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TECHNICAL NOTE

Can Paper and Adhesive alone Sustain Damaging Populations of Booklice?

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Booklice (*Liposcelis bostrychophila*) are pests in museums and libraries, but it is not known whether a population can build up on paper and adhesives alone in the absence of any other significant nutrient sources. Insects were reared on incubated cellulose paper, either alone or combined with different adhesives, in order to observe if any of these conditions could support population growth. A comparison was also made with insects reared on samples of paper combined with a diet mixture used to culture booklice. Changes in the physical condition of each paper were additionally noted. The paper with diet mixture exhibited significant population increase (6142 per cent) after 49 days. The paper alone and the combinations of paper and adhesives were not able to support population growth, although the proportions of insects surviving after ten months differed, with the paper alone and paper in combination with proprietary starch-based glue (SBG) maintaining the greatest proportions of surviving insects. The paper and adhesives had become discoloured and brittle in all of the combinations tested, although there was very little visible evidence of fungal growth outside of the control groups (paper alone). Chemical indicators of paper degradation were not detected in extracts of incubated paper (paper alone). Controlled atmospheres, good housekeeping and close monitoring of the most vulnerable collections are key to preventing infestations of *Liposcelis bostrychophila*. Further work is required to study the effects of a more diverse range of paper and adhesive combinations.

Keywords: Booklice; insect damage; degradation of paper; *Liposcelis*

Introduction

Liposcelis bostrychophila Badonnel (Psocoptera: Liposcelididae) is often found infesting books, and it is because of this association that it has been given the colloquial name, booklouse (New 2005). Colonies of *L. bostrychophila* contribute to the degradation of precious library collections by their feeding activity and by producing, among other things, frass and exuviae, while also dispersing fungal spores (Turner 1987). Booklice require high temperature and humidity to survive (Turner 1988) and books inadvertently stored under these conditions also often develop fungal growths (Zyska 1997) on which the insects feed (Rees 2004). It has been shown that the composition of fungal colonies growing on substrates other than books can either accelerate or retard the population growth of booklice (Mills et al. 1992). Those fungi that exhibit strong cellulolytic activity, such as *Chaetomium* and *Trichoderma* spp., can release additional nutrients from paper (Florian 2002). To protect books from microbial attack many libraries are thus now climate-controlled, while modern archival quality adhesives are formulated using pH neutral polyvinyl acetate (PVA), making bindings glued with these products more resilient to degradation by microorganisms (Semenov et al. 2003) and therefore less nutritive to insects. Before the development of PVA adhesives, books were often bound and sized using glues derived from animal bone and fats (Lambert 1905). Books bound using plant-based starch adhesives are also common (Allsopp et al. 2004). Additional nutriment is available to insects from these plant adhesives and animal glues.

This study primarily aimed to provide some information on the population dynamics of booklice reared on paper and different adhesives. It was also possible to look for physical changes in paper in all the conditions and for the presence of chemical markers of paper decay in the control group. Booklice were reared on paper alone or paper and adhesives which were all incubated in a high temperature (28 °C) and high humidity (75 per cent relative humidity (RH)) environment over the course of a year in order to promote the growth of fungal mycelia, and they were compared with a colony fed upon a nutritionally optimal culturing diet.

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Experiment set-up		Results summary	
Adhesive/diet mixture introduced to filter paper in Petri dish	Number of dishes prepared	Mean number of surviving insects per dish (± SEM) after ten months	Notes
SBG[a]	10	7 ± 1	
PVA1[b]	10	1 ± 1	
PVA2[c]	10	0	
Diet mixture[d]	10	See note	The dishes became overcrowded with insects one month after their introduction and so this experiment set-up was halted.
Control (paper only)	10	13 ± 2	

[a]**SBG**: 'Pritt Stick' solvent free adhesive. Henkel Consumer adhesives, Hemel Hempstead, UK. Starch adhesive with sugar binders.
[b]**PVA1**: Archival quality, neutral pH PVA adhesive. Lineco Inc., Holyoke, MA, USA. Item 901–1008 1.
[c]**PVA2**: Conservation grade PVA M218 adhesive. J. Hewit and Sons, Livingston, UK.
[d]**Diet mixture**: 1:1:1:1 mixture – by weight – of brewer's yeast, dried skimmed milk powder, wheatgerm and wholemeal flour.

Table 1: Adhesives and diet mixture presented to booklice with results summary.

