Pest comparison of three treatment methods for archival materials against grey silverfish (*Ctenolepisma longicaudatum* Escherich, 1905): re-evaluation of the efficacy limits of freezing, heating and anoxic treatment with oxygen absorbers

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ABSTRACT The museum pest *Ctenolepisma longicaudatum* Escherich, 1905 (long-tailed silverfish, grey silverfish) has been spreading rapidly in Europe for years and endangers the collections of archives, libraries and museums. Therefore, there is an urgent need of recommendations for curative and preventive control strategies, which can be implemented in a way that is gentle to the object, rapid and cost-effective. In the study conducted as part of a Masters project in conservation sciences, the efficacy of three non-chemical treatment methods – freezing, heating and oxygen deprivation – and the lethal effects for *C. longicaudatum* was evaluated under laboratory conditions. Standardised test samples (archival boxes 40 × 28.2 × 11 cm) were prepared and an infestation situation was simulated, in which all developmental stages were examined: adults, nymphs and eggs. Mortality rates were determined by controlling time, temperature and oxygen levels. The results show that freezing at –20 °C without first reaching core temperature required only 12 hours to kill all stages. The anoxic treatment was successful in 48 hours at 22 °C, 50% RH and 0.1% residual oxygen. In the heat treatment studied, 47.5 °C held for one hour was already sufficient.

KEYWORDS *Ctenolepisma longicaudatum*; paper; archive; library; non-chemical treatment; freezing; heating; anoxic treatment; oxygen absorbers

Introduction

With the detection of the grey silverfish (*Ctenolepisma longicaudatum* Escherich, 1905) in Europe, a new threat to collections of written cultural property and works of art on paper has been identified. In Germany, the first finding was detected and published by Udo Sellenschlo in 2007. It is suspected that the international trade in goods has favoured the massive spread and for this reason it is also increasingly found in art and cultural heritage institutions. The pest enters libraries, archives and museums through new acquisitions, object loans, infested packaging materials, paper tissues or toilet paper. Often the quantity of these potentially contaminated objects or packaging materials exceeds the capacity for quarantine. The damage caused by the insect is noticeable as abrasions on the surface of the affected paper and even pitting. If an infestation is not detected or treated, there is a risk of severe

Figure 1 Different stages of *C. longicaudatum* in a live trap (in cm). (© Judith Wagner).

Table 1 Methods of non-chemical insect pest treatments in museums.

Method	Equipment	Temperature	RH	Residual oxygen	Time of treatment	References
Freezing	freeze chamber, freeze container, household freezer, chest freezer	–18 °C	~50%	–	14 days	Strang 1992; Pinniger *et al.* 2016; Lauder and Pinniger 2019; Strang and Kigawa 2009
		–25 °C		–	7 days	
		–30 °C		–	3 days	
Heating/ humidified warm air	heating chamber, heat bubble	Mind. 55 °C	45–55%	–	24 hours	Xavier-Rowe *et al.* 2000; Pinniger *et al.* 2016; Strang 1992, 2001
Anoxic treatment	nitrogen chamber, nitrogen bubble, bags with scavengers	27 °C	~50%	0.5% O_2 1.0% O_2	21 days	Selwitz and Maekawa 1998; Landsberger *et al.* 2019
		24 °C	~50%	0.5% O_2	21 days	

loss of substance or irreversible insect damage. Therefore, the solution appears to be the application of curative and preventive control measures that are targeted to control the grey silverfish.

Aim of the study

The grey silverfish is a synanthropic species and considered a material pest for paper and cardboard because it prefers to feed on carbohydrates, such as cellulose, starch and sugars (Lindsay 1940). The grey silverfish reaches a maximum length of 18 mm without antennae (Beijne Nierop and Hakbijl 2002; Sellenschlo and Weidner 2019). Reproduction is continuous, regardless of season, with about 60 eggs laid per year (Aak *et al.* 2019). These hatch into nymphs, which reach sexual maturity at the 14th instar and a body size of approximately 9.5 mm (Fig. 1). A temperature of 22–26 °C and a relative humidity (RH) of 55% or above is ideal for its development. According

