/ISSN Number	Editors Name	Language	Evaluation
Abdel- Rahman H A	Biological study on the black carpet beetle, *Attagenus scalaris* Pic (Coleoptera: Dermestidae).	Paper	The Entomological Society of Egypt 63, 1980, pp. 231- 241.			English	
Ackery P R	Enhanced pest capture rates using pheromone-baited sticky traps in museums stores.	Paper	Studies in Conservation 44, 1999, pp. 67- 71.			English	
Ackery P R	Effects of high temperature pest eradication on DNA in entomological collections.	Paper	Studies in Conservation 49, 2003, pp. 35- 40.	0039- 3630		English	
Ackery P R	Heat treatment of entomological drawers using the Thermo Lignum heat process.	Paper	Collection Forum 19, 2005, pp. 15- 22.			English	
Ackery P R	Safe high temperature pest eradication - Is the answer in the bag?	Paper	Biology Curator 22, 2002, pp. 13- 14.			English	
Adams R G	The first British infestation of *Reesa vespulae*.	Paper	Entomologists Gazette 29, 1978, pp. 73- 75.			English	
Adriaens A	Non-destructive analysis and testing of museum objects: An overview of 5 years of research.	Paper	Spectrochimica Acta Part B: Atomic Spectroscopy 60, 2005, pp. 1503- 1516.			English	
Akerlund M	Angra-finns dom...?	Book	Svenska museiforeningen.			Swedish	
Akerlund M	Fran silverfisk till halsorisk.	Book	Stockholm, Sweden: LTs.			Swedish	

Fig. 1: Screen shot of database system 'IPM References' (Crossman and Pinniger 2011).

2. Material and methods

Currently there are a total of 399 records on the database system. Initially the references were abstracted from some of the key recent IPM publications, such as the books written by Florian (1997) and Pinniger (2001). Further references were then added from the reprint collections of the authors, other publications, such as Winsor *et al.* (2001, 2011), and on line reference data bases, such as Biological Abstracts. They therefore reflect the authors' interests and papers written in English.

We specifically excluded on-line only publications from the database as they are sometimes unsubstantiated and can be ephemeral, although this could form a basis for a future study.

Each reference has been arranged alphabetically by author and co-author with the title of publication and the publication date. Language and publication type have also been included. Each reference has then been categorised according to eight subject areas of Collections/Environment, Strategies, Conservation, Monitoring and trapping, Treatment/Physical, Treatment/Chemical, Biology and General. The criteria we used for these categories are listed in Table 1. The categories were chosen because of their relevance to IPM, and were found to be the main focus of the references.

It is acknowledged there may be blurred lines along which certain references fall and some may fall into more than one category. The categorisation of references on the database system is based on what was considered most appropriate by the authors. Each reference has been allocated to one category only.

Although references to pests in domestic environments have been found as early as the 17th C, their occurrence is irregular and unrepresentative (Allen 1699, Lettsom 1772, Howard 1896). Therefore, the analysis of the database system has focused on the time period from 1970's onwards, as this is most representative of the majority of the data, providing an accurate and consistent reflection of events.

While eight categories were originally chosen in which to place the references, only five categories; Collections/Environment, Biology, Treatment/Physical, Treatment/Chemical and Conservation, will be analysed and presented in this paper. Categories of Strategies, General and Monitoring and trapping will be omitted, as they are more difficult to analyse and are less specific to conservation.

The 2010 dataset is included here as to give indicative results so far this decade, although since we are only a third into the current decade, the 32 references experienced so far may be unrepresentative of the decade as a whole. The 2010's have not been included in the analysis presented in Fig. 1-3 as the dataset is incomplete.

Table 1: Categories (relevant to IPM) used.

Category	**Including the following topics**
Biology	• Effects of temperature and humidity on biology and behaviour of insects • Effect of climate change on biology and behaviour of insects • Biology and life cycle of pests including *Anthrenus* sp., *Attagenus* sp., *Tineola* sp. and *Tinea* sp. • Damage caused to objects due to pest activity
Collections/Environment	• Pests as indicators of environmental conditions • Use of environment to control pests • Climate change • Environmental surveys • Building design to modify environmental conditions • Case studies
Conservation	• Effect of freezing on objects • Effect of heating objects • Effect of anoxia on objects • Effect of chemicals on objects • Removal of contamination from objects • Effect of repeated treatment on objects
General	• Building design • Insect identification • Rodent identification • Control methods • Biodeterioration • Case studies
Monitoring and trapping	• Data interpretation • Pheromones • Detection methods • Light trapping • Case studies
Strategies	• Risk zones • Building design • Approaches to strategies • Health and safety • Case studies
Treatment/Chemical	• Fumigation methodology • Health and safety • Effects of treatments on objects • Targeting treatment • Effectiveness of pesticides/insecticides

	• Case studies
Treatment/Physical	• Anoxia methodology • Environmental methodology • Effect of treatment on pests • Effect of treatment on objects • Case studies

3. Results

Table 2 gives the breakdown of data by decade and category. The trends and patterns experienced by all the categories are similar. Both Collections/Environment and Biology follow analogous trends (Fig. 2). Treatment/Physical and Treatment/Chemical also follow parallel development (Fig. 3). The only category to deviate from this trend is Conservation (Fig. 4).

There are a total of 381 references on the database system which date from the 1970's onwards. Based on raw data, just 19 references were published in 1970's, whilst in the 1990's there was an explosion of papers generated, spiking at 181 references. Almost half the references are from the 1990's, when IPM first became recognised as an important field within preventive conservation/collections care.
Throughout the decades to date, the category receiving the lowest amount of references is Collections/Environment, receiving just 5% of the overall total, closely followed by Conservation, which receives 7% of the overall total. Conversely, the categories receiving the highest volume of publications are Treatment/Physical, with a significant 27% of the overall total, Strategies receiving 17% and Biology receiving 16% of the overall total for the period.

Collections/Environment and Biology both follow similar trends, increasing in volume of publications from the 1970's, until the 1990's where both peak at 52 % for Collections/Environment and 54% for Biology, and drop in the 2000's to 23% for Collections/Environment and 12% for Biology. Throughout the decades, Biology edges just above Collections/Environment, with the exception of the 2000's, where Biology decreases significantly in comparison with Collections/Environment.

Table 2: Breakdown of references by category throughout the decades.

Category	**1970's**	**1980's**	**1990's**	**2000's**	**2010's**	**Proportional (%)**
Collections / Environment	1	3	9	4	3	5
Strategies	2	10	22	16	14	17
Conservation	1	5	8	11	1	7
Monitoring and trapping	1	3	19	7	2	8
Treatment/Physical	3	16	59	21	4	27
Treatment/Chemical	2	8	21	10	0	11
Biology	5	14	31	7	3	16
General	4	9	12	5	5	9
	19	**68**	**181**	**81**	**32**	

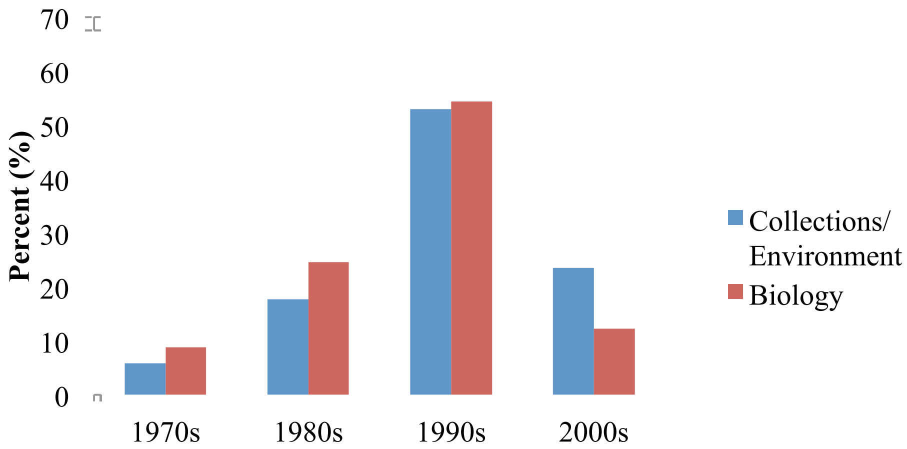


Fig. 2: Analysis of IPM relevant references in the Collections/Environment and Biology categories (according to Table 1) by decade.

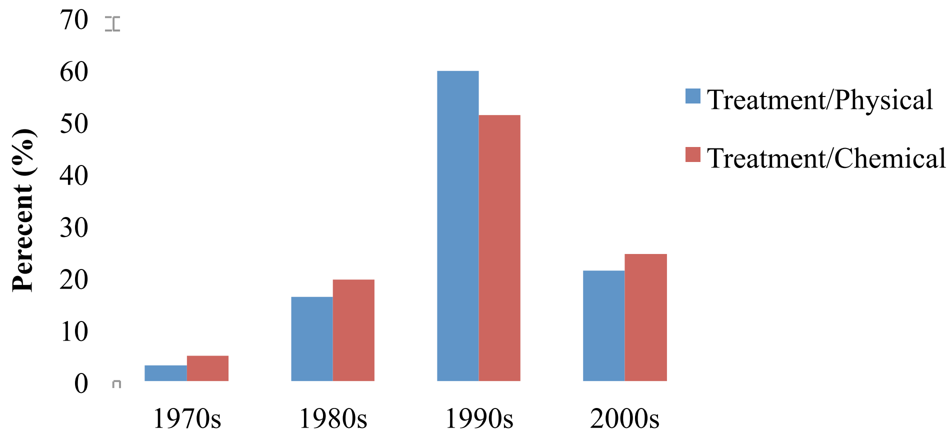


Fig. 3: Analysis of IPM relevant references in the Treatment/Physical and Treatment/Chemical categories (according to Table 1) by decade.

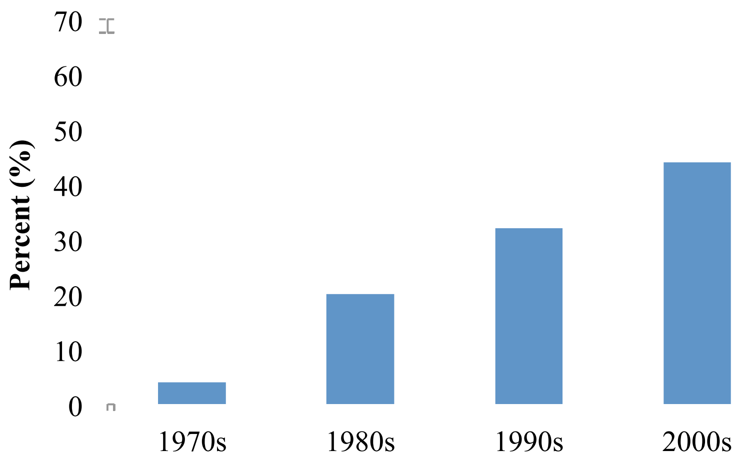


Fig. 4: Analysis of IPM relevant references in the Conservation category (according to Table 1) by decade.

4. Analysis and discussion

4.1 Biology

Looking specifically at Biology of pests / relevant to IPM in detail, we can see the amount of literature generated increases from the 1970's, peaking in the 1990's with 54% of literature generated during this decade, decreasing significantly into the 2000's, with just 12% of literature generated, but remaining higher than the 1970's. Within a decade (1990-2000), the Biology category incurs a significant decrease of more than a half, perhaps as a direct result of the loss of research facilities worldwide. Key government research centres in the UK (DEFRA) and the USA (USDA) which have published many relevant research papers over the years, no longer carry out research on the biology of stored product and museum pests (personal correspondence between the authors and staff at the organisations).

Interestingly, the Biology category is the one category which remains constant throughout the duration of the database, with references to this category as early as the 1600's until present day. Although Biology is not directly related to conservation or collections, it is important to note that it is a continual theme throughout the decades. Our knowledge and understanding of the biology and behaviour of insects underpins and furthers our knowledge of treatment methods, pest response to treatments, improves our knowledge of effective monitoring and trapping techniques and allows for targeted treatment of different pest species.

4.2 Treatment/Physical and Treatment/Chemical

The amount of Treatment/Chemical literature relevant to IPM declines from the 1990's to 2000 in response to the loss of chemicals which can be used. With changes in legislation, the use of Dichlorvos (DDVP) by the UK Health and Safety Executive in 2002, was reviewed, resulting in the suspension of the use of this chemical from 2002, and its prohibition from April 2004 (HSE E076:02 2002). The ability to use methyl bromide fumigant gas was phased out in developed countries by 2005 (United States Environmental Protection Agency 2013). The Treatment/Physical category increases during the 1990's as alternative safer methods are sought as replacements for these effective chemical treatments. The Biocides Directive is due to come into force in September 2013, and it too is likely to have significant implications on the chemicals and treatments that can be employed within museums in the future (Child 2013). Consequently the Treatment/Physical category during the 2010's may experience a further generation of research in this area. Although physical treatments see an increase in the 1990's, during the 2000's interest in Treatment/Chemical is reignited, perhaps due to a renewed awareness of the hazards caused to health, and investigations to measure pesticide levels applied to objects in historic practises and to investigate decontamination methods.

4.3 Conservation

Conservation is the only category to deviate from the trend described above, peaking in 2000's with 44% of literature published in this decade, compared to the 32% generated in 1990's. The generation of literature in this category has risen steadily decade by decade, from just 4% in the 1970's, to 44% in the 2000's. This may demonstrate how our increased knowledge of IPM can be applied to conservation, providing increased and greater understanding of how to better preserve our collections. It shows how the application of other fields is taking time to filter into our specialist knowledge, indicating a time lag from specialist/scientific work to the conservation profession. Conservation is a relatively new profession, and within that, preventive conservation and IPM are considered yet 'younger' disciplines within it (Henderson and Dollery 2000). This also emphasises the gap in knowledge between conservators and researchers, with conservators now better placed to be more proactive in asking of researchers to investigate specific gaps in our knowledge. This is being seen more and more in the conservation profession, with the new 'Mind the Gap!' initiative by The National Archives and Tate (www.nationalarchives.gov.uk/about/mind-the-gap.htm).

More recently, particularly in 2000's, detailed examination and research has been taking place into what is happening at a molecular level with regards to treatment techniques. For example, studies into the effects of high temperature pest eradication on DNA in entomological collections (Ackery *et al.* 2004) and research into the effects of fumigants of DNA molecules (Kigawa *et al.* 2011a). Although currently isolated in incidence, interest in the molecular level is gathering momentum, and it is anticipated that research in this area will flourish in the future.

In combination with more detailed research into specific collection areas and material responses, collaboration with experts in other disciplines is becoming crucial. This is evidenced by furthering knowledge and understanding of insect pests, and also the response of materials to treatments, provides a real understanding of the damage treatments can cause to objects. Evidence of this is found in Rowe's (2004) research into the effect of insect fumigation by anoxia of textiles dyed with Prussian blue, in which the author collaborated with experts in the fields of Neurology and Chemistry in order to use, analyse and interpret specialist equipment and technology to further conservation understanding. Collaboration with other researchers is becoming increasingly important, however, conservators still tend to be insular in their approach, core expertise is crucial for the development of the profession, which needs the input of a diverse range of functional groups.

Since the UK joined the European Union in 1973, there has been increased funding and opportunity to encourage greater collaboration, sharing of data and international debate at EU level. This has increased funding in conservation, with projects such as 'Climate for Culture' an EU funded project, which hopes to include a focus on IPM.

The more specific the category in relation to cultural heritage, the less research and literature generation there is, as is the case for the Conservation category and for Collections/Environment, which receive 7% and 5% respectively. The more generic the category, it appears the greater the interest in the subject area. This is perhaps due to their applicability across numerous professions, being relevant to not only just conservation. Categories specific to cultural heritage take more time to filter through from the generic to the specific, as the specific knowledge is limited in its impact and reaches a more limited audience.

Of the papers in the database from 1970's onwards, a significant 80% of the literature takes the form of papers within conference proceedings. Of the 27% of literature in Treatment/Physical category, 4% are to be found in books, 1% is to be found in leaflets and 92% are to be found as papers in conference proceedings. Examination of the category with the least amount of literature generated, Collections/Environment (5%), reveals that 10% of literature generated is found in books, 5% in bulletins and 86% in papers from conferences. Both categories follow the similar trends, with papers from conferences being the most popular method by which to disseminate information. The percentage of papers found in conferences may be higher for both categories, due to the fact IPM often focuses on specific case studies, which other types of publications, such as journals do not readily accept. Conferences appear to be an effective method for conservators to more rapidly disseminate specific information to a targeted audience. A brief survey of the last 10 years of publications in the journal Studies in Conservation found of the 243 papers published, just six were devoted to IPM, Ackery *et al.* (2004), Rowe (2004), Kigawa *et al.* (2011b) and Brimblecombe and Lankester (2013), plus only two specific case studies, Riegel *et al.* (2005) and Anheuser and Garcia Gomez (2013). Alternatively, it is possible that the conservation profession is reluctant to share and publicise information which could appear to have a negative perspective on how it cares for collections.

The relevance of the source links into obscurity of literature. The more specialised and tailored to a particular audience or receiver, the more limited it is in its impact and consequence. Papers published only for conservation-specific audiences will have limited impact, and will be difficult for non-conservators to uncover, unless members of conservation specific professional bodies. Papers published in more general publications will reach wider audiences.