1. Materials and Methods

Preparation of dishes

Two sheets of unsized cellulose filter paper (9 cm diameter) Fisherbrand QL100 (7.4 ± 0.01 mg/cm^2, mean ± sem, N = 100) from a newly opened packet were placed into a Petri dish of the same diameter. Ten dishes were prepared in this way for each experimental group and for the control group (paper only) (**Table 1**). For the experimental groups, samples (1 g ± 1%) of either different adhesives or of a diet mixture were sandwiched between the two sheets of filter paper. All dishes had been prepared with a 0.5 cm band of Fluon liquid polytetrafluoroethylene (PTFE) around the inside rim to prevent the escape of insects. Dishes were incubated in a growth cabinet (Binder, 28 ± 1 °C and 75 ± 1.5% RH).

Introduction of booklice

After two months, a group of adult insects (N = 6–20 individuals) was added to each dish. After a further two months, and then at monthly intervals, the numbers of surviving insects were recorded and additional groups of adult *L. bostrychophila* (N = 10, per dish) were added. After one year of incubation (i.e. ten months since adding the insects) the experiment was halted and the numbers of surviving insects and the condition of the adhesive and/or paper were recorded. In the results section, the total incubation time is presented first, with the time elapsed since insects were added in parentheses.

Data analysis

The numbers of insects alive at different stages of the experiment and the overall proportion surviving after a year from the total numbers introduced were compared among adhesive treatments using the Kruskal-Wallis test (KW) and between each adhesive treatment and the control using the Mann-Whitney U test (MWU). Analyses were performed using Genstat v. 14.2.0.6297.

Paper extraction and analysis by gas chromatography-mass spectrometry (GC-MS)

After the removal of any surviving insects at the end of the experiment (one year's incubation), the paper used for the control group (paper only, without adhesive or diet mixture) was brushed gently with a soft bristle paintbrush to remove any visible insect debris and exuviae. A sample of the paper (7.4 g) was chopped into 1 cm squares and 30 ml of hexane was added to it. After 48 hours an aliquot (5 ml) was removed for analysis by GC-MS to determine whether volatile organic compounds (VOCs) were present; these are chemical indicators of paper degradation. Samples were analysed using a 6890N Gas Chromatograph (GC) (Agilent), linked to a 5973 Mass Selective Detector (MSD) (Agilent). The column was an Agilent DB5 non-polar column (30 m × 0.25 mm internal diameter × 0.25 μm film thickness). The carrier gas was helium (at 1 ml/min) and the oven temperature was programmed to go from 40 °C to 240 °C at 4 °C/min then held at 240 °C for ten minutes. The injection volume was 2 μl. Compound identification was confirmed by comparison to published data (Adams 2009; Ausloos et al. 1992).

Handling of the paper

To simulate the contamination resulting from the regular handling of paper, the paper in each dish was touched with bare hands every week, within a 1 cm band around the circumference, ensuring that no insects were injured in the process. Hands were washed 30 minutes before each handling using non-perfumed household soap and were also washed 30 minutes before the assessments of each set of experiments.

2. Results and Discussion

Population studies

After two months the dishes containing diet mixture became infected with fungus (*Aspergillus* sp.), visible as greyish green colonies on the surface of the paper

Figure 1: A representative close-up of the fungal colony growing on the diet mixture and paper after incubation for 61 days.

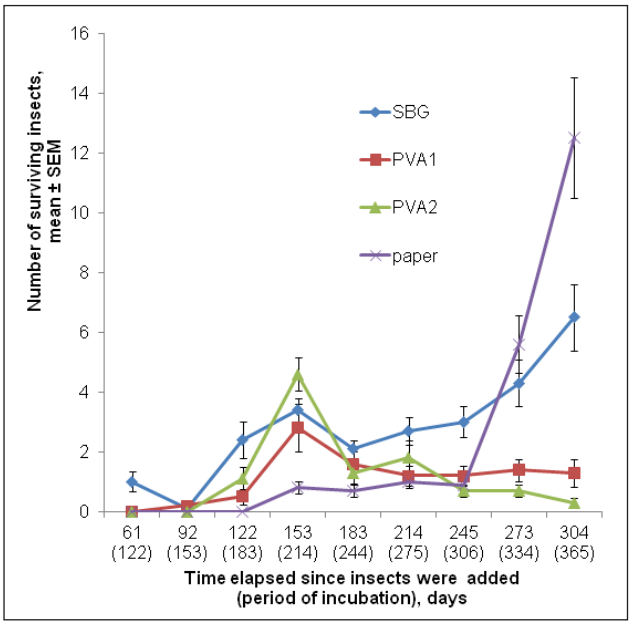

Figure 2: Mean number of surviving insects per dish (± SEM) with the time of exposure to either incubated paper or incubated paper and adhesives.