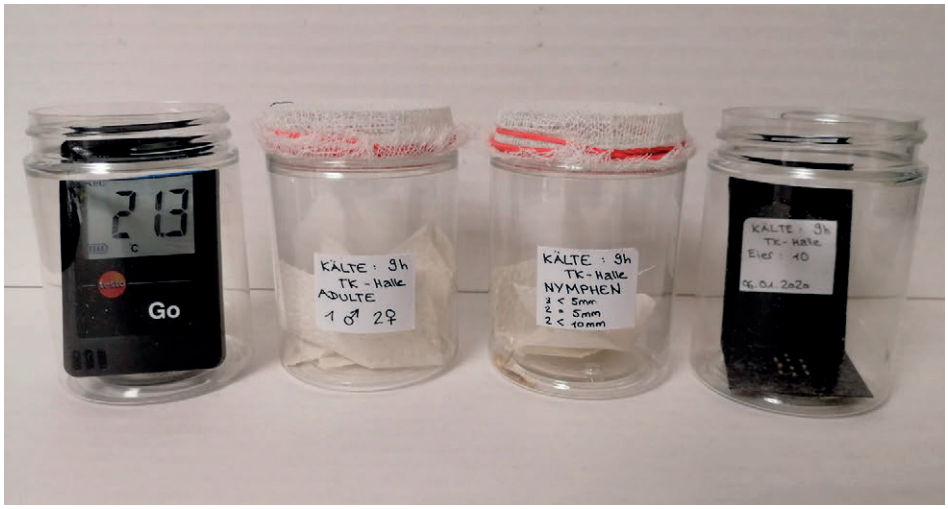

Figure 2 Plastic test container with *C. longicaudatum* – separated into adult, nymph and egg stages – and a climate data logger (© Judith Wagner).

to Lindsay (1940), temperature values below 0 °C and above 41.5 °C have a lethal effect, although adults can survive and recover after brief exposure.

The established system of integrated pest management (IPM) provides a comprehensive strategy of prevention, detection and appropriate control of a pest infestation (Brokerhof *et al*. 2007; Pinniger *et al*. 2016). For preventive or curative control, the chosen treatment methods should be compatible with the principles of conservation of cultural heritage property (Florian 1997). This means the condition of the treated objects should not be affected in any way. In addition, the chosen methods must be residue-free in application to protect humans, the environment and the object. Physical pest control using high and low temperatures or anoxic treatment by creating a modified atmosphere via nitrogen enrichment or oxygen removal fulfill all these requirements (Querner and Kjerulff 2013). An overview of the common guidelines for assured treatment success applied to pests is summarised in Table 1, which also gives the effective values of the parameters' temperature, RH, time of treatment and residual oxygen.

Based on the proven recommendations for the three non-toxic treatment methods, the aim of this study was to adapt the different parameters of the methods to the biology of this particular pest species by reducing the temperature gradient or the time of exposure. There should still be a 100% mortality rate of all the different developmental stages of *C. longicaudatum.*

In collection repositories containing paper and cardboard objects, the climate is ideally adjusted to their needs (~18 °C and 50% RH). Exposure to climatic changes leads to physical stress of the objects: even if an immediate damaging effect cannot be confirmed for most materials (Beiner and Ogilvie 2005), long-term damage cannot be ruled out. In addition to saving financial resources, the shortening of the time of exposure also increases productivity as treatments can be better integrated into the daily routine of institutions.

Material and methods

Preparation

C. longicaudatum was cultivated to ensure the presence of enough test individuals in all developmental stages – adult females and males, nymphs and eggs. Breeding at temperatures between 18 °C and 30 °C with an average RH of 50–60% resulted in sufficient individuals for the experiments. To exclude increased stress to the insects, they were prepared at least three days before the experiment. The individuals were differentiated into adult and nymphal stage based on body length, and for each experimental run 10 specimens of both sizes were placed in separate 100 ml plastic containers. Ten eggs per experiment were mounted on black sample cards specially prepared with double-sided tape (using a magnifier) before being transferred to the containers. The containers were sealed with a gauze and placed back in

Figure 3 Five archival boxes prepared for the experiment, filled with telephone directories and four milled round recesses per box (© Judith Wagner).

the breeding container until immediately before the experiments.