5. Further work

The data analysed provides a snapshot of the last 40 years only. Analysis will need to be carried out in another 10 years' time to ascertain if the trends change or remain the same. The database will be therefore be added to as new references are published or come to our attention. A literature review will take place to pinpoint key milestones in the history of IPM. Each reference will be critically assessed for its contribution to IPM and, significant factors influencing IPM will be identified, as well as defining moments which changed the direction of IPM. It is also intended that the database will be available on a website resource for others to use and add to. The format and mechanism for this is yet to be decided.

Conclusion

The majority of publications (381) date from the 1970's onwards. The 1990's provided a rich decade for research and literature generation into IPM, perhaps as a result of the rapid development of the conservation profession during this period. It is hoped that the database system will go some way to enabling key, relevant IPM literature to be identified and easily accessed, no matter how obscure the source. The conservation community needs to take the initiative and be more exacting in what it asks of researchers, developing a more collaborative approach to their work. Conservators are being forced to find alternative safer working practices in response to external pressures, such as changes in EU legislation. There is a definite shift in focus with literature becoming more specific to cultural heritage. With background research in other areas declining, conservation and collections related studies are becoming more specific. The influence of other professions is clearly seen in categories such as Treatment/Physical and Treatment/Chemical, with many references being adapted from other fields into IPM. It will be interesting to see over the next 10 years where IPM will be, without the vital work taking place in some related underpinning disciplines.

Acknowledgements

The authors would like to thank Paul Lankester for his assistance with data analysis and interpretation.

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Past, present and future: changes in status and distribution of museum insect pests

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Abstract
Insects have been able to exploit the artificial environment created by man since the dawn of civilisation. Warmer conditions in dwellings and abundant food have allowed some insect species to thrive in climates which would not allow them to survive outdoors. Some collections pests, such as common clothes moth (*Tineola bisselliella*), and varied carpet beetle (*Anthrenus verbasci*) have been found in the UK and other European countries for many years. They still cause problems, but there are other species which were rare or unknown before 1960 and have now become established in many museums and historic houses. The Guernsey carpet beetle (*Anthrenus sarnicus*) was first recorded from London in 1963 and is now widespread in London and parts of south east England. It has also spread to many other museums across the UK. The brown carpet beetle (or vodka beetle, *Attagenus smirnovi*) arrived in London in the 1970's and is now well established in London. It appears to be spreading to other museums, but at a much slower rate than the Guernsey carpet beetle. It has now been found in 17 countries in Europe. Another Dermestid, the Berlin beetle (*Trogoderma angustum*) has now become established in a few natural history collections in the UK. Although at the moment its range is restricted, it has become a serious problem in some European countries. The fourth new pest to occur in the UK is the Australian carpet beetle (*Anthrenocerus australis*) All these species have the potential to cause serious damage, particularly to wool and fur textiles and natural history collections. It is important to be vigilant in identifying and distinguishing these new pests, and also to use effective inspection and quarantine procedures to help reduce the risk of increased damage to collections. Many factors determine the success of insect pests, particularly temperature and humidity. Any changes to climate will influence their distribution and abundance in Europe and increased temperatures may result in spread of some Mediterranean species and introduction of some semi-tropical species. Better tools and communication are needed to enable pests to be identified accurately and distribution data to be recorded so that new trends can be quickly analysed.

Keywords: pest evolution; pest distribution; climate change; housekeeping; loans; communication; training; detection; identification tools; "What's eating your collection" website; Dermestidae

1. Introduction

There are many insects which attack museum collections and from the viewpoint of the 21st century it can be difficult to recognise why some species are such important pests and have spread around the world. Winged insects are an ancient group dating back 300 million years to the Carboniferous. Some fossil cockroaches and silverfish are very similar to present day species. They lived successfully eating decaying organic matter, a niche they still exploit today. Beetles and moths arrived later on the geological scene, probably closely connected to the evolution of flowering plants. Some species of wood boring beetles found in amber from the Eocene period are closely related to the furniture beetle or woodworm (*Anobium punctatum*). They lived happily in dead trees and fallen logs well before man came on the scene. Moth specimens tend to be less well represented in the fossil record than beetles, mainly because of their more fragile bodies, however, some species have been found in amber. Because Tineid clothes moths live in fur, feathers and skins, they are associated with bird and mammal nests and have less opportunity to become fossilised. The same is also true for the Dermestid beetle species which also live on fur, feathers and skins.

2. Past civilisations

Undoubtedly many beetle and moth pests became more closely associated with man as he abandoned his hunter-gatherer nomadic life style for a more settled agriculture based existence. Houses, clothes, domestic animals and stored products all provided a ready source of food for many species now called pests, whose success is now closely linked to that of man (Woodroffe 1952, Robinson 1996). The first unequivocal records of modern day collections pests are from Egyptian tomb burials where specimens have been collected from objects and identified before things became contaminated. Biscuit beetle (*Stegobium paniceum*), cigarette beetle (*Lasioderma serricorne*), hide beetle (*Dermestes*) and spider beetles (*Gibbium* sp.) have all been recorded in the 19th century from objects dating back to 2-3 M BC (Chaddick and Leek 1972). More recently, a number of other species have been identified from Egyptian material. One of the main problems is ensuring the integrity of insect identification because it is very easy for archaeological material to become cross contaminated many years after it was collected. Dobney *et al.* (1997) have discounted a number of records of pest species in archaeological material because of the likelihood that they became contaminated after collection. There are convincing records from England of *Anobium punctatum* from Roman material and there is also evidence of infestation of wool by *Tinea* sp. (Dobney *et al.* 1997). It is very likely that the Romans spread pests around Europe as they expanded their empire. Increased trade in infestable material would also have contributed to the spread of pests from more exotic countries.

After the fall of the Roman Empire, little is recorded or known about pests until the 16th and 17th centuries when books start to refer to ravages of pests attacking food, clothes and furnishings. Linneus' seminal 'Systema Naturae', in the 10th edition published in 1758, records a number of species which we still recognise as pests although the names may have been altered over the years. The huge increase in trade in this period also stimulated the desire for collecting. Plants, animals and curios started to arrive in Europe from across the globe. John Coakley Lettsom's *'The Naturalist's and Traveller's Companion'*, first published in 1772, is one of the first treatises on protecting collections from insect attack. In the 19th century there was another big leap in trade with the Industrial Revolution providing larger and faster ships to carry tea, grain and wool. The Australian spider beetle (*Ptinus tectus*) was so named because it was found on grain ships coming from Australia. However, like many common insect names, this one is very inappropriate as the species is from Northern Europe. It probably hitched a ride on ships going to Australia, became established breeding in grain residues and then cross-infested Australian grain on the way back to the UK.

The common clothes moth (*Tineola bisselliella*) is not mentioned by Linneus, and research by Plarre (2011) has concluded that the species was introduced into Europe from South Africa in the 19th century. He has also convincingly dispelled the myth that its natural home is bird nests. While this might be true for the case-bearing clothes moth (*Tinea pellionella*), *Tineola* probably has its natural origins in animal nests and carcases. Urbanisation in the 19th century was also a big influence on the success and proliferation of many species of urban insect pests such as cockroaches, fleas and bedbugs (Robinson 1996). The rapid growth of towns and cities and accumulation of possessions kept in warm houses will also have provided carpet beetles and clothes moths with an almost inexhaustible food supply to exploit.

3. The Twentieth and Twenty First Centuries

The first half of the 20th century saw a rise in frequency of carpet beetles, particularly the varied carpet beetle (*Anthrenus verbasci*) (Fig 1b), maybe encouraged by the quantity of wool used and discarded in uniforms in WW1 and WW2. There was also an increase in infestations of furniture beetles (*A. punctatum*) in the UK brought about by the use of poorer quality timber used in house construction following the extensive destruction of buildings in WW2 (Berry 1995). This increase was then followed by a decline in the 1960s and 1970s, initially thought to be because of the widespread use of persistent insecticides. However, this decline continued and Berry links the decrease in infestation to the widespread adoption of central heating in domestic housing which lowered the relative humidity and moisture content of the wood to a level which does not permit the breeding of *Anobium*.

The latter half of the 20th century saw the introduction of species new to the UK which have proved to be potent pests in museums (Pinniger 2001). The first of these was the Guernsey carpet beetle (*Anthrenus sarnicus*) (Fig. 1a) first recorded in England in South Kensington in 1963 (Peacock 1993). A study by Nigel Armes (1988) confirmed that *A. sarnicus* was first established in the Natural History Museum and that subsequently it had spread to bird nests near the museum. It has since become the major pest in this museum and has replaced the varied carpet beetle (*Anthrenus verbasci*) previously the dominant pest. Within a few years *A. sarnicus* had colonised the adjacent Science Museum and the Victoria and Albert Museum 100 yards away. Movement of objects from both the Victoria and Albert Museum and the Science Museum to the main store at Blythe House in Olympia enabled *A. sarnicus* to travel west and infest the store. Other early records were from the Commonwealth Museum and the first infestation in a museum outside the London area was in Liverpool (own observations). Specimens were soon found in other museums including Edinburgh, Cambridge and Oxford showing that the insects had probably arrived on loan materials which had not been quarantined or treated by freezing (Pinniger 2001).

Fig. 1: The various species of Anthrenus. 1a Adult *Anthrenus sarnicus* (3mm in size)*;* 1b Adult *Anthrenus verbasci* (3-4 mm)*;* 1c Adult *Anthrenocerus australis* (3mm).

The spread of *A. sarnicus* has continued and although it appears to be more common in south east England, it has also been found in many other places in the past few years including as far north as Aberdeen (own observations) (Fig. 2). It is clear that *A. sarnicus* has been very successful in exploiting the museum and domestic niche and replacing *A. verbasci*. There are many reasons which influence the success of a pest and those which have given *A. sarnicus* the edge over *A. verbasci* include: faster development with no diapause, tolerance of higher temperatures, good dispersal with very mobile larvae and active, strong-flying adults. With the trend to warmer winters across the UK it is likely that this species will become far more common as a domestic pest and will spread more widely into museum collections.

Fig. 2: Distribution of *Anthrenus sarnicus* in the UK in 2013 (www.whatseatingyourcollection.com). Produced by Google maps.

In addition to being a museum pest, it has also become a serious domestic pest in houses in London and some other urban areas. However, although there are a few records from France, it does not yet seem to have become established in mainland Europe, but as it is easily confused with other *Anthrenus* species and is rarely mentioned in references, it may have been overlooked.

The second new Dermestid beetle species to become a pest in the UK was the brown carpet beetle (*Attagenus smirnovi*), often called the vodka beetle. It is well known in Scandinavia (Stengaard Hansen *et al.* 2011) and was first found in London in 1979 (Peacock 1979), but has a much more limited distribution in the UK than *A. sarnicus*. It has become established in many museums and buildings in London where the larvae have become entrenched in organic debris in the buildings and are exceedingly difficult to control. The success and proliferation of vodka beetles is usually a sure sign of poor housekeeping and current cut backs in services are bound to favour this species. However, it is far less travelled than *A. sarnicus*. In 2001, the only known infestation in the UK outside of London was from the Fitzwilliam Museum in Cambridge (own observations). It is still there, and not only has it increased in numbers in recent years, but it has spread to the nearby Scott Polar Institute, the Sedgewick Museum and the Natural History Museum (own observations). I suspect this pest hitched a lift on a loan from London in 1995, but has since spread in the centre of Cambridge because of the strong flying habit of the adult beetles in warm weather. It is very rarely reported from anywhere else in the UK. However, since 2011 adult vodka beetles have been found in the Ashmolean Museum, so it has now spread from Cambridge to Oxford. Despite its apparent restricted range in the UK, it is now a serious museum and domestic pest in most parts of Europe and there are records of *A. smirnovi* from 17th countrie (Table 1).

Table 1. Countries where *Attagenus smirnovi* has been recorded (Source www.faunaeur.org except France*: Adult beetles seen in Paris by the author in 2011).

Austria, Belarus, Czech Republic, Denmark, Estonia, Finland, France*, Germany, Ireland, Latvia, Norway, Poland, Romania, Russia, Slovakia, Sweden, Switzerland, United Kingdom

The third new Dermestid beetle species to become a museum pest was *Trogoderma angustum,* first found to be infesting dried plants, bones and skins in the Natural History Museum in Stockholm (Akerlund 1991). This had also previously been recorded from Poland, Germany and Finland. The first UK infestation recorded was in the natural history collections in the Royal Museum of Scotland in Edinburgh and in the herbarium at the Botanic Gardens in Edinburgh (Shaw 1999). A few specimens of this species were found occasionally in London and Cambridge over the next ten years, but with no reported damage to collections. However, following the discovery of *T. angustum* in the herbarium of the Royal Botanic Gardens at Kew in 2005, it has now spread in the building and has become a well-established pest (Pinniger and Harvey 2007). Specimens seen by me in 2013 confirm that it is also still present in the Botanic Gardens in Edinburgh. *T. angustum* is well established in parts of Europe and is now such a pest in Berlin that it is now been given the common name 'Berlin beetle'. It has also become an important domestic pest and does not seem to be restricted entirely to dried plant material. However, the most serious infestation of *T. angustum* seen by the author was in an art installation, in storage in a Berlin art gallery where the larvae were feeding on thousands of dried peas embedded in lead sheets. In 2013, an infestation in ethnographic material in Vienna was identified as being *T. angustum*. It transpired that the collection had recently been moved from Germany and it seems likely that this species may also be spreading in Europe.

The fourth new Dermestid beetle to cause problems is the Australian carpet beetle (*Anthrenocerus australis*), (Fig 1c). This species was found infesting a carpet in the Victoria and Albert Museum (V&A) in London in 2010 (Pinniger 2011a). Although occasional specimens have been found in various places since 1938, they were often associated with wool warehouses with the obvious link to Australia. The V&A occurrence was the first infestation in the UK known to be from a museum. Since then a few adult beetles have been found on traps in Kensington Palace in London, only a short distance from the V&A. There are also recent records of this species from buildings in Glasgow (Hancock *pers. com.*). In 2013 an infestation was discovered in a flat in Bradford, initially the beetles were misidentified as *Anthrenus*, but it was confirmed as *Anthrenocerus* by two entomologists. Subsequently it was established that the building which had been converted into flats had originally been a wool warehouse. How many other infestations are out there waiting to be discovered?

The cause of the rapid increase in frequency and severity of infestations of *Tineola bisselliella* in the UK since 2001 is not known. There could be many contributing and interacting factors: warmer winters, higher indoor temperatures, wider use of wool instead of synthetic fabrics and loss of potent insecticides, particularly dichlorvos (DDVP). A further and more unexpected explanation might be that we now have very effective low cost moth pheromones which are much better tools for detecting moths earlier and in much greater numbers than before. There is no doubt that controlling infestations of *Tineola* is now the major challenge facing museums and historic houses (Blyth and Smith 2011, Lauder 2013). An apparent change in the behaviour of this species has been its ability to live in organic debris found in voids and dead spaces. Many museums and houses now have endemic infestations in their buildings which are proving very difficult to eradicate. Treatment with insecticides may kill adult moths, but physical removal of debris and sealing of dead spaces are often the only effective solution for eradicating population pockets (Blythe and Smith 2011).

4. What factors are likely to influence change in insect abundance and distribution

4.1 Climate change

Climate change is a controversial subject, but undoubtedly there are a number of climatic factors which will influence the distribution of insects in the future. The most obvious of these is the increase in average temperature levels which can have a number of effects on insect populations. Climate change will not only affect outdoor conditions and pest species but will have an indirect effect on pest species which live in buildings including museums and historic houses (Brimblecombe and Lankester 2013). Although insects are protected from the outdoor environment, rises in outdoor temperature are likely to have an influence on indoor temperatures. Stengaard Hansen *et al.* (2011) have investigated the effect of temperature increase on populations of *Attagenus smirnovi* and predicted an expansion in range through Northern Europe together with more successful populations in other areas. This species is also a good flyer in warm conditions and therefore higher temperatures could lead to an increase in spread from building to building. Some species which are at the margins of survival in Northern

European countries may well be able to spread further northwards. This also may mean that semi-tropical species may be able to survive in Mediterranean countries. The most obvious pests to cause concern if this happens are drywood termites which cause great destruction in hot climates. An increase in overall temperatures would also have the effect of preventing some of our near arctic and temperate species from being able to breed. It is possible that some moths and spider beetles would then be restricted to more northerly parts of Europe.

Climate change is not just about temperature and the most obvious signs which we have experienced in recent years are extreme weather events. Heavy precipitation over short periods of time has led to localised flooding in buildings with consequent damage from mould and increase in some insect pest species (Brimblecombe and Lankester, 2013).

4.2 Housekeeping

Many of our insect pests survive and succeed in buildings because of their ability to live in accumulations of organic dirt and debris. In a more challenging economic climate with global recession many cuts have been made in the heritage sector. An easy target for cost cutting is a reduction in levels of housekeeping. The consequence of this is increased levels of dirt and debris with an inevitable increase in risk from pests. If this risk is not recognised by museum management then this could be a major factor in leading to increase in pest diversity and numbers when combined with higher temperatures as discussed above.