(**Figure 1**). *Eurotium amstelodami* L. Mangin (*Aspergillus* anamorph) has previously been isolated and identified from a similar culture medium (Green 2008), so it is possible that this was the same or a similar fungus. Following the addition of insects, the fungal growths on the paper and diet mixture combinations disappeared, as the insects grazed upon these colonies. After 110 (49) days the Petri dishes containing diet mixture had become overcrowded with insects, so these dishes were frozen and the insects counted: the population had increased from 96 to 5887 individuals.

Within the remaining dishes there was a build-up of dead insects after 183 (122) days. Cannibalism of living insects upon these cadavers was observed in representative samples of the control group and all other paper and adhesive combinations. The dead insects had largely disappeared by 214 (153) days and could have caused the sudden increase in survival observed at that time, especially for the insects presented with the PVA2 subtype of PVA adhesive (MWU, $U = 8.5$, $P < 0.001$). The numbers of insects surviving upon the paper and starch-based glue (SBG) combination and the paper alone increased until there was a clear distinction between the insects reared in these two conditions and those reared on PVA and paper (**Table 1**; **Figure 2**; MWU, $U = 0$ to 15, $P < 0.001$). Despite the regular additions of insects and the increase in survival, fewer than 8 per cent of all the insects exposed to different paper and adhesive combinations were living at the end of the experiment. There was a difference in the percentage survival among adhesive treatments (KW, $H = 40.5$, $P < 0.001$), with a lower proportion of insects on either the Lineco or Hewit PVA adhesives and paper (MWU, $U = 13$ and 2, respectively) than on the paper alone. SBG Pritt adhesive did not affect the proportion of insects surviving (MWU, $U = 32$, $P > 0.05$) when compared with the paper alone.

Changes in the physical condition of the paper and adhesive

Over the 12 months, gradual discolouration of each paper and adhesive combination and of the paper with diet mixture occurred. Discolouration originated in the centre of the paper, around the adhesive (paper and adhesive; **Figure 3**) or spread out from the food in the dish (paper and diet mixture). The paper and adhesive developed colours ranging from yellow to green (**Figure 4**). All of the samples of paper became less pliable, presumably as the bonds in the cellulose had started to hydrolyse. Visible fungal contamination of the paper in the control group was limited to small black spots of approximately 1–2 mm in diameter, which became visible after 306 (245) days; this may explain the subsequent increase in the numbers of insects recorded. Regular handling of the paper, albeit with recently washed hands, did not cause visible changes in the paper in the region that had been touched.

GC-MS chemical analyses

Chemical indicators of paper degradation (VOCs) were not detected by GC-MS analysis in the extract of incubated paper. There are three possible explanations for this. First, the compounds may have evaporated from the paper and then vented from the growth cabinet so that there were not any residues to extract. Well-ventilated areas are less likely to accumulate aldehydes, when compared with areas subjected to restricted airflow (Fenech et al. 2010). Second, the paper may not have been incubated for a sufficient amount of time for the cellulose to produce indicators of breakdown, such as furfural (e.g. Strlič et al. 2009), in detectable quantities even though the physical condition of the paper had changed i.e. exhibiting fungal growths and changes in pliability. Finally, cellulose papers may not produce significant levels of VOCs under these experimental conditions.

3. Conclusions

Incubation of cellulose paper and modern adhesives for 12 months does not provide sufficient nutriment to sustain populations of *L. bostrychophila*. By contrast, a population of insects provided with sufficient food that promoted

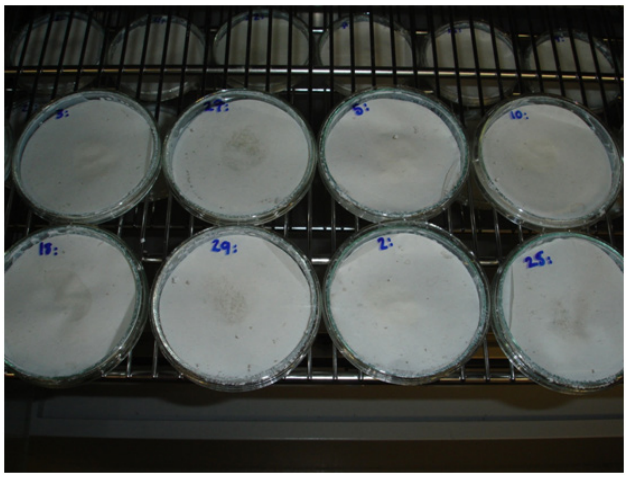

Figure 3: Condition of different paper and adhesive combinations after incubation for 244 days[Ψ].
[Ψ] 2, 3 & 10 = Pritt stick adhesive; 18 = Lineco PVA adhesive; 25, 27 & 29 = Hewit PVA adhesive.

