Insect and mite control by manipulating temperature and moisture during chemical-free storage

S. J. Beckett*

CSIRO Entomology, GPO Box 1700, Canberra ACT 2601, Australia

Abstract — Insect and mite control by sufficient drying and cooling of commodities would satisfy growing market desire for pesticide-free storage and help control increased insect resistance, particularly to phosphine. The response of insects and mites to such conditions is reviewed. The responses to temperatures within the range 9 to 55°C are examined which include those that induce individual mortality, those at the threshold for population growth, and those where rates of growth are slow. Drying is examined mainly in terms of an enhancement to the detrimental effects of temperature. A 10°C range in minimum threshold temperature for population growth was found among the insect and mite species examined. A substantial level of protection was seen at temperatures just above these thresholds. For example, at 22°C, 35% r.h. Oryzaephilus surinamensis has the greatest two monthly multiplication rate at 5.6 while at 22°C, 70% r.h., Sitophilus oryzae has the greatest rate at 65. At conditions roughly 6°C below the threshold for population growth, >99% mortality of major coleopteran species is possible after 9 months at 45% r.h. Insect mortality at moderately elevated grain temperatures (35 to 55°C) is examined as an opportunity to disinfest grain during drying. Several Coleoptera and Psocoptera species were found to suffer at least 99% mortality at 50°C after 2.5 h. The extent of variation among species is discussed in terms of targeting particular susceptibilities to moderately high or low temperature at low humidities as an alternative to chemical treatments.

Key words: insects, mites, drying, cooling, protection, disinfestation, phosphine

*Corresponding author and presenter. Tel.: +61 2 6246 4196; fax: + 61 2 6246 4202. E-mail address: stephen.beckett@csiro.au

Introduction

One of the major consequential benefits of improvements in drying and cooling processes for stored products is the control of arthropod pests, particularly in an environment where chemical treatments are coming under greater and greater pressure. There are, indeed, growing market and regulatory constraints on the use of chemicals for pest control and serious insect resistance problems, especially with the major fumigant, phosphine (Nayak et al., In press).

It is timely, therefore, to consider a circumstance where chemically treated commodities may be generally shunned and phosphine fumigations are severely
compromised by repeated occurrences of very high levels of pest resistance. In such circumstances, how effective would drying and cooling be at delivering non-perishable goods sufficiently free of insects and mites that would either satisfy market demand or simply provide a break in routine chemical treatments as a strategy to reduce high levels of resistance?

Because drying and cooling have not generally been considered processes that give high levels of control easily and reliably, there is often a tendency to take a broad view when considering how pests behave under these conditions. However, the range of responses of stored product insect and mite species to most strategies of pest management can be substantial and what may have little impact on one species may be catastrophic for another.

There are many excellent reviews that detail insect and mite responses to the full range of physical processes possible during storage and handling (e.g. Fields and Muir, 1996; Banks and Fields, 1995; Bell and Armitage, 1992), often as part of integrated pest management more broadly. However, in this review, the focus will be limited to two themes. First, the conditions achieved by drying and cooling that protect commodities by slowing population growth of a given species to negligible levels, or stop it all together, or cause it to decline. Second, those conditions achieved by the same processes that disinfest a given species to levels at or above 99%.

Not only will existing data be considered on insect and mite response to the combined effects of drying and cooling, but also data on response to the effects of high suboptimum grain temperatures that can be achieved during grain drying. Thus, opportunities for minimising infestations at in-loading and for successful chemical-free protection against and disinfestation of pest species during storage can be reconsidered as part of strategies to fulfil potentially stringent market requirements and assist in limiting the increase in pesticide resistance.

**The response of insect and mite populations to environmental conditions**

For convenience, insect and mite population responses to environmental conditions tend to be considered in general terms, often in combination with the other main threats to non-perishable products in storage. One of the best known depictions of these simple but effective rules of thumb is from Hall (1970) (figure1). In the diagram, generalized thresholds to germination loss, insect infestation, and fungal growth are shown relative to temperature and moisture content (m.c.). The effect of mites has also been added to other versions of the diagram.

Of course, in reality, insect population growth thresholds and the change in population response as temperature and moisture increase or decrease vary considerably for each individual species. Using simplified contour diagrams based on demographic data collected over a wide range of temperature and grain moisture levels (Beckett and Evans, 1994; White, 1987; Cunnington, 1984; Longstaff and Evans, 1983; Smith, 1965), figure 2 shows the degree to which this occurs for five major stored product insects, *Cryptolestes ferrugineus* (Stephens), *Oryzaephilus*
surinamensis (L.), Rhyzopertha dominica (F.), Sitophilus oryzae (L.) and Tribolium castaneum (Herbst), and a major stored product mite, Acarus siro (L.), in terms of the weekly finite rate of population increase ($\lambda$).