4.3 Loans and exhibitions

Many museums and organisations are reliant on income from temporary exhibitions particularly those regarded as 'Blockbusters'. The increase in recent years of collections moving from country to country for such exhibitions has provided insects with an additional opportunity to travel. A number of examples have been reported in the last few years of collections arriving at an institution with accompanying infestation. Vigilance by conservation staff has meant that the insects, including termites, wood boring beetles and Dermestids, have been detected and objects treated to prevent them becoming established in the building. An issue which has made this problem even more difficult is the wide variety of materials which can be used in some art installations. Materials not normally found in museums and galleries which can be attacked by insects include trees, wool rags (Fig. 3), beans, pasta, dried shrimps and even pig heads. (French 2011, Pinniger 2011b, Blyth 2013) There is a need for increased awareness of the pest issues which can be raised by such installations, including information on IPM programmes in loan agreements, but this also means an increasing load on existing, often overstretched, staff.

Fig. 3: A potential pest risk: e.g. ‘Venus of the Rags’, Michelangelo Pistoletto, Marble and rags, Tate Modern, London. Picture taken 2011.

4.4 Pest management

An effective IPM programme relies upon prevention of pests by good housekeeping, monitoring of collections and good quarantine procedures. All of these require staff time and effort and we have seen increased demands on staff in some institutions which have led to pressure to reduce input to IPM. This can only have a detrimental effect on care of collections. Although we have much better detection tools such as moth pheromones, they are only of value if results are regularly recorded and analysed. A loss of some of the treatment methods which we have at the moment may lead to greater difficulties in controlling pests in the future. We currently use a far more restricted range of residual insecticides than we did 20 years ago because of restrictions in registration and outright loss of some fumigant gases and insecticides. The European Biocides Directive is having a detrimental effect on the availability of insecticide products which we are currently using in the heritage sector. The niche market of museums and heritage organisations is not sufficiently profitable to encourage manufacturers to continue to support their products in this area (Child 2013). Most museums now use low temperature for treating infested collections and some use high temperature with controlled humidity. However, it may not be advisable to use thermal treatments for some fragile objects and anoxia is a preferred method. This means that the restriction by the EU Biocides Directive on the use of safe alternatives for fumigation, such as CO_2 and anoxia is of particular concern. The complexities surrounding the registration of these products are extremely difficult to untangle and uninformed bureaucracy could result in us being unable to use safe and effective methods in the future.

5. What do we need to help us in the future?

Better detection systems will help us to find pests sooner, determine their spread and target control measures. Improved trap design together with possible new pheromones will give us better tools. However we need to have staff educated and aware in order to maximise the benefits of insect monitoring systems. Training is also needed for the identification of insects particularly with the introduction of new and unfamiliar species. Pest awareness training workshops have proven to be very effective in the UK and lead to the discovery of previously unrecorded species. For example, a pest workshop held in Aberdeen in 2012 resulted in the identification of *Anthrenus sarnicus* and *Reesa vespulae* in natural history collections in Aberdeen. A similar pest workshop in Glasgow in 2013 also resulted in the confirmation that both of these species were also present in Glasgow. Examples from all over Europe show that training workshops where people can look at specimens of pests and learn how to identify the different species is the most effective way of spreading knowledge. However, workshops can be costly to run and organise and with restricted budgets are getting more difficult to fund.

Tools to help identify pests are vital. There are many books and papers with keys to enable entomologists to identify pests accurately to species. These can be very difficult to use and are also very daunting to a non-entomologist. An approach which we hope will be successful is to use a web-based identify and solve tool, such as 'What's Eating Your Collection?' (www.whatseatingyourcollection.com). This is still 'work in progress' and the range of images and information is being added to continually. The principal is that the user can select and sift images on the basis of size, colour, shape and antennal length etc. and then match the image with the specimen they have in front of them (Fig. 4). Most of our pests are very small, less than 5mm long and can only be identified with the aid of magnification. The availability of plug and play digital microscopes has revolutionised insect identification by removing the barriers of cost and difficulty of use of conventional optical microscopes. The National Trust for Scotland runs regular pest awareness and identification workshops and a part of the success of these is due to the staff being able to use USB microscopes with their laptop computers. The ability of USB microscopes to record good quality images, and even video, enables people to send images by e-mail which can rapidly speed up the process of identification.

Fig. 4: Screenshot of *Attagenus smirnovi* information from 'What's Eating Your Collection' website (www.whatseatingyourcollection.com).

The ability to identify new pests is made far more valuable if there is a good system of recording the distribution and abundance of these insects. Many organisations, such as English Heritage, have an excellent system for data collection, recording and analysis (Lauder 2013). Many other organisations have adopted similar methods for pest recording and analysis. What has been lacking has been a method or system for mapping the distribution of pests across the UK. 'What's Eating Your Collection?' provides a pest recording data base for existing and new species. Data are being continually added to this website and although there are still geographical gaps caused by lack of data, very interesting patterns of distribution of pests are being revealed. The spread of some species over recent years shows the link between institutions and loans as well as spread by other means. Although at an early stage in the development of this project it clearly has the potential to be expanded to become a European wide database. This will provide a vital source of information in the future to plot changes in pest distribution and abundance.

To enable us to manage and contain pests over the next decade we need to expand on what we are doing at the moment. The key to this is **communication**. If we develop methods, tools and techniques which help us in our struggle against pests it is essential that we share these with others and do not remain in isolation. All too often I have seen people 're-inventing the wheel', the electronic communication tools we have now can transform our ability to send information and images to each other. We can use existing groups, such as ICON, and also set up international forums and data analysis groups. This has got to be the way forward but it will need energy, enthusiasm and commitment to make it work.

Acknowledgements

The information presented in this paper is thanks to all my friends and colleagues working in museums, galleries and historic houses, both in the UK and overseas.

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Assessing and managing pest risks in collections

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Abstract
To include pests and integrated pest management in the bigger framework of risk management, we need to be able to assess the risk of pests to collections. Risk assessment begins with developing a 'risk scenario' that describes what is expected to happen. It describes how a threat comes from a particular source, how it follows a pathway from the source to particular objects, how it affects the objects and what the effect will be in terms of loss of value. The risk is the probability that damage will occur, usually expressed as chance times effect or probability times impact (R = P x I). To determine the magnitude of a specific insect risk we need to estimate the probability of insect attack and the severity of the impact of such an attack to the collection. How often do we expect insect attack and how bad will that be for our collection? Despite the large number of publications on insect species, their distribution, development and behaviour, treatment methods and integrated pest management, there is hardly any data on the probability of insects entering the building, the effectiveness of protective measures, the number of objects that will be damaged and how badly so. Strang and Kigawa (2006) have described the relationship between levels of control and damage to materials and thus setting the first step towards risk management. This paper aims to provide the next step. It introduces the insect 'scenario scheme', a tool that sketches possible scenarios for insect pests in collections. The scheme shows how insects come from various sources, follow various pathways to the objects, and affect these. The scheme helps identify how insects enter the building, analyse which route they take to the collection, which protective measures they meet on their way, and predict the most likely effects. It also helps in identify mitigation options and assess their effectiveness. Collected data on pest incidents allow for semi-quantitative estimates of a number of insect risk scenarios. Once assessed the pest risks can be evaluated and compared with the risks of other agents of deterioration thus allowing setting priorities for their mitigation within the larger framework of collection care planning.

Keywords: Risk assessment; scenario scheme; insects; collection preservation

1. Knowledge and acceptable levels

This paper reflects on integrated pest management (IPM) from the perspective of risk management and collection care planning. The aim is to determine what is currently known and done, and what knowledge is missing, when it comes to quantifying risks and comparing them with other threats to the preservation of the collection. It highlights some of the challenges for future research, especially for those researchers that come from outside the field of collection management and would like to contribute to the preservation of cultural heritage. The point of departure is the definition of IPM as given by the Food and Agriculture Organization of the United Nations (FAO 2013) and the United States Environment Protection Agency (US EPA 2012). In combination they state:

'*Integrated Pest Management is the careful consideration of <u>all available pest control techniques</u> and subsequent <u>integration of appropriate measures</u> that discourage the development of pest populations* *and keep pesticides and other interventions to levels that are economically justified and reduce or minimize risks to people, property, and the environment.*'

The underlining [by the author] stresses that IPM is not necessarily non-toxic, it considers all methods and integrates the appropriate measures. The aim is to find the right balance between acceptable levels of insects, pesticides, effort and losses to people, collections (in our case), and the indoor and outdoor environment. What the acceptable level is differs for each situation. There are some obvious differences between agriculture and stored product protection where the above definition has its origin, and collection care. The former deals with repeatedly produced crops and relatively short storage periods of a product that will be consumed. The latter aims at long term protection of mostly irreplaceable objects. In agriculture the challenge is to balance economic loss of the commodity due to insect damage with the costs of intervention measures (financial as well as negative effects on people and planet). Losses to the commodity can be covered by another producer and the consumer can still buy the product, be it at a higher cost. In the case of cultural heritage damage may be restored, yet in most cases that still constitutes a non-recoverable loss of cultural value. Moreover, most heritage objects cannot be replaced by something similar. Therefore the challenge for collection managers is to keep loss of value due to insect damage to an absolute minimum. They need to carefully consider how much loss of value they are willing to accept and define which levels of both pest populations and interventions they find acceptable. The need to assess where there is a threat of exceeding these levels and design strategies to ensure staying below the acceptable levels.

2. Integration

Heritage management integrates pest management and all appropriate measures in the preservation and collection care activities and procedures. One of the leading and guiding frameworks for this is the Canadian Conservation Institute's 'Framework for Preservation of Museum Collections' (CCI 1994). The approach has been presented as a wall chart with a nine row by seven column matrix. The rows correspond with the nine agents of deterioration: physical forces, water, fire, thieves and vandals, pests, contaminants, radiation (light, UV, IR), incorrect temperature and incorrect humidity. Robert Waller later added the tenth, non-material agent 'dissociation' (Waller 2003). The seven columns outline methods of control at different levels: building features (storage, display and transit), portable fittings (storage, display and transit), and procedures. The control measures are divided into five stages: avoid, block, detect, respond/confine, recover/treat. One can recognize the fire protection chain of response in these stages and the actions they promote. Fig. 1 shows the relationship of the stages in the lemniscate or 'lazy eight' of an ever ongoing process. Obviously the aim of preservation is to have enough control over the two steps of 'avoid' and 'block' so that whatever one detects remains within the defined acceptable levels and there is no reason for control treatments.

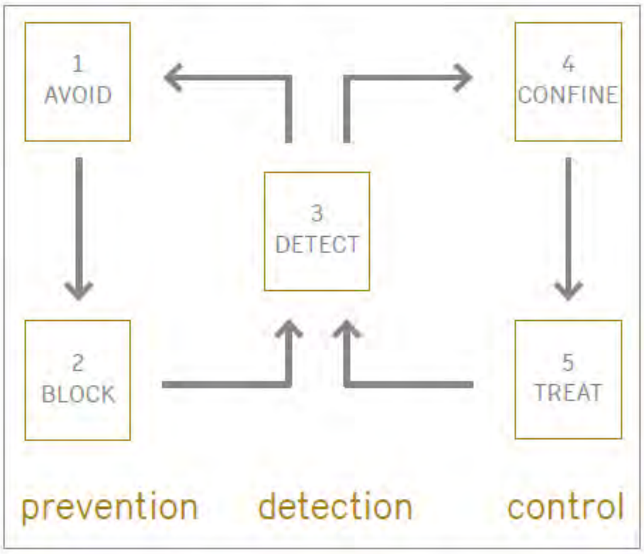

Fig. 1: The ‘lazy eight’ of integration (from Brokerhof *et al.* 2007), i.e. the five stages of control measures and their relationship.

IPM requires integration of pest management activities in collection care, especially in the prevention loop where activities overlap with avoiding and blocking threats from other agents of deterioration. Sealing cracks in the building envelope serves to block moisture, air pollutants and dust from outside in addition to various pests. Yet sometimes measures directed at specific agents need to be prioritized. For this purpose, one needs to know what the biggest or most urgent risk is. Pests are only one of the many threats.

Looking at past and current research there is a large number of publications describing damage, pest control treatments, conservation and restoration treatments, monitoring, identification, population development and implementation of IPM strategies in organisations. Yet inclusion of pests in the larger context of collection risk management requires some additional data, information and knowledge. We need to quantify the probability of pest attack, the rate of degradation, severity of damage, costs, and effectiveness of control measures and treatments in order to assess and manage the risks.

3. The risk management process

Risk can be defined as the chance of loss of value. With risk management the focus of preservation shifts from retrospective improvements, where losses have occurred, towards a prospective view of minimizing future losses. The risk management process involves assessing risks, identifying options for risk reduction, deciding on and implementing the best option (Fig. 2). Best options are usually selected on the basis of reducing magnitude of risk or uncertainty with preference for the most effective option, where effectiveness is improved preservation. However, with competing resource requirements, cost-effectiveness analysis should also be included in decision making. Ultimately, it should be possible to assess and quantify risks and, on this basis, to compare and rank options for risk reduction. This would allow to determine priorities for collection care in order to avoid the largest or most imminent losses to the collection.

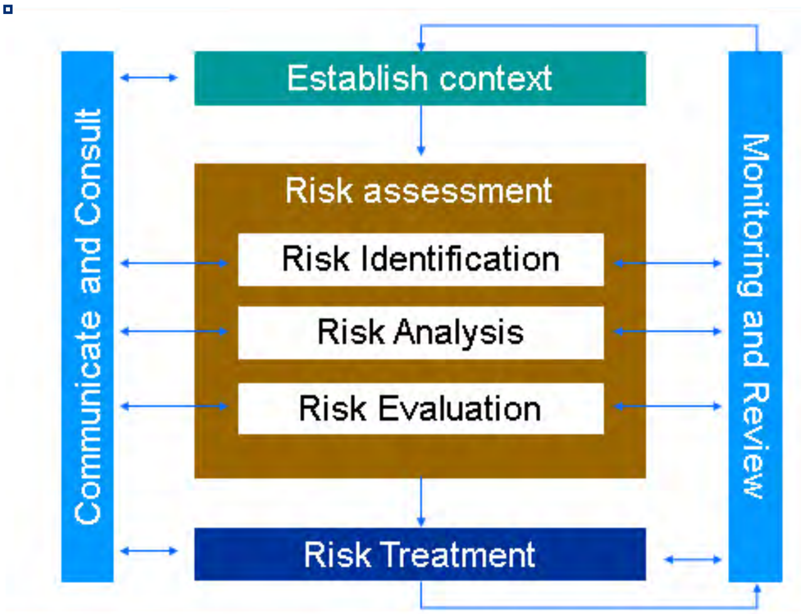

Fig. 2: The risk management process as described in ISO 31000:2009 Standard 'Risk Management'.

4. Risk scenario scheme

To quantify risks (R) one needs to quantify the probability (P) and the impact (I): R=PxI. In other words how soon or how often do we expect something to happen and how bad will that be in terms of loss of value? One way to visualize the event or process leading to loss is to develop a risk scenario which describes how the agent starts at a source (the cause), follows a pathway with or without barriers (walls, cabinets, boxes) and reaches the object where it has an effect leading to a loss of value. Fig. 3 shows a few examples of moths coming from a particular source, following a pathway past barriers to the objects and affecting them in a certain way. It also indicates the information and data required to be able to assess and quantify the risk of the various scenarios.

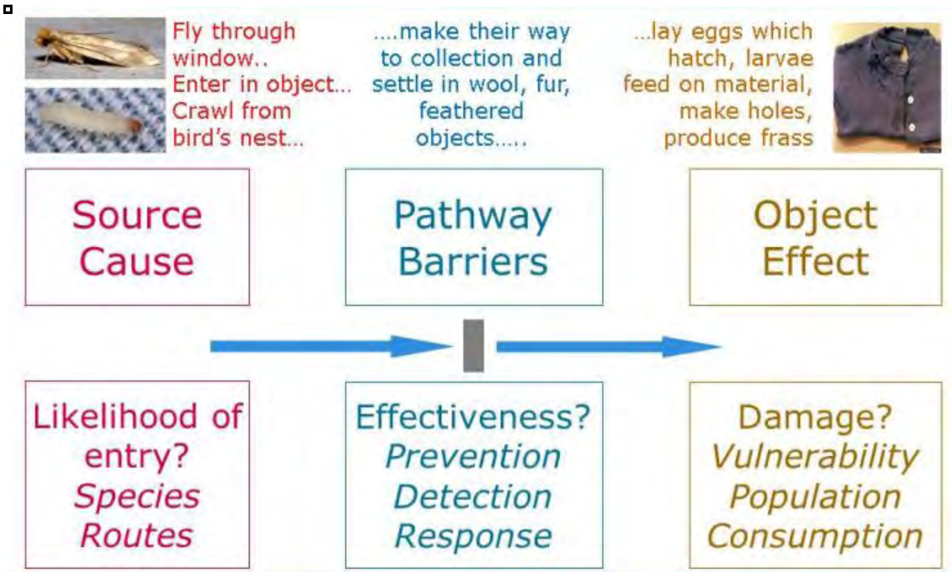

Fig. 3: Developing risk scenarios using the 'source-pathway-effect' method with an indication of information and data needed to assess and quantify the risk for each scenario.

Specific scenarios can be combined in a so-called ‘scenario scheme’ which structures the various scenario sketches for all possible pests, their sources, possible pathways and effects. The scenario scheme is one of the risk management tools that have recently been developed at the Cultural Heritage Agency of The Netherlands to facilitate identification, analysis and reduction of risks. They exist for all ten agents of deterioration.