For freezing and anoxia treatment, archival A4 format boxes (external dimensions 400 × 282 × 110 mm) were filled with six layers of telephone directories. Four cylindrical recesses were milled into the stacks at even intervals, into each of which the plastic containers with test insects and a data logger were inserted (Figs 2 and 3). To create comparable baseline conditions, the archival boxes were pre-conditioned at 18±2 °C and 46%±3% RH for two weeks prior to the experimental runs.

Freezing

The tests were carried out in a Liebherr GGPv 6570 ProfiLine freezer cooled to –20 °C. The test specimens were wrapped with polyethylene (PE) film in accordance with the process recommendations. The time parameter was investigated by setting the treatment intervals to 4, 6, 12 and 24 hours (without reaching core temperature). After the end of the treatment period, a thawing phase of 24 hours took place.

Heating

The experiments were carried out in an ATMOS MTH-4100 Temp/Humidity Stress Chamber. The lowest temperature selected was 40 °C which was increased by 2.5 °C to 50 °C at systematic intervals. The RH was set at 50% but was subject to slight fluctuations owing to the equipment. Due to a lack of a control sensor, the time intervals needed to be adjusted and finally programmed based upon prior experiments. Using the knowledge of the length of the heating phase, the climatic chamber was then programmed to ensure a gradual heating phase was followed by a one-hour holding phase before the temperature was slowly lowered again. The plastic containers containing the insects were placed directly in the chamber.

Anoxic treatment

Mortality of *C. longicaudatum* was studied at a residual oxygen concentration of 0.1% and a temperature of 22 °C. The time intervals to be tested were set at 12, 24, 48 and 168 hours. An oxygen-free atmosphere was created in 42 × 68 cm bags (ceramic-coated PET on one side and aluminium composite film A 30T on the other) by adding 10 ATCO FTM 1000 oxygen absorbers. A RH of 50% was controlled by PROSorb silica gel. The residual oxygen content was monitored with a GOX 100 oxygen meter and the treatment intervals started as soon as the desired concentration of 0.1% residual oxygen was reached, after about 20 hours.

Data collection

During each test run, temperature and humidity values were recorded using the data logger

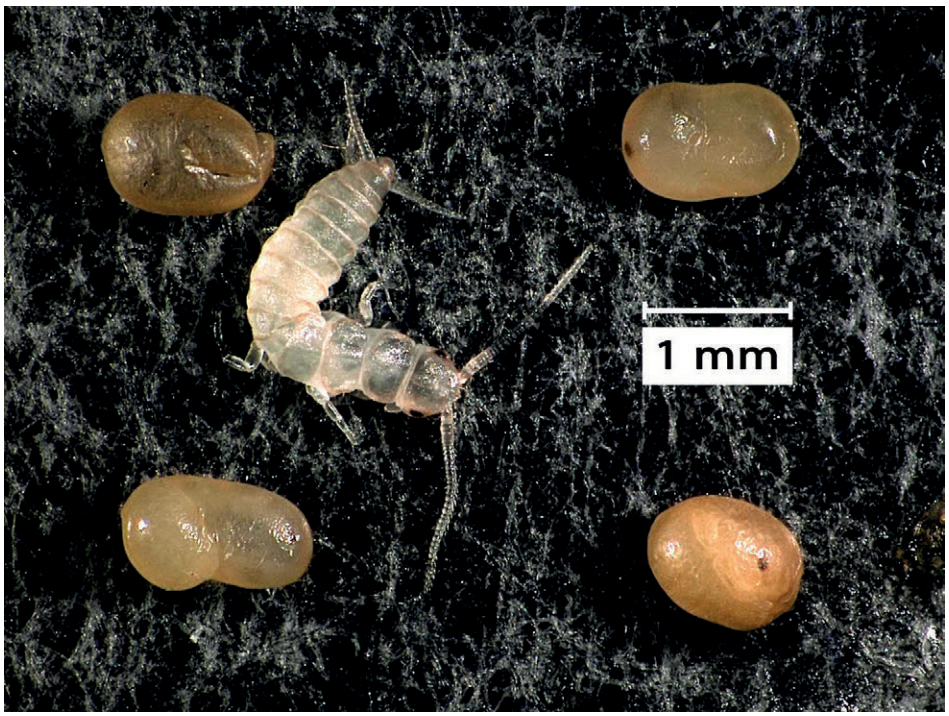

Figure 4 The hatching of a nymph after a treatment demonstrates this as unsuccessful (original magnification ×50) (© Judith Wagner).