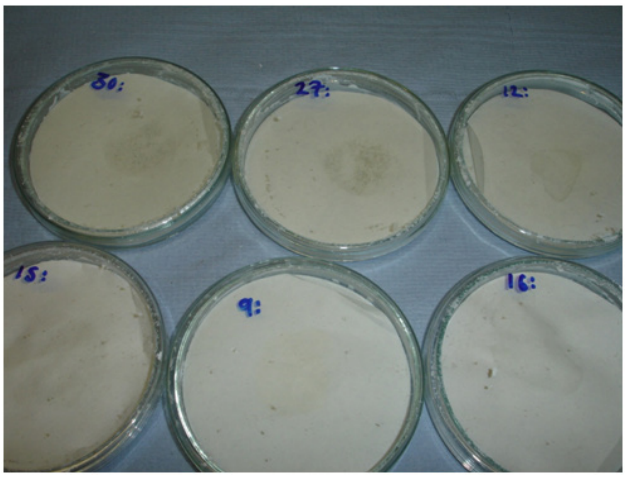

Figure 4: Condition of adhesive paper and adhesive combinations (a) and paper only (b) after incubation for twelve months[Ψ].
[Ψ] 9 = Pritt stick adhesive; 12, 15 & 16 = Lineco PVA adhesive; 27 & 30 = Hewit PVA adhesive.

growth of microorganisms increased rapidly. There was a general trend towards greater survival of insects over time and this was most noticeable in the control groups and in the SBG and paper combinations, although fewer than 10 per cent of all insects survived in these conditions.

4. Incorporation of Findings into an Integrated Pest Management Strategy

Environmental controls

Booklice are attracted to fungi (Diaz-Montano et al. 2014; Green and Turner 2005) and feed upon fungal structures (Mills et al. 1992). Fungi convert the nutrients in paper into a form that is available to insects (Manente et al. 2012). Environments with controlled humidity, recommended for storage of archival materials (BSI 2012), are already impacting upon the problem of booklice infestations. These conditions reduce the 'bioreceptivity' of papers, meaning that they are less likely to support fungal growth (Guillitte 1995).

Good housekeeping

(i) *Identification of vulnerable collections*

Books or ephemera that are more nutritive i.e. bound using animal glues or starch-based adhesives should be identified and regularly inspected as populations can build up more rapidly on these collections.

(ii) *Reducing contamination*

Handling of the paper with recently washed hands did not add sustaining levels of nutriment. Dusts and other organic debris, however, could provide potential nucleating sites for microorganisms and food for booklice and other insects. Therefore, further preventive measures might include placing the books identified in (i) into cabinets.

Physical barriers and quarantine

When booklice are subjected to nutriment restriction by environmental controls and good housekeeping the population decreases; thus, physical barriers and quarantine to prevent reinfestation become more important. Freezing material is often sufficient, but may not be appropriate in all circumstances. Traps for monitoring should be placed near to the most vulnerable collections.

Future considerations

Further work is required to investigate the biodeterioration of a greater range of papers and adhesives and how this affects the population dynamics of *L. bostrychophila.* It would also be informative to investigate the pH and mechanical properties of the paper under consideration, in combination with chemical data, in order to identify characteristics that make books particularly vulnerable to insect infestation. More extensive chemical analyses could compare the VOCs produced by different combinations of paper and adhesive. For example, historic books consisting of paper made from cotton and linen produce less furfural but a greater quantity of other straight chain aldehydes than wood-pulp books (Clark et al. 2011). Overall, this information could help further to refine the conservation, restoration and insect control policies in libraries and museums. It may be that climate-controlled libraries together with modern papers and adhesives neither provide sustaining levels of nutriment nor a suitable environment for booklice. In that case resources might be better focussed on safeguarding historic books and preventing contamination with new insects.

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