Fig. 4 shows the scenario scheme for insects. The scenario scheme is an abstract representation of a map of a building. At the top is the outside. At the bottom is the object, most probably inside the building, inside a room, maybe even inside a box or display case. The red squares represent the sources for insects and their main entry routes. They can be outside or already inside in the building, in a specific room or even in a display case. The grey boxes are possible barriers that insects have to pass on their way from outside to object inside. The text in the grey box helps think of aspects of the barriers that will determine their performance. If the object is outside, there will be no wall barriers, maybe a protective layer around the object. The coloured lines represent the way insects move. The different colours represent different insect types. The thickness of the lines indicates the likelihood. In general each barrier will reduce the likelihood of insects to come to the object. The blue box represents the object(s) which can have various sensitivities for pests. The orange blocks at the bottom are the extent of possible damage. Each line that can be drawn from a source via one or more barriers to the object and the damage that may occur, sketches a specific risk scenario.

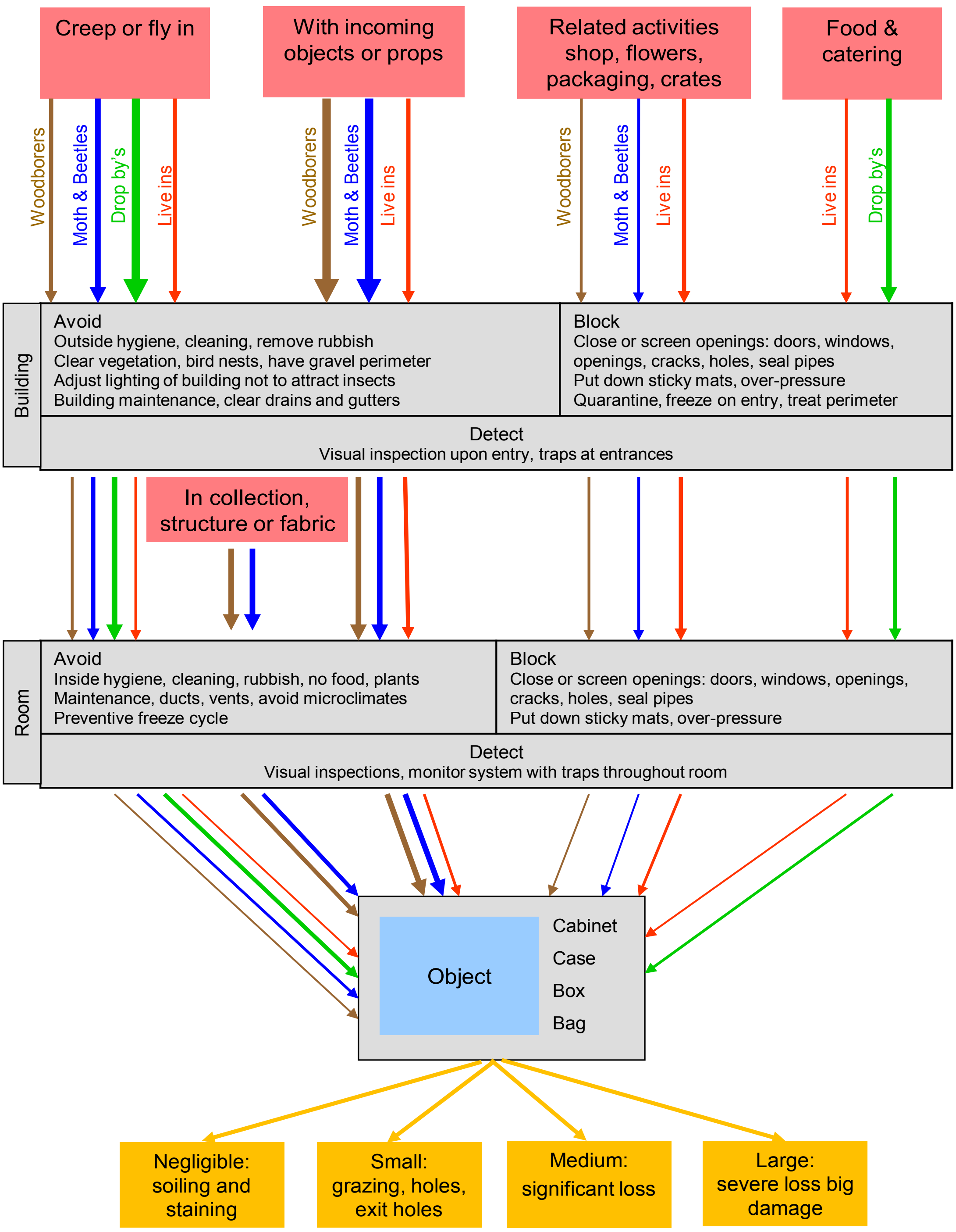

Fig. 4: Risk scenario scheme for insects.

5. Assessing probability and impact

There are a number of very useful publications on assessing current situations and detecting pest presence in buildings and collection areas. Methods for trapping and mapping pest populations in premises have been described by for example Child and Pinniger (1994) and Molineux *et al.* (2012), and can be found in bibliographies such as on the Museumpests.net website. Many museums know how to do condition surveys and can identify and interpret pest damage, but predicting the future is a bigger challenge than explaining the past. Knowing how big the risk is and whether there is a need to treat is still an area under construction. To determine whether there will be damage in the future we need to have insight in population dynamics and damage functions (Strang 2013). The principles and methods are known but the data for museum pests is not there yet.

To quantify the specific risk described in a scenario we need data on likelihood of entry (depending on species and entry routes), effectiveness of measures (prevention, detection, response) and extent of damage (depending on vulnerability of the object, population growth, consumption rate). Over the past decade the author has attempted to collate evidential data from colleagues attending conferences, courses and workshops. Participants were asked to answer questions about a pest incident they could remember. The questions followed the risk scenario and asked which species was encountered, how it came into the building and the collection, which measures were in place at the time and what the effect was. The approach was too rough and the sample of participants too diverse to do proper incident analysis and produce data that can be interpreted statistically correct. Yet a number of useful insights and trends could be distinguished which have proven their use in helping organisations manage their pest risks.

5.1 Insect species

To simplify the sources of insect risks, the commonly known museum pest insects can be grouped according to their behaviour, feeding and means of control. Through the years this grouping has worked quite well for providing museum staff with the basic knowledge and tools for managing pest problems (Brokerhof *et al.* 2007). Four groups of insects are distinguished:

- (Wood)borers: wood boring beetles and related species with larvae that bore into the material to feed (Anobiid beetles such as *Anobium punctatum*, *Xestobium rufovillosum*, *Stegobium paniceum*, *Lasioderma serricorne*, powder post beetles (*Lyctus* sp.), and old house borer (*Hylotrupes bajulus*))
- Moth & Beetles: moth and all other beetles that feed mainly on the surface of materials (Tineid moths and Dermestid beetles such as *Tineola bisselliella*, *Tinea* sp., *Anthrenus* sp., *Attagenus* sp., *Trogoderma* sp.)
- Live-ins: harmful insects living inside the building, moving around and feeding on objects as they pass (such as cockroaches, silver fish, thermobrats)
- Drop-by's: insects that are found in the building but are harmless (such as flies, wasps, bees, ladybird beetles, Carabid beetles)

5.2 Route of entry

All insects have various ways of entering the building and reaching the collections. These can also be grouped and five main routes of entry can be distinguished:

- Creep or fly in from the outside,
- Hitch hike along with objects or props as a 'Trojan horse',
- Enter with related activities such as shop, flowers, packing and crating,
- Come along with food and catering,
- Already live in the structure or fabric of the building.

5.3 Pathways and barriers

As they enter the building the insects pass the outer shell, the first of several barriers on their way to the objects (unless the object is located outside). They may encounter more barriers once inside: inner walls with openings, boxes or cases around objects. Finally they reach the objects which they can damage if they are made of susceptible material.

Respondents to the survey mentioned in the introduction to paragraph 5 were asked how many barriers were in place at the time of the incident. According to the concept of equivalent effectiveness the number of barriers provided an insight into the level of control. An impermeable building subject to quarantine procedures may be just as effective as one having holes in the outer shell if objects are protected by well-sealed cabinets, boxes and display cases.

One expects smaller probabilities and/or smaller damage when the level of control is higher. This will be the case when the barriers are more effective and when there are several barriers to pass before reaching the objects. Four levels of control were distinguished from which to choose in the incidents analysis (see Table 1).

Table 1. Levels of control with description of barriers using the principle of equivalent effectiveness.

Level of Control	Description
No	· Occasional household cleaning and building maintenance · Building not sealed or screened · Open storage racks and displays · No inspection of incoming materials and objects · No monitoring, visual detection only when damage · No preventive treatment · No special pest procedures or responsibilities
Low	· Regular average cleaning, average building maintenance · One of the following: ▪ Building sealed and screened ▪ Closed cabinets and display cases ▪ Inspection of incoming materials and objects ▪ Regular visual inspections or monitoring ▪ Preventive treatment, crevice spraying or freezing cycle · Pest awareness and some procedures or responsibilities
Medium	· Regular thorough cleaning, proper waste disposal, building maintenance · Two of the following: ▪ Building sealed and screened ▪ Closed cabinets and display cases ▪ Inspection of incoming materials and objects ▪ Regular visual inspections or monitoring ▪ Preventive treatment, crevice spraying, freezing cycle · Pest awareness and some procedures or responsibilities
High	· Regular thorough cleaning, proper waste disposal, building maintenance · Building sealed and screened or closed cabinets and display cases · Inspection of incoming materials and objects and quarantine · Regular visual inspections and monitoring · Optional: preventive treatment, crevice spraying, freezing cycle · Procedures and planning with allocated staff

5.4 Damage to objects

Finally the insects reach the objects which they can damage if these are made of susceptible materials. The effect can be damage with different extent:

- negligible damage, soiling and staining to affected items
- small damage like grazing, holes and exit holes to affected items
- medium damage with significant loss of material to affected items
- severe damage with large loss of material, structural damage and even total loss of affected items

5.5 Trends from incident analysis

The answers to the questions about the incidents that participants remembered allowed some rough incident analysis. It was possible to look for relationships between insect group and entry route. The answers also gave insight into the relationship between the number of barriers or the level of control and the damage to the collection (Fig. 5).

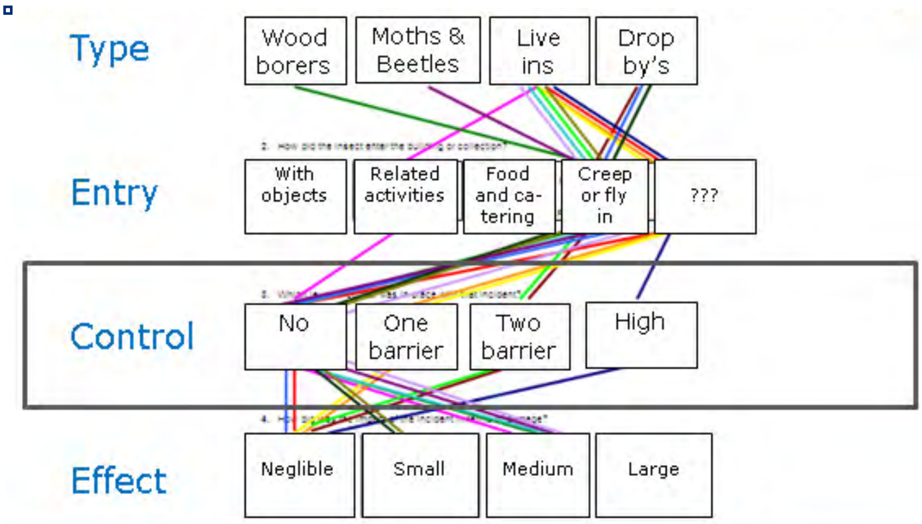

Fig. 5: Example of emerging patterns in pest incidents from surveys.

With 900 descriptions of incidents it was possible to do a rough calculation of probability for combinations of insect type and entry route and establish main routes of entry. Woodborers for instance showed an average of two incidents in ten years per institution, entering mostly as Trojans with objects. Live-ins had the same frequency, either creeping in or hitchhiking with objects or packaging material. Moth and Beetle had a slightly higher frequency of entry mostly with objects or flying or creeping in. Drops-by's were seen the most often, creeping in or coming along with related activities. These experiences have been useful in guiding consultancy and improvements when and where needed.

Looking at the relationship between level of control and damage the main trend is that if there are no specific control measures in place (response upon detection on insects or damage) most incidents lead to small (grazing, holes, exit holes) and medium (significant loss of material) damage. As soon as there is one barrier in place at the low level of control the most reported damage shifts towards the negligible soiling and staining yet there are still a considerable number of small and medium damage incidents. At a high level of control the number of medium damage incidents with significant losses reduces to just a few. Again these are trends and indications. Everyone seems to be able to recall examples of severe damage, even in situations with a high level of control. Or is that hearsay and anecdotal? Are the images of total destruction that come to mind in reality low level of control situations or are they an exception to the rule?

6. Qualifying risks

With the presently available data it is difficult to properly quantify insect risks. All that can be generated is qualitative or semi-quantitative rules of thumb for the probability of damage to a certain extent in 100 years related to the level of control (Table 2.)

Table 2. Rules of thumb for the risk of insect damage depending on level of control.

Level of Control	Impact until detection			
	Negligible soiling and staining	Small grazing, holes and exit holes	Medium, significant loss of material	Large, severe loss and structural damage
No	Likely	Likely	Likely	Possible
Low	Likely	Probable	Possible	Unlikely
Medium	Probable	Possible	Possible	Unlikely
High	Probable	Possible	Unlikely	Unlikely

Strang and Kigawa (2006) have also looked at levels of control and the expected damage. They distinguish eight levels, which roughly follow the same logic as the here described number of barriers. They have listed time to noticeable damage for the eight levels (Table 3). So there are two tables that support assessment of the probability of a particular extent of damage and the time to noticeable damage in relation to the level of control.

Table 3. Eight Levels of Protection with the estimated time until noticeable damage for materials of different susceptibility (reworked from Strang and Kigawa 2006). Left the corresponding levels of control from Table 1.

Level of Control as in Table 1	**Level of protection**	**Prognosis**	**Obdurate** mineral, hard, unattractive	**Robust** wood, posts, planks, framing	**Soft** coarse fabrics, hides, books	**Delicate** hair, insects, botanical specimens
No	**0. Outside** Totem poles, farm machines No barriers, no protection, no maintenance	Algal, fungal, rodent, insect, bird, bats	**Surface growths**	**Years**	**Months**	**Days**
No	**1. Roof, tarp** Shrines, under eaves Shelter from sun and rain, drainage, annual visit, residual pesticides	Rodent, bird contaminatio n in one year, structural attack under 30 y, surface mould 30 y	**Building lifetime**	**Decades-Century**	**Years**	**Months**
Low	**2. Roof and walls** Temples, sheds, barns	Fly specs, rodent invasion,	**Building lifetime**	**Decades-Century**	**Decades**	**Years**

	Shelter from wind, dirt and snow, drainage, cleaning chance observation, boxes, repairs tactical pesticids	insect grazing				
	3. Basic habitation Historic homes, churches, temples Weather protection, winter heating, drainage chests, boxes, cabinets, daily incidental inspection, repairs, cleaning Freezing	Multiple rooms affected, chronic pests	**Building lifetime**	**Building lifetime**	**Decades-Century**	**Years**
Medium	**4. Commercial adapted** Civic archives, private gallery HVAC for extremes, disinfestation, storage barriers, periodic inspections, repairs, treatments Quarantine, CA treatments	Local outbreaks, imported more than infiltration, more insects than rodents	**Building lifetime**	**Building lifetime**	**Century**	**Decades**
	5. Purpose built Older provincial and national museums HVAC for human comfort, drainage Procedures trapping, inspections Heat	Sporadic outbreaks in non-collection areas	**Building lifetime**	**Building lifetime**	**Building lifetime**	**Century**
High	**6. Preservation designed** Collection preservation centre HVAC for preservation, special site Tight barriers, procedures, traps and visual inspection	Incidental	**Building lifetime**	**Building lifetime**	**Building lifetime**	**Building lifetime**
	7. Ultimate Clean room, vault HVAC for preservation hermetic barriers and procedures Annual individual item inspection	Not	**Building lifetime**	**Building lifetime**	**Building lifetime**	**Building lifetime**

7. Challenges for future research

Most caretakers of cultural assets apply the principles of risk assessment in their work on a daily basis, much of the time unconsciously and implicitly. Certainly the IPM approach contains many risk-based aspects. Yet, performing explicit and quantitative risk assessment for insect and other pests in cultural heritage assets still poses some research challenges. This paper illustrates where efforts are required. Four main areas for data generation can be distinguished:

- Experience and incident analysis will generate proper data on probability of entry and extent of damage for different species or types of pest.
- Impact studies incorporating population growth models for museum pests under museum conditions complemented by studies into the rate of feeding and creating damage to a variety of materials will provide data to predict the impact of risk scenarios. These studies are nowadays referred to as 'damage functions'.
- Studies into the effectiveness of barriers, prevention and control methods will provide insight into how much barriers and control methods will block insects, slow down their development or reduce populations and how much that reduces collection losses in the end.
- Combination with costing of these measures and methods, both financially and in terms of side effects and introducing new risks, will allow determination of the cost-effectiveness of control strategies.

There are a considerable number of scientists and heritage professionals studying pests in the laboratory and a heritage environment, i.e. the critical mass to generate the knowledge to properly assess risks is available. And indeed, there are many studies underway that may produce useful data in the near future. Hopefully this paper stimulates those who still wonder which direction to go with their research, that they will become enthusiastic about the risk management approach and feel challenged to fill the gaps in our knowledge.