Table 2 Summary of results for freezing: an overview of tested parameters and stages of grey silverfish.

Temperature	**In freezer:**	**– 20** °C
	In archival box:	below 0 °C after ~3 hours

Treatment time [hours]	***C. longicaudatum* specimen**			**Survival analysis**			**Final results**
	stage	quantity	sex	R	R+	R++	
4 h	A	1	♀	1	1	1	A = 3/3
		2	♂	2	2	2	
	N	7		7	7	7	N = 7/7
	E	10				10	E = 10/10
6 h	A	1	♀	X			A = 0/3
		2	♂	1	1	X	
	N	7		X			N = 0/7
	E	10				4	E = 4/10
12 h	A	1	♀	X			**A = 0/3**
		2	♂	X			
	N	7		X			**N = 0/7**
	E	9				X	**E = 0/9**
24 h	A	1	♀	X			**A = 0/3**
		2	♂	X			
	N	7		X			**N = 0/7**
	E	8				X	**E = 0/8**

A	adults	R	recording after treatment
N	nymphs	R+	recording one day after treatment
E	eggs		
X	dead	R++	recording two months after treatment / end of the study

Final results: surviving individuals at the end of the study/number of individuals tested

Table 3 Summary of results for heating: an overview of tested parameters and stages of grey silverfish.

Treatment time [hours]	**1 h**						
	Heating phase: ~1 h			Cooling phase: ~0.75 h			
Temperature	***C. longicaudatum* specimen**			**Survival analysis**			**Final results**
	stage	quantity	sex	R	R+	R++	
40 °C	A	2	♀	2	2	2	A = 4/4
		2	♂	2	2	2	
	N	7		7	7	5	N = 5/7
	E	10				9	E = 9/10
42.5 °C	A	2	♀	2	2	1	A = 3/4
		2	♂	2	2	2	
	N	7		6	6	5	N = 5/7
	E	10				8	E = 8/10
45 °C	A	2	♀	X			A = 0/4
		2	♂	X			
	N	7		X			N = 0/7
	E	10				5	E = 5/10
47.5 °C	E	10				X	**E = 0/10**
50 °C	E	10				X	**E = 0/10**

A	adults	R	recording after treatment
N	nymphs	R+	recording one day after treatment
E	eggs		
X	dead	R++	recording two months after treatment / end of the study

Final results: surviving individuals at the end of the study/number of individuals tested

(Testo 174H) in the test environment. Test runs were evaluated according to the principle 'dead or alive'. The condition of the test insects was checked and recorded by visual inspection and by slight mechanical stimulation using a fine brush, based on the reaction in the form of perceptible movement. Surviving individuals and eggs were checked regularly. Potential hatching of nymphs from the eggs could only be fully evaluated after two months (Fig. 4).

Results and discussion

Freezing

During cold treatment over a period of 12 and 24 hours, all stages of *C. longicaudatum* were successfully killed (Table 2). In both cases, the targeted treatment temperature was reached in the core of the test specimen after about 12 hours. This could not be achieved for the treatment times of 4 and 6 hours. A temperature drop below 0 °C could be measured in all archival boxes after three hours. After the treatment time of 6 hours, the death of adults and nymphs was recorded, but hatching occurred after about 30 days in 4 of the 10 eggs tested. The additional time and material required to pack objects can be avoided if equipment with an adaptive freezing treatment is used in which controlled reconditioning of humidity occurs within the rewarming phase, as described by Yoshida (2020).

Heating

A lethal effect of heat on all stages could be detected at the temperature of 47.5 °C for one hour (Table 3). Although 45 °C was already lethal for adults and nymphs, hatching was still observed. It was striking that at 42.5 °C, a state of shock was initially observed in adults from which they recovered the following day. In the case of the nymphs, moulting was observed after treatment, indicating that no long-term damage was caused by a short-term

Table 4 Summary of results for anoxic treatment with oxygen scavengers: an overview of tested parameters and stages of grey silverfish.