Conclusion

To manage pest risks one needs to be able to assess their probability and impact and determine the magnitude of risk. Then risks can be evaluated, various scenarios can be compared and ranked. Pest risks can be considered in the larger context of collection care and compared with the risks of other agents. This allows setting priorities at the overall collection care level. Then the 'P' for Pest in the definition of IPM becomes the 'P' for Preservation and all agents can be managed in such a way that they remain at acceptable levels that are economically justified and have minimal risk for people, property and the environment.

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Integrated Pest Management as European standard

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Abstract
Currently, a standard for Integrated Pest Management (IPM) is being written within CEN/TC (technical committee) 346, Conservation of Cultural Heritage. This paper describes briefly what a standard is, why a standard is desirable for IPM, and how experts in the field can join the work.

Keywords: standardisation; IPM standard; CEN/TC 346

1. Introduction

Since 2009, work has been underway to create a European standard for Integrated Pest Management within the cultural heritage sector. The standard is part of CEN/TC 346 Conservation of Cultural Heritage, Working Group 4 – Protection of Collections.

The European Committee for Standardisation (CEN) is composed of its National Members, i.e. the National Standards Bodies (NSBs) of the 27 European Union countries, Croatia, The Former Yugoslav Republic of Macedonia, and Turkey plus three countries of the European Free Trade Association (Iceland, Norway and Switzerland). There is one member organisation per country.

The standardisation system in Europe is based on the National Standardisation Bodies or the members of CEN. A National Standards Body is the one–stop shop for all stakeholders and is the main focal point of access to the entire system, which comprises regional (European) and international (ISO) standardisation.

2. What is a standard?

There are different ways of explaining what a standard is. The two most common are these:
a) A solution to a recurring problem,
b) A recommended way of doing something.

Historically, standards were introduced with trade – having different sizes and weights would complicate trading between areas and countries. Today, standards form part of everyday life. Many items in daily life have been decided by standards, for example the A4-format on paper, durability of tooth-brushes (they have to pass the 'fatigue resistance' test), and not least, safety standards for brakes in cars, etc. The standardisation business itself defines standards as a technical document designed to be used as a rule, guideline or definition. It is a consensus-built, repeatable way of doing something. A standard can deal with technical details for electric installations. There are, however, interesting examples of other types of items that can be standardised: in 2010 a new ISO standard for Corporate Social Responsibility (CSR) was introduced for companies and organisations dealing with topics such as environment, minimum wages, workers' rights, etc.

The end result is always a publication that provides rules and guidelines for a specific action and/or occurrence. In our particular case, we are trying to provide guidelines for implementing IPM.

3. Why create a standard for IPM?

During the work of the technical committee CEN /TC 346, Conservation of Cultural Heritage, the need became clear for a standardised way of looking at pest problems in museums, archives and other places housing collections and/or objects of cultural significance. There are many reasons for this. One is that many biocides throughout Europe are being banned. There is a need for non-toxic and preventive methods to combat pests. Another reason is the rising of mean temperature. At the time of writing, the Intergovernmental Panel on Climate Change (IPCC) has just published its Fifth Assessment Report (www.ipcc.ch/report/ar5), stating that rising mean temperatures is very much a fact. This will in turn mean better living conditions and higher reproduction rates for many pests. A third reason is the movement of art and objects between museums, thus increasing the risks of spreading pests.

The standard will, however, not be limited to museums. As a comprehensive standard method of managing pest problems, it will be of benefit to other end users such as archives, libraries, historic houses, art dealers and auction houses, art transport companies, and commercial storage companies.

4. Contents of the standard for Integrated Pest Management

The scope of the standard is to define IPM principles and describe procedural, as well as physical and practical methods, for preventing and reducing pests, and responding to pest infestation/contamination within cultural heritage.

The standard is not a handbook on IPM. It is a management tool which describes IPM policies and procedures. It does not replace practical handbooks and adequate training on the subject.

Prevention and risk management are two key components of the standard draft, with descriptions of methods such as avoid, block, detect and respond. There will also be appendices with general description s of treatment methods, check lists, etc.

5. Experts are welcome to join

At the present time, experts such as entomologists, biologists, collection managers and conservators from eight countries are directly involved in the creation of the standard. There is however a geographic emphasis on Northern and Western Europe. We hope that experts from other countries will join the work, or at least make comments on the text when it is sent out to all national standardisation bodies for public enquiry. A draft will be submitted for public enquiry in 2014, which means that anyone, through the national standardisation body, can comment on the draft, and suggest changes and alterations. Later, there will be a vote on whether to accept the standard or not. If accepted, it will be translated, and available for purchase in each country.

To join and comment, the best procedure is to contact one's own national standardisation body. Contact details can be found at www.cen.eu. You can also contact the author of this article for more information.

Acknowledgements

The author wishes to thank the Swedish National Heritage Board for financial support to present the work of CEN/TC 346 Conservation of Cultural Heritage, WG 4 Protection of Collections, at the IPM conference in Vienna, 5-7 June 2013.

Fungi and insects as deterioration agents in museums - a comparison

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Abstract

In museums, integrated pest management (IPM) is a strategy to prevent the attack of materials and artefacts by (a) insects and other 'animal' pests and (b) by fungi and other microbiological agents. We compare the different aspects of IPM and microbial deterioration for both agents and try to highlight differences and parallels concerning prevention, monitoring and treatment. Climate - especially humidity - is the most important parameter for the prevention of fungal growth, insects are best prevented by sealing the building and by a good quarantine. Even under optimal growth conditions, serious infestation by insects takes months to years before it results in a large damage. Fungi in contrast are fast growing and only a few days of raised humidity might be sufficient for a very destructive manifestation. For both agents, regular cleaning of the artefacts, rooms and small spaces like cracks or shafts are a very important part of IPM. For insects this is mainly a preventive measure e.g. to reduce food sources for moths and beetles. Concerning fungi, the removal of dust and other deposits goes along with the removal of the source of infection itself, namely the fungal spores. Cleaning of objects with fungal infestation requires special methods that have to take into account the composition and state of the materials itself, as well as the health risks connected with fungal spores. An active insect infestation is best prevented by controlling all incoming objects. A pest-free environment is difficult to establish but should be aimed for. In contrast to this, fungal spores are present everywhere and therefore an outbreak can potentially happen anytime and anywhere depending on the climate conditions (especially microclimate). Different treatment methods are applied in museums today for both active insect infestations and fungi.

Keywords: fungi; insects; prevention; monitoring; treatment

1. Introduction

Integrated Pest Management (IPM) is an important part of preventive conservation focusing on the prevention of pest infestations and the reduction of pesticide and fungicide application. The concept of IPM has been successfully applied in museums since the 1980s to reduce the population of animal pests like webbing clothes moths (*Tineola bisselliella*), drugstore beetles (*Stegobium paniceum*), common furniture beetles (*Anobium punctatum*) or different carpet beetles (*Attagenus* sp. and *Anthrenus* sp.) but also microorganisms like fungi, archaea and bacteria. Because of tradition, education and specialization in the two fields of biology, cooperation of entomologists and microbiologists in museums is still rare and prevention as well as treatments against each group of organisms are often strictly separated. This might lead to (a) confusing and apparently contradicting instruction for conservators/restorers and museum curators and (b) to a needless duplication of effort.

In this paper we show that the concept of IPM as proposed for insect and other animal pests by Brokerhof (2007b), Florian (1997), Pinniger (2004, 2008), Querner *et al.* (2013) is very similar as compared to concepts for microorganism prevention and treatment (see Florian 1997, Brokerhof 2007a, Sterflinger 2010, Sterflinger and Pinzari 2012, Sterflinger and Piñar 2013).

In general IPM, independent of the pest species or organism type, is based on the following basic strategies:
(1) Prevention of attack and contamination by sealing the entry points of buildings against the pests or by air-filters,
(2) Control and adaptation of the (micro-) climate,
(3) Maintenance of high hygiene standards,
(4) Quarantining new and incoming objects, and
(5) Monitoring for pest infestations and microbial contaminations.
For cleaning and treatments, the choice of an appropriate biocide is limited by the European Union`s Biocidal Products Directive (BPD) (http://ec.europa.eu/environment/biocides/index.htm) . Due to this and numerous problems connected with biocide applications such as environmental aspects, limited effect and possible resistance, treatment methods are changing towards non-chemical methods.

2. Fungi in the museum environment

Although the history of biodeterioration of houses and art is long and cases of red and green 'leprosies' (caused by Mycobacteria) in houses have been described in the Bible (e.g. *Leviticus* Ch.14 v.36, 37), its importance has been neglected for a long time, during which chemical and physical processes were believed to be the dominant factors of material decay. In recent decades, however, the dogma has changed and it is now generally agreed that fungi and bacteria not only cause serious aesthetical destruction of paintings, costumes, ceramics, mummies, books and manuscripts, they inhabit and penetrate into the materials, resulting in material loss, due to acid corrosion, enzymatic degradation and mechanical attack. Objects of art in museums and their depots are seriously threatened by fungal contaminations. The prevention of mould growth in museums as well as the development of appropriate treatment measures for contaminated objects is a challenge for conservators/restorers, museum curators and architects. Fungi are able to inhabit, to alter and to degrade all types of organic and inorganic materials.

Most fungi playing a role for deterioration of cultural heritage are so-called microfungi, mould, hyphomycetes, or 'Schimmelpilze' (German), which do not have asexual reproduction ('imperfect fungi', anamorphs) and often produce numerous spores. Phylogenetically they belong to the division of Euascomycetes; Hemiascomycetes – the classical yeasts – are rarely isolated from art objects. Fungi with sexual reproduction cycles ('perfect states', teleomorphs) are rarely found and the only teleomorph genera that frequently occur are *Chaetomium* – mostly on paper, wood and feathers – and *Eurotium* – in environments with low a_w values (water activity). Occurrence of basidiomycetes (mushrooms, toadstools) is restricted to wood rotting fungi in churches or other protected historical monuments. Lignin degrading fungi are rarely observed in indoor environments, but considerable damage can be caused by the cellulose degraders *Serpula lacrymans* or *Coniophora puteana* in churches and other objects of cultural heritage if wooden altars or the roof structures are attacked. Wood decaying fungi, however, often occur in close association with wood boring insects, some of latter even depend on the pre-decay by fungi.

Fungi have some special features that have to be taken into account for IPM and treatment: fungi are able to release numerous spores into the environment that are transported by the air. Especially the spores are dangerous as they contaminate rooms, objects and air conditioning systems. Fungi produce three-dimensional mycelia, i.e. a mass of branched, tubular filaments (hyphae) that are able to penetrate deep into materials. These mycelia cannot be reached by mechanical cleaning and also a chemical decontamination might not be sufficient to kill deep-seated mycelia. Fungi – and especially their spores – are very resistant against heat and stand long periods of Nitrogen treatment without losing their ability to germinate. Nevertheless, fungi and insects have some common features that could be the basis for a combined approach in IPM. The aim of this paper is to compare insect and fungi infestations, with regard to detection, prevention and treatment in modern museum IPM. We compare the different aspects of IPM for both agents of biodeterioration and highlight differences and parallels. A synopsis is presented in Table 1.

2.1 Origin of infestation and sealing of buildings

Both fungi and insects enter museum buildings through doors and windows. Visitors transport fungal spores on clothes and shoes. Since insects have a considerable size, the sealing of doors, windows or constructional joints is an appropriate measure to limit their entry. Fungal spores are only very few µm in size and invisible to the naked eye. In open museums and exhibition rooms, their entry through doors cannot be prevented. In closed stores, however, appropriate air filters (class F, HEPA filters are only necessary for vacuum cleaners and in clean rooms) can minimize the amount of spores in the air and deposits on the objects. In stores shoe protectants and lab coats should be considered as additional hygienic standards. Quite frequently insects and microbial contaminations enter the building with objects coming from other collections and from private estates. For this reason the availability of quarantine rooms is of high importance and time should be invested to observe and analyse possible microbial or insect contaminations. Objects have to be quarantined until they are sufficiently decontaminated – this should be tested by an expert – and are no longer a contamination risk for the museum rooms and other objects.

2.2 Detection of contaminations and infestations

For both, fungi and insects, a regular visual inspection is the most efficient and important tool for detection. Experienced conservators/restorers are very well able to detect and locate colour changes, crusts and layers or etching and feeding traces caused by organisms. If mould is suspected a specialist should be consulted. For the long term monitoring of insects, traps – stick blunder, pheromone or UV - are very efficient. Monitoring of fungal contaminations has to be more elaborative: air samples have to be taken with special air collection systems (e.g. ECO MAS) in regular terms, surfaces can be checked for spores by using swabs and contact plates. In any case a microbiological laboratory is necessary for further cultivation and analysis of samples. Novel molecular techniques are based on extraction of DNA or RNA and can be used for the detection of viable versus non-viable microbes, both for their quantification and for the analysis of whole communities. This may even allow a reconstruction of storage conditions, since different conditions might have triggered different microbial infections. The latter approach is made possible by so-called metagenome analysis, an approach that is based on high technological laboratory facilities (next generation sequencing systems). Currently the costs for molecular analysis are still high in relation to the overall costs that are usually available for the restoration and conservation of an object. However, recent genomics and transcriptomics technology opens more possibilities to understanding the activity and function of whole microbial communities and will enter the procedure of routine analysis within the next decade (Sterflinger and Piñar 2013).

2.3 Climate

Generally, humidity is a crucial factor for the development of fungi and insects. However, big differences exist in between different species of fungi and between different species of insects. Silverfish and the wood-boring beetle (*Anobium punctatum*) for example are good indicators for high humidity levels, whereas clothes moths might exist at low levels of water availability. Many fungi need water levels far above 75% rH but some species of *Aspergillus* / *Eurotium* – which might then occur as mono-cultures in a museum – can live at levels slightly above 65%. In order to prevent fungal and insect growth, a control of possible microclimatic niches is important: hot spots of possible humidity might be outer walls, corners and niches and compact shelves with little ventilation. Data loggers with warning systems have to be installed in such niches rather that in the free space of a room and best prevention is to keep rH lower than 55% also in this niches that are delicate in view of condensation, low ventilation or hygroscopic effects of materials.

It is important to note here that development of an infestation of insect pests takes months to years, whereas fungi – especially after water damages or a breakdown of the air conditioning system – might contaminate a full store within very few days. For this reason a continuous monitoring has been installed and coupled to alarm systems, also and especially during holiday periods. Emergency schedules should be available to guarantee a fast climate correction or even a rapid evacuation.

2.4 Treatments

As mentioned above, fungal spores might be extremely resistant against physical and chemical treatments. Whereas fumigation with N_2, CO_2 or argon can be efficient against insects and their larvae (see Querner and Kjerulff 2003, Strang and Kigawa 2009), most fungal spores survive. Freezing is not effective against fungi, but stops their growth and thus can be appropriate to prevent progressive damage before cleaning. Biocides frequently used in restoration are:
(1) Formaldehyde releasers (Sterflinger and Sert 2006, Piñar *et al.* 2009),
(2) Quaternary ammonium compounds with an optimal chain length of C14-C16 (Diaz-Herraiz *et al.* 2013),
(3) Isothiazolinone, a more recent biocide, which was documented to be not only effective but even preventive on paper objects (Polo *et al.* 2010),
(4) Ethanol, the most common disinfectant used in microbiology: can also have a good fungitoxic effect if the contact time is at least 2-3 minutes (Nittérus 2000b).
For insects, sulfuryl fluoride (SF or Vikane) and phosphine (PH_3) are effective fumigant gases. Contact insecticides such as pyrethroids can be applied to objects but they may not be 100% effective as they do not penetrate the material. A broad spectrum of chemical and non-chemical mass treatments has been utilized to kill microfungi attacking paper objects in an attempt to inhibit degradation (Magaudda 2004). Ethylene oxide (EtO) fumigation is banned in many countries – including Austria - because it is extremely toxic, but it still represents the most efficacious system for mass treatment of mouldy library materials. Gamma-radiation is very effective against insects as well as fungi and their spores. Since the radiation dose for fungi must be in excess of 10-20 KGy (Nittérus 2000a), this method also negatively affects many materials and its application is therefore limited. The application of gamma rays can result in cumulative depolymerisation of the underlying cellulose and in severe aging characteristics (Butterfield 1987, Adamo *et al.* 1998). Borates might successfully be used against wood borers and wood damaging fungi, however, usually for prevention rather than a treatment.

Table 1: Most important aspects of insect and fungi development, pest prevention, monitoring and treatment.

	Insects	**Fungi**
Origin of infestation	· With objects from other collections or estates	
	· From the building (walls, wood constructions)	
	· Transportation with visitors / staff	
	· Entering through doors and windows	
	· Sealing of doors and	· Fungal spores are invisibly small (µm)

	windows	and transported easily with air: use of air filters.
		· Fungi are ubiquitous: neither rooms nor objects are sterile in view of fungal spores and other microbes.
Detecting an infestation; monitoring	· Visual inspection	
	· Trapping is very effective; checking 4-6 times per year; · Use of sticky blunder, pheromone and UV traps	· Dust / air samples, swabs needed for identification; · Dummies as traps; · DNA extraction and sequencing: detection of viable and non-viable species; · RNA extraction and sequencing: analysis of function and biodeterioration; · Metagenome analysis: characterization of whole communities (microbes and insects); · 1 -4 times per year.
Prevention: climate	· Low temperature slows down the development of most insects. · Some insects depend on higher temperature / rH.	· Humidity is crucial for fungi. · Best prevention is below 55% rH. · Low temperature slows down growth.
	· Silverfish is an indicator for high humidity.	· Daily peaks of rH are sufficient.
	· *Anobium punctatum* needs high wood moisture to develop.	· Microclimate is important.
Time for development of an infestation	· Few months to years	· Only few hours are necessary for spore germination.
Prevention: sealing the building	· Very important to prevent a new infestation.	· Fungal spores and bacteria are transported with the air and deposited in dust.
		· Regular exchange of air filters class F5. F6, F7 (HEPA-Filters only for clean rooms and vacuum cleaners). Shoe protectants.
Prevention: cleaning	· Very important for prevention of pests or fungal outbreaks	
	· Regular cleaning and good housekeeping	· Spores are in the dust: regular cleaning.
	· Vacuum cleaning to remove food sources and dead insects	· Dust can be hygroscopic and contains nutrients for fungi and bacteria.
	· Cleaning after infestation to detect a new infestation	
Treatment methods		· Regulating the climate (rH)
	· N_2, CO_2, argon	· N_2, CO_2, Argon are not fungicidal.
	· Freezing, heating,	· Freezing is not fungicidal but stops growth.

<table>
<tr><td rowspan="8"></td><td>microwaves</td><td>· Thermal treatment (e.g. for Serpula lacrymans);
· Microwaves</td></tr>
<tr><td colspan="2">· Gamma radiation up to 20 kGy (not for all materials)</td></tr>
<tr><td>· Parasitoid wasps</td><td>· Parasitoid wasps have no effect.</td></tr>
<tr><td>· Pyrethroids
· SF
· PH3</td><td>· Ethanol 70%, Isopropanol 70%</td></tr>
<tr><td colspan="2">· Formaldehyde (only for materials without proteins)</td></tr>
<tr><td></td><td>· Isothiazolinone, carbendazim</td></tr>
<tr><td colspan="2">· Borates (against Serpula lacrymans and wood boring insects).</td></tr>
<tr><td colspan="2">· Problems with resistance of pests, environment, health and safety, damage to objects and materials.</td></tr>
</table>

3. Discussion and Conclusions

Fungi and insects are threatening cultural heritage in museums, art-collections, historic buildings and in the outdoors. Prevention of an infestation, both for insects (and other animals) and fungi is the most important part for long term IPM.

Some common features for both agents of deterioration are the importance of regular monitoring (by visual inspection by experts or trapping / dust and air samples, dummies), cleaning and good housekeeping (the objects but also the building) and finally adjusting the climate is an important regulator for development: Temperature slows down most insects, rH is the most important factor for fungi development. One big difference is that most animal pests need months or even years to develop, but fungi can develop within hours or days! Entomologists and microbiologists should develop and establish common monitoring campaigns, common emergency schedules and work together more intensively in the future.

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Beetles often overlooked in collections: species of mould-feeding beetles found at Royal Museums Greenwich, London

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Abstract
Mould-feeding beetles are often found on insect traps but are frequently not identified by museum professionals. This is due to their small size and indistinct features, as well as the fact that they are usually not regarded as museum pests. This paper introduces five common examples of the family Latridiidae and one species of the family Cryptophagidae that were found in buildings of the Royal Museums Greenwich. Each species is presented with a photograph and the key features are described. The poster highlights their importance as damp and mould indicators which can be crucial in safe-guarding collections.

Keywords: mould-feeding beetle; fungus beetle; damp indicator; Latridiidae; Cryptophagidae

1. Introduction

Mould-feeding beetles are very common throughout the world and are frequently found on insect traps. They are often not identified as a result of their small size and indistinct features, as illustrated by the name 'minute brown scavenger beetle' for the family Latridiidae.

These beetles, which are often colloquially referred to as 'plaster beetles' or 'fungus beetles', can be useful damp and mould indicators in the museum context. They feed on spores, hyphae and conidia, typically found in decaying organic materials that are colonised by fungi. Their natural habitats include bark, animal nests, haystacks and vegetable debris. Many species are synantropic and are regularly found in buildings with damp problems. They occur not solely in old dilapidated dwellings but also in newly built houses, hence 35 the name 'plaster beetle'. They not only feed on mould but can also contaminate materials with mould, as *Cryptophagus acutangulus* has been shown to do. Many of these mould-feeding beetles are not well researched. In particular, information on the life cycle, feeding habits and larvae stages is sparse.

This paper highlights four common examples of the family Latridiidae and one species of the family Cryptophagidae, which were found in buildings of the Royal Museums Greenwich (UK).

2. Identification

Many mould-feeding beetles are very small (i.e. less than 3 mm long) and adults are therefore often found on the underside of blunder traps. Larvae and eggs are rarely found, as they usually live hidden in the food source. Identification by external characteristics requires a binocular microscope with a minimum magnification of x40 and a good light source, as well as identification guides. Usually, artificial keys are used, which systematically group together taxa that share similar morphology regardless of evolutionary relation. They are largely based on simple characteristics; e.g. size, colouration, shape of the pronotum and antennae, density of punctation, etc. The information is compiled both from verbal ID training by David Pinniger (see acknowledgments) and ID books (see references).

3. Mould-feeding beetles identified

3.1 Cryptophagus acutangulus (Gyllenhal 1827)

Length: 1.9 – 2.8 mm
Colour: red-brown, variable
Antennae: 11-segmented, 3-segmented club
Head: not concealed; large, multi-facetted eyes
Pronotum: large and distinctly shaped callosities at anterior of pronotum; pronotum widest at the callosities; lateral margins slightly serrate, with a large tooth in the middle
Elytra: covered with single, decumbent hairs of approximately equal length

Fig. 1: *Cryptophagus acutangulus.* All images © Oxford University Museum of Natural History.

3.2 Corticaria elongata (Gyllenhal 1827)

Length: 1.3 – 1.8 mm
Colour: light red-brown, variable
Antennae: 11-segmented, 3-segmented club
Head: not concealed; punctured; large, multi-facetted eyes
Pronotum: distinctly broader than long; sides rounded; lateral margins finely serrated, coarser towards base
Elytra: pubescence dense, relatively decumbent, hairs of approximately equal length; longitudinal rows of pits on elytra

Fig. 2: *Corticaria elongata*

3.3 Cartodere constricta (Gyllenhal 1827)

Length: 1.2 – 1.7 mm
Colour: dark brown, variable
Antennae: 11-segmented, 2-segmented club
Head: median longitudinal depression; temples behind eyes; multi-facetted eyes
Pronotum: distinctive constriction at lower basal third; longitudinal ridges
Elytra: elytra approximately twice as wide as pronotum; 8 longitudinal rows of pits on each elytron

Fig. 3: *Cartodere constricta*

3.4 Dienerella filum (Aubé 1850)

Length: 1.2 – 1.6 mm
Colour: dark red-brown, variable
Antennae: 11-segmented, 2-segmented club
Head: median triangular depression; no temples; large, multi-facetted eyes
Pronotum: distinctive median oval depression; sides sinuate
Elytra: abdomen comparably flat and hind body at its widest part somewhat broader than pronotum; 8 longitudinal rows of pits on each elytron


Fig. 4: *Dienerella filum*

3.5 Adistemia watsoni (Wollaston 1871)

Length: 1.2 – 1.7 mm long
Colour: light red-brown, variable
Antennae: 11-segmented, 3-segmented club
Head: distinctly longer than broad; wide labrum; eye facets coarse-granular, approximately 6 facets, eyes pale (most other Latridiidae have black eyes); temples behind eyes
Pronotum: slender; sides rounded

Elytra: hind body oval and depressed; approximately twice as wide as pronotum; 8 longitudinal rows of pits on each elytron; longitudinal ridges

Fig. 5: *Adistemia watsoni*

Conclusion

Identifying mould-feeding beetles requires a well-trained eye due to their small size and predominantly indistinct features, and at times help of an entomologist will be required. Many of these mould-feeding beetles are not well researched. In particular, information on the life cycle, feeding habits and larvae stages is sparse. A better understanding of these areas would further increase their value as damp and mould indicators in the museum context.

Acknowledgements

Darren Mann (Head of Life Sciences, Oxford University Museum of Natural History), David Pinniger (Consultant Entomologist) and Birthe Christensen (Head of Conservation and Preservation, Royal Museums Greenwich).

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Investigation into the sex pheromone of the adult female odd beetle (*Thylodrias contractus*)

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Abstract

Museum staff and pest management companies currently lack a readily available monitoring lure for the dermestid beetle species odd beetle (*Thylodrias contractus*). Monitoring programs with sex pheromones can give early indications of the pests and show the location of infestations. This information can lead to the prevention of further damage to museum collections and other animal and insect-based materials being stored.

Identification of the pheromone(s) and subsequent pheromone synthesis and lure production would be beneficial in monitoring for this pest insect. Efforts to isolate the sex pheromone began with dissections of adult virgin females. These dissections demonstrated which parts of the anatomy were producing the pheromone. Further methods of identifying this pheromone utilized the lab method of blowing filtered air across live adult virgin females into an absorbent Porapak Q column and subsequent analysis of the volatiles on a Gas Chromatograph. Also, solvent washes of virgin females using hexane were collected and then a Gas Chromatograph analysis of the solvent wash was performed. Discovery of the pheromone has not been made at this time and further studies are necessary to isolate the sex pheromone.

Keywords: Odd beetle; *Thylodrias contractus*; pheromone; monitoring

1. Introduction

The odd beetle (*Thylodrias contractus*) is capable of causing the biodeterioration of museum objects (Alpert 1988) and is one of the most common pests found in direct association to natural history collections in the USA (Jacobs 1995). This beetle has been suggested to be both synanthropic and cosmopolitan (Mertins 1981) and is known to eat all types of hide, skin and pinned insect collections that are stored in collections or on exhibit in museums (Alpert 1988). Previous studies have shown that the sex pheromone produced by adult female *T. contractus* does influence the behaviour of the adult males (Mertins 1982). Historically, monitoring for *T. contractus* within a museum has delivered un-precise results that make it difficult to locate the source(s) of the infestation. This is true in part due to the fact that the most common monitoring tool has been un-baited sticky traps that have no attraction to the insect, but instead rely on the fact that the insect will simply happen to blunder into the trap (VanRyckeghem 2011).

Sex pheromone lures placed in sticky traps tend to give much more detailed information of where infestations are located and capture a much higher percentage of the adult male insect pests. Sex pheromones for museum pest species such as tobacco beetle (*Lasioderma serricorne*), clothes moths *Tineola bisselliella* and *Tinea pellionella*, and carpet beetles *Attagenus unicolor* and *Anthrenus verbasci* have drastically improved trap capture in museum settings and allowed assertive Integrated Pest Management (IPM) specialists to locate and remove or treat sources of infestation before they spread into greater areas of the museum collection (VanRyckeghem and Kelley 2011).

In an attempt to identify the sex pheromone of the adult female *Thylodrias contractus*, an investigation of the mating behaviour of these insects was necessary. Adult virgin males and females were separated out of the culture as pupae and isolated to study their pheromone production and courtship behaviour. Dissections of different anatomical parts of the larviform adult virgin females were performed and the according reactions of sexually active adult males to these body parts were recorded. This was an effort to indicate the body location of the female where the pheromone production is taking place.

In an attempt to discover the chemical make-up of the female-produced sex pheromone, multiple adult virgin females were placed into air collection containers with the hope of gathering sufficient amounts of sex pheromone from female beetles that would allow for analysis. Solvent washes of the adult females were also performed to try to identify the sex pheromone through gas chromatograph analysis of the wash (Howse et al. 2013).

2. Material and Methods

The insects used were from a laboratory culture derived from an infestation within a natural history museum. The culture has been maintained since 2007 under ambient room temperature, light, and humidity conditions in preserving jars (wide mouth, glass, 1 pint, brand 'Ball'). These jars were covered to contain the insects with open-topped metal screw lids fitted with Whatman No. 1, 90 mm filter paper (Gorham 1991). The filter paper served as a means to allow air passage in and out of the containers. The larval diet consisted of dried insect cadavers, primarily ground larvae and pupae of the fly species *Musca domestica*. Insects for observation were removed from the cultures in the pupal stage and isolated individually in ½ dram glass vials to ensure virginity (Fig. 1). They were observed daily until adult emergence. After eclosion, individual males and females were removed from the ½ dram vials and held in glass test tubes for various periods until investigations were performed.

Dissection of the virgin females was performed under a Nikon stereoscopic microscope with magnification up to 40X and an external high intensity light source. The dissections were performed using micro dissecting needles and a micro dissecting spatula.

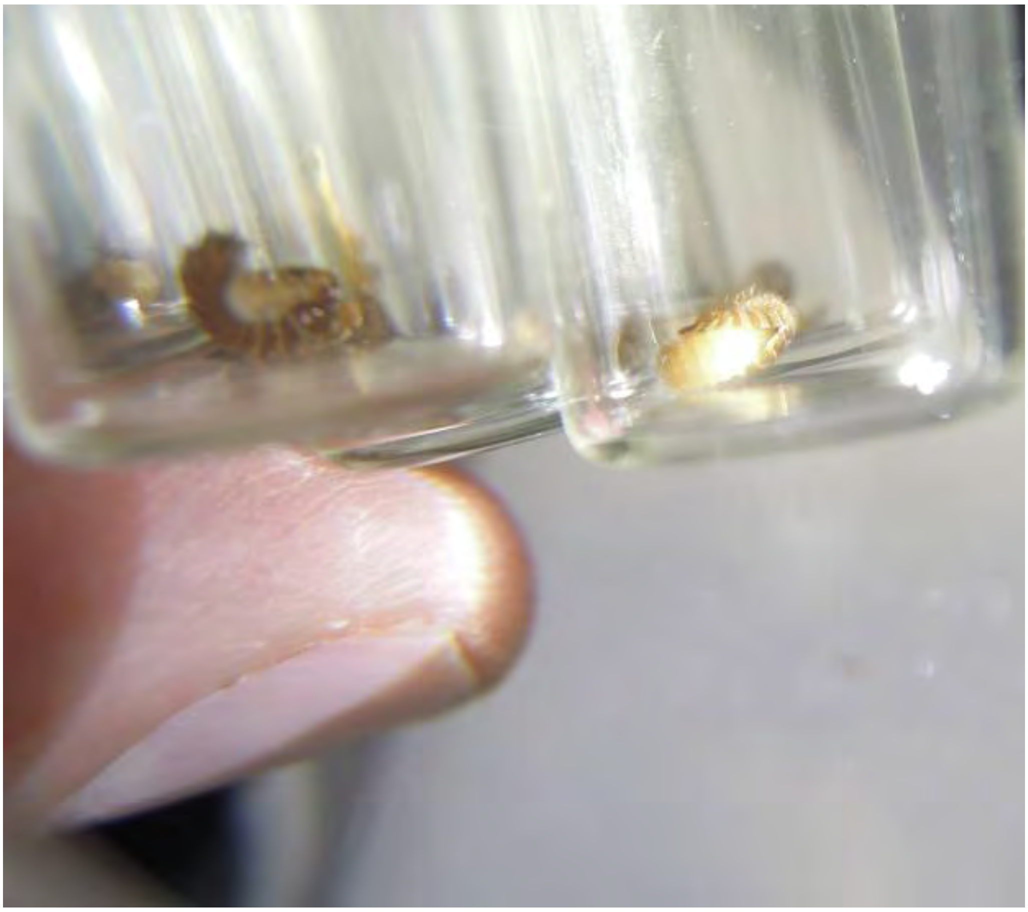

Fig. 1: Pupae from cultures of *Thylodrias contractus* were separated out into glass vials prior to eclosion to ensure virginity.

Activities and mating behaviour of individual pairs of *Thylodrias contractus* were observed with the naked eye in an arena consisting of the bottom of a 90 mm O.D., low profile disposable plastic Petri dish lined with a single sheet of Whatman No. 1, 90 mm filter paper.

The absorbent columns that were used to collect the potential pheromone in the space above the females were filled with Porapak Q 50/80 mesh. Air samples began with a tank of breathing quality compressed air that was regulated and run through a 36 cm tall by 1.3 cm diameter Chemglass condenser column filled with glass wool moistened with distilled water. The air sample was then run through a second 36 cm tall X 2.5 cm diameter Chemglass condenser column containing activated charcoal held in the column by thin layers of glass wool on each end of the charcoal. After the regulated air was filtered through the 2 columns it was then passed across a short glass chamber containing the adult virgin females resting on a 1 cm diameter sheet of Whatman filter paper. Volatiles from the head space located above containers of adult virgin females were collected and captured in the Porapak Q columns for future investigation (Fig. 2 and 3) (Millar and Haynes 1998). These columns were then analysed with the GC. Volatiles were extracted sequentially with 0.5ml of hexane, then 0.5ml of hexane: ether 95:5, and then 0.5ml of dichloromethane. One microliter samples of the extracts were placed onto the GC column. The column was programmed at 35°C for 2 minutes then ramped 10°C /min for 22.5 minutes and held at 260°C for 5.5 minutes for a total analysis time of 30 minutes.