Temperature	**22 °C**
Residual oxygen	**0.1%**
	Time interval to reach residual oxygen concentration: ~20 hours

Treatment time [hours]	***C. longicaudatum* specimen**			**Survival analysis**			**Final results**
	stage	quantity	sex	R	R+	R++	
12 h = 0.5 day	A	3	♀	X			A = 0/10
		3	♂	X			
	N	10		X			N = 0/10
	E	10				8	E = 8/10
24 h = 1 day	A	3	♀	X			A = 0/6
		3	♂	X			
	N	10		X			N = 0/10
	E	10				3	E = 3/10
48 h = 2 days	A	3	♀	X			**A = 0/6**
		3	♂	X			
	N	10		X			**N = 0/10**
	E	10				X	**E = 0/10**
168 h = 7 days	A	3	♀	X			**A = 0/6**
		3	♂	X			
	N	10		X			**N = 0/10**
	E	8				X	**E = 0/10**

A	adults	R	recording after treatment
N	nymphs	R+	recording one day after treatment
E	eggs		
X	dead	R++	recording two months after treatment / end of the study

Final results: surviving individuals at the end of the study/number of individuals tested

increase in temperature and associated stress. Initial investigations in the test specimens showed that the delaying temperature-buffering effect of paper increases the heating and cooling phases. This also leads to a prolongation of temperature intervals whose values are above the optimum of *C. longicaudatum*. Investigations into whether the lethal effect is related to the temperature level or to a longer time interval above a critical value are still pending.

Anoxic treatment

A lethal effect on all developmental stages could already be demonstrated for the time interval of 48 hours at a residual oxygen concentration of 0.1% and a treatment temperature of 22 °C. Deaths of adults and nymphs were recorded for each of the treatment intervals examined (Table 4). The increased tolerance of the egg stage is due to a substantially reduced respiratory exchange rate. It can be assumed that a higher survival rate is observed at lower temperatures, whereas increased mortality can be assumed in an even shorter time at higher temperatures because the insects' respiratory rate is increased at a higher temperature, resulting in rapid water loss (Valentin 1990). The addition of more absorber packs can shorten the time it takes to reach a low residual oxygen concentration but this would involve higher costs and material requirements. The results are transferable to the use of nitrogen chambers in which a larger number of objects can be treated.

Conclusions

The aim of the study was to adapt the treatment parameters for three different treatment methods regularly used in museums to the targeted control of *C. longicaudatum*. The results of the study present the time spans and temperatures needed to kill all developmental stages by freezing, heating and anoxic treatment. The study shows that the egg stage of the grey silverfish is more resistant to treatments than the adults and the nymphs. However, compared to the control of other museum pests such as wood boring beetles or clothes moths, shorter time intervals or temperature changes are required. In the case of freezing at –20 °C, the treatment time can be drastically reduced from 1–2 weeks to 12 hours. The anoxic treatment of objects in bags using oxygen scavengers at 22 °C can also be carried out in the shorter time of only 48 hours compared to previous assumptions of several weeks. When heating, a treatment temperature of only 47.5 °C instead of 55 °C is necessary over the same period of one hour. Thus, physical stress on the objects is reduced and a faster process is generated. All the described treatment methods can be used in a more time-efficient, curative and preventive way when objects and packaging materials are treated if contamination by other pests can be completely excluded in advance.

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Materials and suppliers

- Archival box, Stülpdeckelbox (Brauweiler) Art.-Nr. 2110016, DIN A4, Folio, Material MW 1.6: KLUG Conservation (www.klug-conservation.de)
- Climate test chamber, Sanyo Gallenkamp ATMOS Chamber MTH-4100
- Data logger, Testo 174H mini data logger: Testo SE & Co. KGaA (www.testo.com)
- Freezer, GGPv 6570 ProfiLine: Liebherr (www.liebherr.com)
- Oxygen absorbers ATCO FTM 1000, schwefelfrei: Long Life for Art (www.llfa.de)
- Oxygen meter, GOX 100: GMH Messtechnik GmbH Greisinger (www.greisinger.de)
- PE film bags Flachbeutel Escal/Alu, 42 × 68 cm: Long Life for Art (www.llfa.de)
- PET test container, 100 ml: ecomserv (www.ecomserv.de)
- PROsorb silica gel, 17 × 14 cm, 150 g, 50% rF: Long Life for Art (www.llfa.de)

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