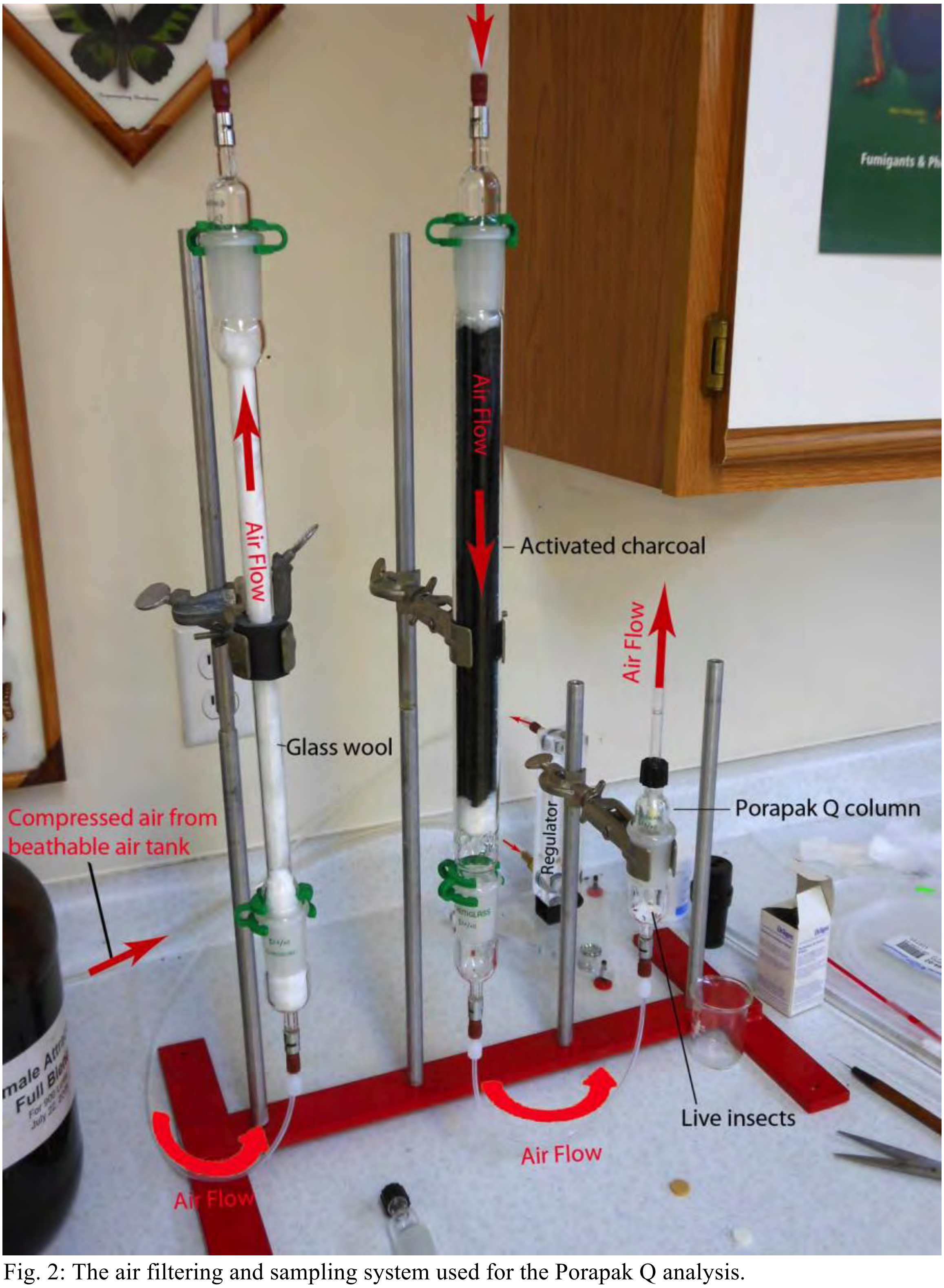

Fig. 2: The air filtering and sampling system used for the Porapak Q analysis.

Fig. 3: Multiple adult virgin female *Thylodrias contractus* placed together to collect potential sex pheromone in the head space above with the Porapak Q column.

The gas chromatograph used to analyse the insect pheromone is a Shimadzu model GC-17A FID. In an effort to determine which part of the anatomy of the adult virgin female produces the sex attractant pheromone, adult virgin females were dissected and the dissected parts of the anatomy were presented to sexually active adult males on clean filter paper in plastic petri dishes. Observations of the adult male responses to the different parts of the female anatomy were recorded into one of the following categories; No Response, Slight Response, Definite Response and Strong Response. An observation of No Response meant that the adult males did not exhibit any behaviour changes at all to the dissected body part within the arena.

An observation of Strong Response meant that the majority of males in the arena had immediate and extended behavioural changes when exposed to the dissected body part. All behavioural changes noted by the males were attractive in nature and the Strong Response reactions would last for several minutes where the males would desire direct contact with the dissected body part. Slight Response and Definite Response corresponded to the degree of behavioural change exhibited by the males.

The dissected parts were divided into these 5 areas which included: head, thorax, tergites, legs and abdominal tip (Fig. 4).

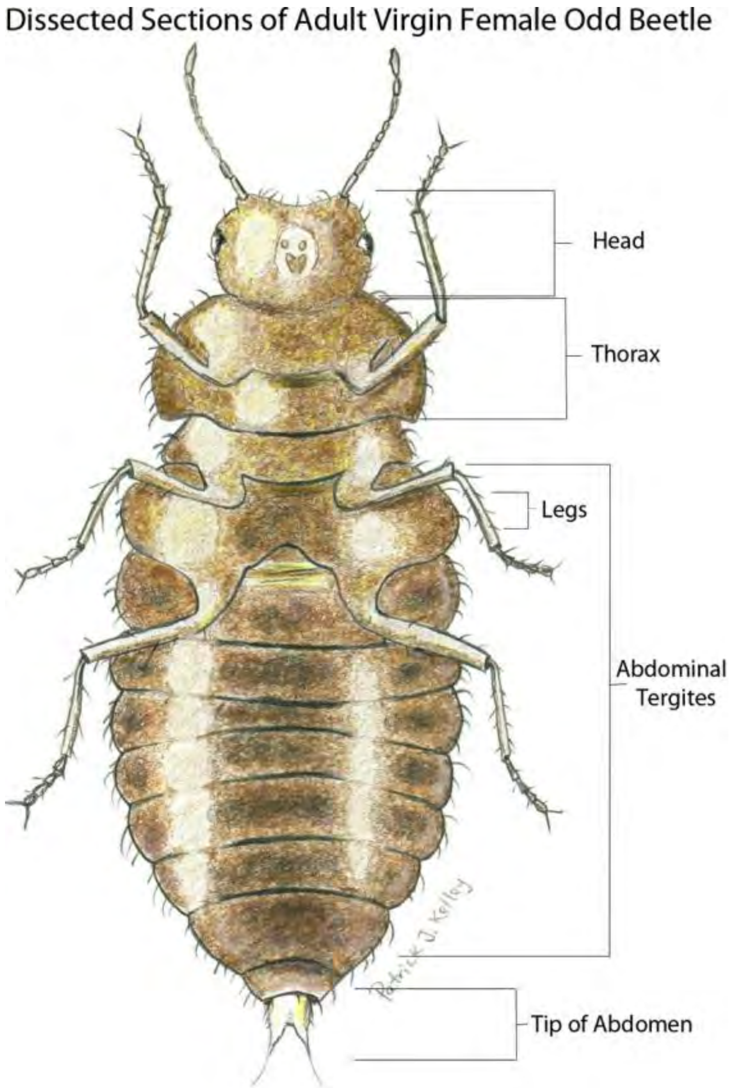

Fig. 4: Drawing of an adult odd beetle (*Thylodrias contractus*) female, showing the 5 areas that were dissected and presented to sexually active males to observe their response.

3. Results

The only parts of the adult female anatomy that elicited a Strong Responses from the males were the tip of the abdomen and the abdominal tergites. The head of the female elicited a Definite Response while the thorax and legs elicited No Response from the males. No observations of Slight Response were recorded. When multiple males were exposed to the tip of the abdomen of the adult virgin females, several males were observed attempting to mate with the body part and some even attempted to mate with the other males that were in contact with the body part. It is interesting to note that the empty pupal case of the virgin females also elicited a strong response from the males. The pupal cases had been in direct contact with the female throughout pupation and the 24 – 48 hours since eclosion.
A gas chromatograph (GC) analysis of the pertinent anatomical parts was performed. The tip of the abdomen yielded GC definitively higher peaks at the 6.74, 7.44, 15.23, 15.47 and 15.90 minute marks. The tergites also yielded peaks at 6.74, 7.44, 15.23 and 15.90 minute marks.

GC readings varied greatly over several samples of between 1 and 7 females. There were several common peaks for a few of the samples. A common peak at the 15.23 minute mark correlated with peaks for the tip of the abdomen and tergites.

Samples in the Porapak Q from mated females and virgin males were also collected and compared to the GC reading from the virgin females. The peaks in the GC analysis that occurred in both the mated and virgin females were cancelled out as potential sex pheromone (Fig. 5). GC analysis was also performed on the dissected body parts of the adult virgin females that had elicited strong responses. These peaks were also compared to those of the mated and virgin female air samples. GC peaks for virgin males that were not common to the peaks for virgin females occurred at the 18.3 and 20.40 minute marks. GC analysis of solvent washes over the adult virgin females also produced some similar peaks that were seen in the Porapak Q GC analysis of the virgin females.

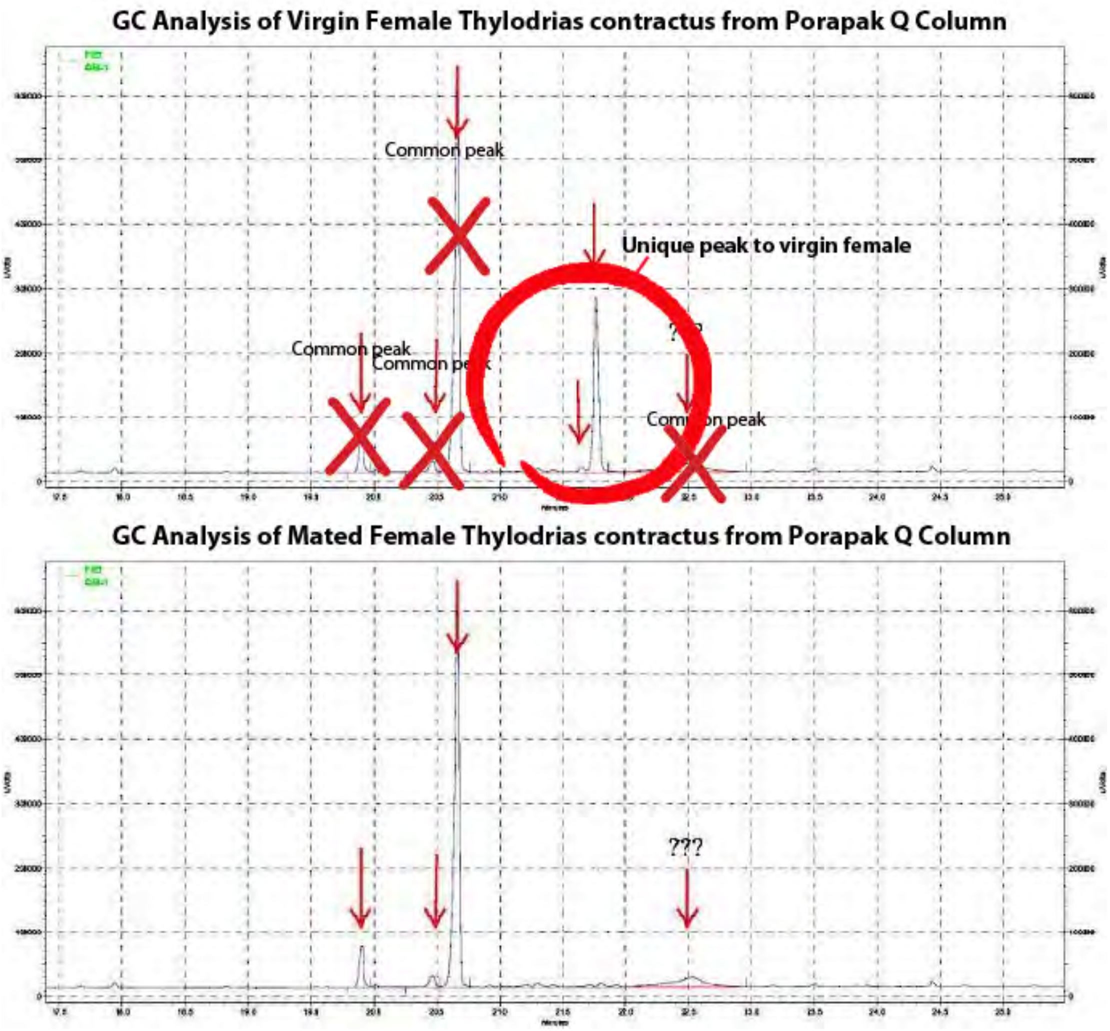

Fig. 5: Method used to determine the sex pheromone of the adult female *Thylodrias.* Determination was based on the comparison of the GC analysis of the odours produced by virgin females to that of mated females. When similar peaks occurred in both, it was assumed that these did not correspond to the sex pheromone and were disregarded as potential pheromone. The analysis on top shows a strong peak in the virgin female that was not present in the mated female analysis. The circled area represents that peak with potential for pheromone activity.

4. Discussion and Conclusion

From the dissection of the female *Thylodrias contractus*, it seems likely that the pair of glandular setae at the tip of the abdomen is producing a sex pheromone. This abdominal tip region elicited the strongest response from the males. The tergites also elicited a strong response and this area is in close proximity with the glandular setae. We can forecast that pheromone from the female prior to eclosion must have also been rubbed onto or absorbed into the cast pupal skin from the direct contact with the female. It is yet unclear why the head of the female elicited a definite response from the males. Further research into sex pheromone production of the females would be beneficial.

The GC analysis from the different air and wash samples of the virgin females was inconsistent. A single analytical peak or peaks was not seen throughout all samples. Some of this inconsistency may have been due to contamination of the GC from earlier pheromone samples run through it. More information is necessary before the sex pheromone can be determined. It will be necessary and perhaps valuable to have live adult females sampled through a GC/ mass spectrometer combination. This could supply valuable information about the chemical make-up of the air space around the adult females including information regarding the sex pheromone. With this information, the chemical make-up that corresponds to the GC peaks that we have identified as potential pheromone can be found. Once a chemical determination has been made, then synthesis routes can be explored and testing can begin to see how attracted the adult males are to the synthesized pheromone.

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Use of ultra-wideband (UWB) technology for the detection of active pest infestation

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Abstract

This paper discusses a novel approach for detection and monitoring of pest infestations in museum objects. Ultra-wideband (UWB) sensors transmit radio waves that penetrate non-metallic materials and can be used to detect movements of tiny objects such as termites under the surface. The technical challenges and how they are addressed will be briefly introduced. A suitable sensor concept is selected and experimental results with termites inside a wooden block are shown.

Keywords: UWB sensing; pest detection and monitoring

1. Introduction

Integrated pest management (IPM) is a young yet very successful concept that has not only attracted research but is also being actively applied in many museums and art collections today. One of the most challenging tasks is the detection of pest infestations and to quantify their extent (Koestler *et al.* 2000, Lewis *et al.* 2009). It is often impossible to look into the objects without destroying them and in most cases moving or close inspections must be done with extreme care. Using harmless ultra-wideband (UWB) radio waves in the microwave region that penetrate into materials like wood and tissue promises a new solution for non-destructive testing which can even be applied without touching the art object as opposed to e.g. ultra-sound technology. However, there are demanding physical and also practical issues that need to be addressed which means that not just any sensor concept can be used. In this paper, a short overview of these issues will be given and a suitable sensor solution will be described. To verify the feasibility of the approach, results of laboratory experiments for the detection of a small termite colony in a wooden block will be presented.

2. Principle of UWB sensor based pest detection

Remote sensing using electromagnetic waves is well known in applications such as traffic speed monitoring radar or ship and aircraft navigation radar. The same principle can also be used to do measurements over very short distances using low power and high resolution devices (Sachs 2012). Such sensors have in common that a signal generator is used to provide a radio frequency wave that can be transmitted by an antenna. This wave propagates into the environment and interacts with all objects - reflections, diffraction, and penetration into materials occur (Orfanidis 2008). The backscattered waves are coherently registered by receive antennas and fed into data processing. The processing finally decides which information is extracted, i.e. what kind of wave interactions is taken into account and how they are interpreted (Kostylev and Astanin 1997, Daniels 2004). Fig. 1 depicts the general sensing method and a simplified scattering situation for pest detection in a wooden object. The transmit antenna (Tx) sends out an UWB signal *x(t)* that can be modelled as a short pulse. In most cases it is not desirable or even impossible to let the antenna touch the surface of the object under test. Therefore, the wave is transmitted into air and hits the object's surface at first. Each material boundary provokes a reflection. The surface reflection **A** is often by far the strongest component received. A part of the energy enters the object (**B**). Since pests consist of materials very different from wood or stone, they also cause a small reflection (**C**, later denoted as $y_{\text{insect}}(t)$).

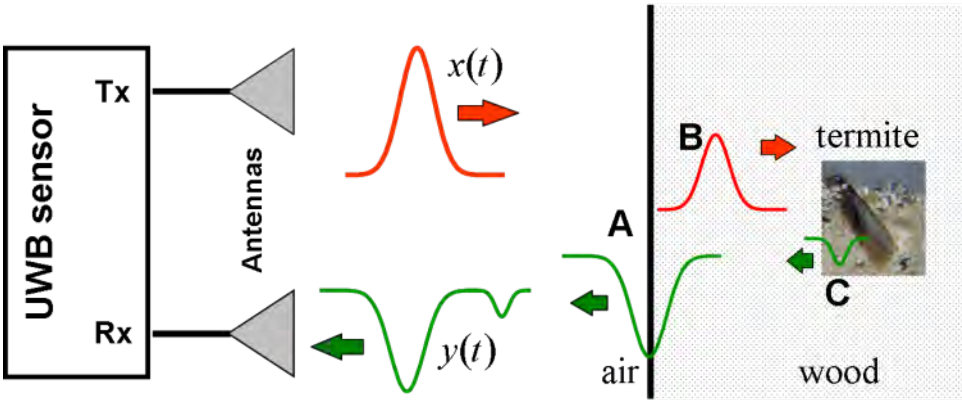

Fig. 1: UWB sensing principle and typical scattering from pest-infested wood.

The final receiver (Rx) signal *y(t)* contains both reflections **A** and **C** as well as further components originating from other scatterers. Of course, there are usually several insects inside and all of them cause similar reflections. Given the simple setup of Fig. 1 with only one Tx and Rx channel, all pest responses will overlap in *y(t)* and may not be separable at all. However, by using appropriate data, processing the presence of pests in the illuminated area can be detected. As long as antennas and test object are not moved or otherwise manipulated, the surface reflection **A** will not change over time, i.e. it will be a static signal component when the measurement is repeated. On the contrary, pests will move inside the object thereby changing their distance to the antenna and the shape of the reflection signal **C**. When the measurement is repeated, the received signals will slightly differ from each other. Such variations can be recognised and indicate a pest infestation. After observing one spot of the test object over a sufficient time window, the sensor can be moved to check a different point. In this way, the extent of an infestation can be assessed iteratively.

3. Challenges of UWB pest infestation detection

3.1 Physical properties of backscattering from small insects

There are two requirements for the described method to work that lead to contradicting sensor properties. It is obvious that the radio waves need to be able to penetrate into the art object. In principle this is possible for non-metallic materials but the amount of energy that gets reflected on the surface as well as the attenuation the wave suffers while travelling through an object depend on material properties such as dielectric permittivity, permeability, conductivity, etc. (Kostylev and Astanin 1997). For common materials of art objects such as wood, stone, or tissues, penetration is possible for waves in the lower GHz frequency range (microwaves). The higher the humidity of the material, the lower frequencies should be used because water causes significant wave attenuation (Sachs et al *et al.* 2005).

The backscattering amplitude of reflection **C** in Fig. 1 not only depends on the material differences between pest and wood, but also on the relation of wavelength to the pest's size. When the spectral content of the sounding signal *x(t)* falls into the low GHz range, wavelengths will be in the order of a few cm. However, pests are usually much smaller of mm or even sub-mm size. Therefore, the individual insect can be modelled as a point scatterer that is much smaller than the wavelength. This condition is called Rayleigh scattering (Mie 1908, Bohren and Huffmann 1983) and the reflected signal $y_{\text{insect}}(t)$ is proportional to the second derivative of the stimulus and the volume V of the scatterer according to (1).

$$y_{\text{insect}}(t) \propto \frac{d^2 x(t)}{dt^2} \cdot V \qquad (1)$$

This means that high frequencies are strongly preferred over low frequencies to produce a signal that is detectable, i.e. that does not vanish in the unavoidable receiver noise. Furthermore, the smaller the insect, the higher the demands on the receiver sensitivity for a given frequency range. It is important to note that simply building a very low noise receiver is not sufficient - the device must be able to register extremely weak backscattering from pests while at the same time coping with the strong surface reflection, i.e. the overall dynamic range of the Rx must be as high as possible. It can be concluded, that UWB sensors with their extremely wide bandwidth are best suited for pest detection since they combine low and high frequencies which ensures operation with many different materials and pests.

3.2 Properties of suitable UWB sensor devices

UWB sensors can be realised using very different concepts (Sachs 2012) each with specific pros and cons. The most simple and affordable approach is to directly generate short pulses and a sampling receiver (pulse radar). However, since *x(t)* and consequently also the surface reflection contain extremely high amplitudes, it is very difficult to build receivers that can handle them while still being able to register the weak pest reflection signals. Moreover, the high amplitudes cause stability issues in the pulse generators which usually lead to signal shape variations. Such variations must be avoided if possible because they limit the repeatability of the surface reflection, i.e. they cause the surface reflection to change significantly between measurements. In such a case, data processing can no longer distinguish signal changes caused by moving pests from residuals of the unstable surface signal. Consequently, only sensor concepts that provide a very stable UWB stimulus signal as well as sampling time base are suitable.

Apart from these technical challenges, a number of practical aspects must also be addressed. If a sensor device is employed outside a lab (e.g. in a museum), it must be small enough to be moved around. This is especially important when trying to assess the extent of an infestation by measuring at different points and the art object itself cannot be moved. An alternative would be to use a device with many Tx and Rx channels that are connected to multiple antennas distributed over the test object. Such a setup could speed up the measurement time when many points need to be checked. However, hardware costs increase with the number of channels and low device costs will play a major role in the spreading of this detection methodology and its practical deployment. Applications where the sensors should be used for long-term or even continuous monitoring of object are especially cost sensitive. Low energy consumption and ruggedness are also important aspects in this regard.

In conclusion, the mentioned requirements can only be fulfilled by a sensor technology that can be highly integrated into a small number of core components and that can be easily scaled in terms of Tx and Rx channels. ILMsens M-sequence UWB sensors are one example originally developed at the Ilmenau University of Technology (Sachs *et al.* 2006, Kmec *et al.* 2007). These sensors employ a special stimulus based on pseudo-noise signals which provides UWB operation while avoiding high peak amplitudes. The stability of the transmitted signal as well as the sampling timing are excellent and the devices can be miniaturised to facilitate flexible deployment. Fig. 2 shows a prototype of such a sensor device with one transmitter and two receivers working in the frequency range from near 0 up to 8 GHz. Tx and Rx are general purpose and must be connected to suitable antennae for pest infestation detection. The device provides an USB2.0 interface as data connected to a processing unit.

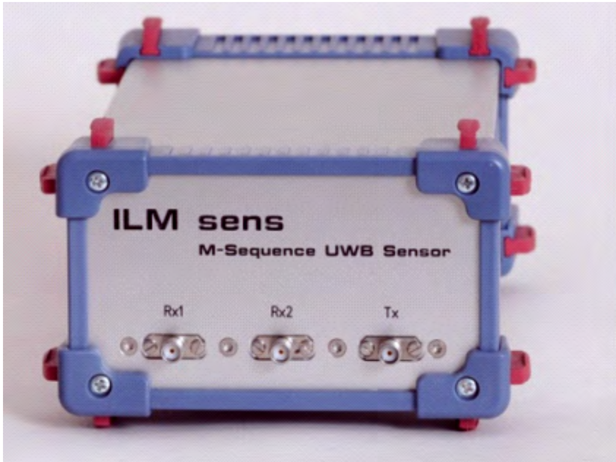

Fig. 2: 0-8 GHz UWB sensor prototype from ILMsens. The size is 12 cm x 7 cm x 22 cm.

4. Experimental results for proof-of-concept

4.1 Measurement setup

In order to assess the feasibility of UWB sensors for pest detection, a simple experiment has been carried out in the laboratory. A wooden block made of MDF (medium density fibre-board) of size 30 cm x 30 cm x 30 cm was prepared with a void in the middle. Small colonies of different termite species were placed in the void for different measurements. One Tx and one Rx horn antenna connected to the UWB sensor from Fig. 2 were placed at opposite sides of the block. Please note that the Tx antenna was simultaneously used as a second receiving antenna similar to the simple setup depicted in Fig. 1. The antennas were fixed to ensure a constant relation to the block's surface. The experimental setup is shown in Fig. 3. The measurement was run over the course of 20 to 30 seconds and the receivers repeatedly recorded the waves scattered by the MDF block.

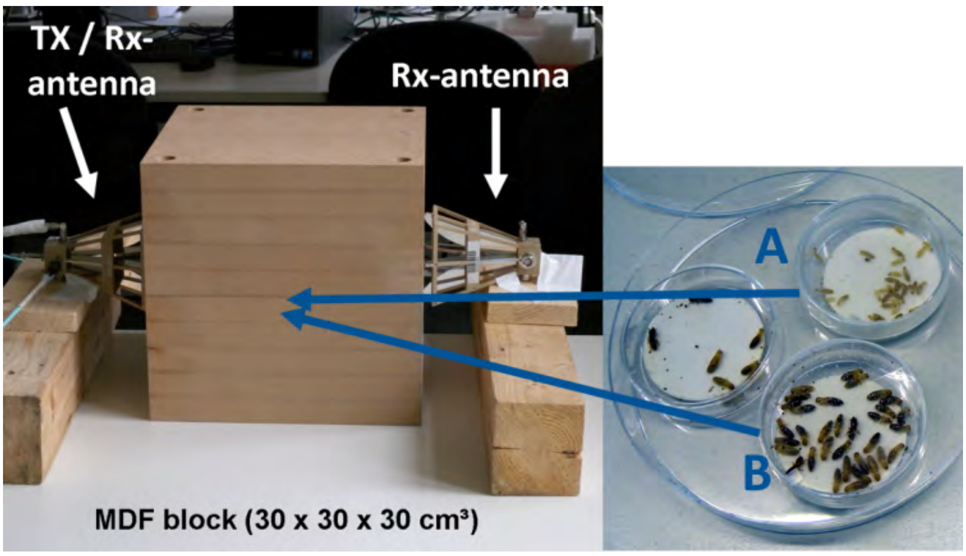

Fig. 3: Experimental setup with MDF block and horn antennas (left). Termite colonies placed inside the block (right); **A**: *Kalotermes flavicollis* (F.), **B**: *Incisitermes marginipennis* (Latr.) - with two different colony sizes (only results for measurements of the small colony are shown in this paper).

4.2 Measurement results

Static signal components that do not change between waveform acquisitions have been removed by data processing and the amplitudes of the remaining signal components have been encoded into a colour scale. Fig. 4 shows one results of experiment A with 30 termite larvae of *Kalotermes flavicollis* (F.) termites inside the block.

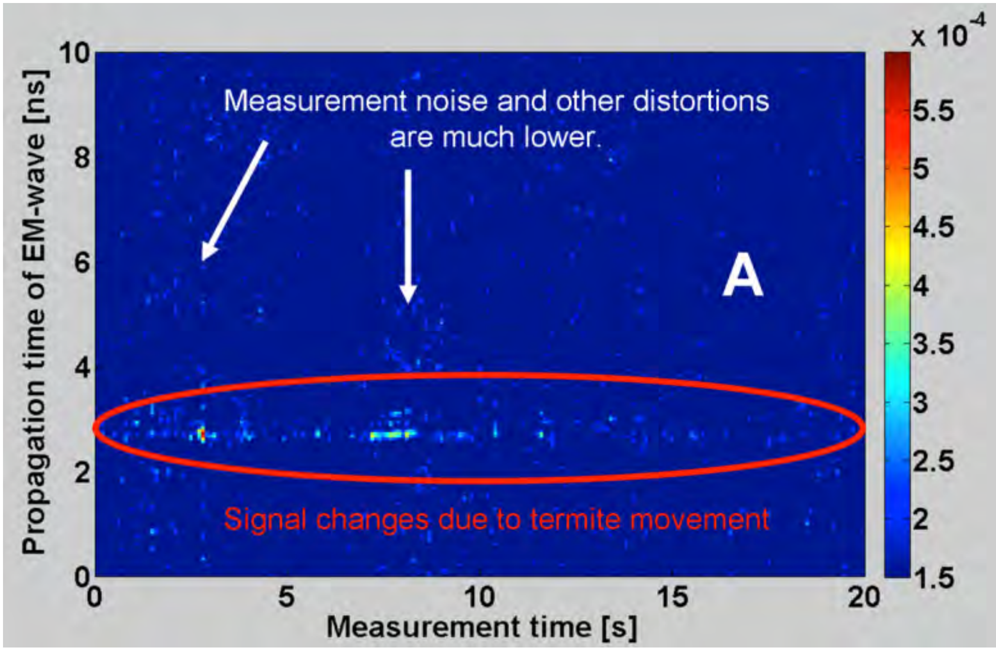

Fig. 4: Measurement result of experiment **A**. Static signal components have been removed, while remaining signal variations are encoded as colours.

The electromagnetic waves need about 3 ns travel time from the transmit antenna through the block until it comes back to the receiving antenna. Dark blue colours indicate the receiver noise floor while detectable signal amplitudes are shown in green and red colour. The data set contains irregular amplitude variations around 3 ns propagation time. They stem from movements of the termites inside the block which change the backscattered signal shape. The termites are very small and as it could be expected from (1) the overall signal amplitude is rather low and often close to the noise floor. However, the activity of the termites could still be detected with the employed sensor device.

The experiment was repeated in case **B** with six larvae and two soldiers of the larger termite species *Incisitermes marginipennis* (Latr.) in the same block. The result is shown in Fig. 5 after similar preparation of the dataset as in case **A**. Termite activity caused varying signals again after about 3 ns. The colour scaling is the same as in Fig. 4 and this time variation amplitudes are more pronounced than in case **A**. As expected, changes caused by larger insects are easier to detect. In a final control experiment, the termites have been removed from the block and the measurement has been repeated with an empty (i.e. uninfested) block. This was done to check the stability of the ILMsens sensors and to verify that the signal changes in Fig. 4 and Fig. 5 really come from moving insects. The control dataset (not included here) did not show any signal variation at 3 ns other than the noise floor also present for the other propagation times. These results clearly demonstrate that pest infestation detection is possible using the M-sequence UWB sensors and further studies are encouraged.

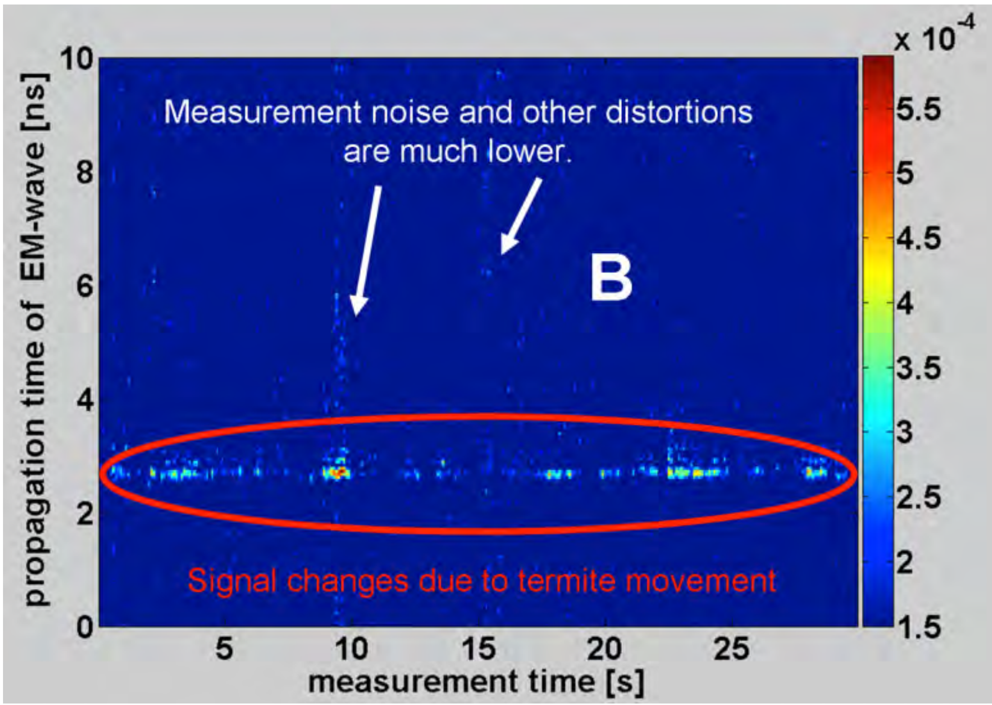

Fig. 5: Measurement result of experiment **B**. Static signal components have been removed, while remaining signal variations are encoded as colours.

5. Future work and conclusions

Non-destructive testing technologies are a valuable and promising tool for IPM applications. Such techniques specifically address the problem of in-situ detection and monitoring of pest infestations and their extent. UWB sensors using radio waves are especially attractive since they enable contactless measurements. An art object in question can be observed over some time with repeated measurements. After removal of static signal components, residual variations caused by insect movements can be detected. Suitable devices must provide high performance properties such as large dynamic range receivers, excellent signal and time-base stability, compact size, low cost, and flexible measurement configurations. ILMsens UWB sensors using the M-sequence principle match those requirements and have been successfully tested in laboratory experiments. The capability of detecting termite infestations has been verified.

The sensor that has been used works with frequencies up to 8 GHz. As expected from theoretical considerations, backscattering amplitudes decrease with the size of the insects. To improve robustness for the detection of very small specimens, a further increase of operating frequency range should be tested, e.g. a shift to the 20 or 30 GHz range could result in significantly higher reflection amplitudes from pests. However, such frequencies will probably only penetrate dry materials. Although the prototype sensor used is already quite compact, it was not optimised for this task. Further size and cost reductions will be mandatory to facilitate practical deployment. Furthermore, numerous measurements with other pests and under real-world conditions should be conducted to improve sensor properties and to quantify detection performance.

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