Each species shows a different range of conditions that in part favour its population growth over potential competitors. In general terms, cooler drier conditions tend to favour S. oryzae, warmer moister conditions favour C. ferrugineus, while warmer drier conditions favour T. castaneum. Populations of O. surinamensis can do better at drier conditions while populations of R. dominica probably grow over the greatest range of environmental conditions. In contrast to the insect species, populations of A. siro can grow at much lower temperatures and at very high rates in some circumstances. However, it requires high levels of environment moisture and struggles at higher temperatures where most insect pests thrive.

We shall see that there is also considerable variability among insect and mite species in response to conditions below the minimum and above the maximum threshold temperatures for population growth, where fertility is increasingly reduced and ultimately halted, and adult and immature mortality is induced, albeit, relatively slowly. Again at such conditions, the degree of aridity plays an important role.

**Figure 1**

**Figure 2**

**Protection and disinfestation from grain drying**

Grain can be harvested dry, but due to climate, this is often not the case. Grain can also be harvested early at higher moisture content to reduce the risks of weather damage and harvest losses. In these situations it must then be dried to maintain quality during storage (Banks, 1999). Moreover, drying has a considerable impact on insect and mite control, both in terms of protection and disinfestation.

**Protection**

Substantial levels of protection against insects and mites can be achieved under arid conditions. In general, a dry environment ensures that these pests do not get established and if the moisture content is just sufficient to sustain some survival and reproduction, numbers can be kept very low. In these circumstances, adults do not live as long, the number of eggs laid per female is reduced and immature stages take longer to develop and struggle to survive. For example, Beckett and Evans (1994) observed that immature mortality of O. surinamensis was 46% at 20°C, 70% r.h., but 99% at 20°C, 30% r.h. White (1987) observed that larval mortality of T. castaneum was approximately 8% at 25°C, 55% r.h., but 100% at 25°C, 35% r.h. and Currie (1967) observed that immature mortality of Cryptolestes pusillus (Schönherr) was 16% at 25°C, 70% r.h., but 97% at 25°C, 50% r.h.
Thus, the impact on population growth parameters can be considerable. If we consider population growth over two months, for example, at 30°C the multiplication rate of C. ferrugineus is 668 at 70% r.h. but about 35 at 35% r.h. (calculated from Smith, 1965). The rates for O.surinamensis, and R. dominica are 1364 and 585 at 70% r.h. but 179 and 81 at 35% r.h. respectively (Table 4), while their development times increase from 22.4 and 34.7 days to 27 and 51 days respectively (calculated from Beckett et al., 1994).

With regard to complete control, mites are particularly susceptible at any temperature if the relative humidity is kept below 65% r.h. (Navarro et al., 2002). Psocids too, as a group, can be controlled at all temperatures if humidity is kept below 60% r.h. (Rees, 2004), and populations of the major stored product pests, S. oryzae and T. castaneum are unable to grow below 35% r.h. (Beckett et al., 1994; White, 1987). Thus, when populations are already present, they can often be forced to stop growing or decline if commodities are dried to a level where physiological stress from aridity causes mortality to equal or outpace recruitment from reproduction.

Disinfestation
In some circumstances, the temperature of grain at harvest can be moderately elevated which will challenge insect survival. Inadvertent high temperatures at the periphery of commodities in storage can also have an adverse effect on pests that are unable to escape, such as eggs and pupae of stored product moths (Abogast, 1981). Moreover, when commodities are dried using thermal energy, the resultant grain temperatures may afford a degree of disinfestation. Depending on the species, temperature and exposure time, this could be considerable. Advantage can also be made of grain’s low thermal conductivity (Hill, 1999) and hence excellent ability to hold temperature.

Table 1 gives the LT99 in hours for a range of major species at several moderately elevated temperatures. It can be seen that disinfestation can even be achieved at temperatures below 45°C in about one to four days, particularly for species such as S. oryzae. By 46°C most species can be disinfested in under a day, and at 48°C most species can be disinfested in about 9 h or less. However, data for R. dominica (Table 1) indicate that initial grain moisture will effect treatment time. There are limited data available for major stored product moths, but what are available suggest that these species are quite susceptible to elevated temperatures. For example, at 60 to 70% r.h., 100% mortality of diapausing larvae of Ephesia elutella (Hübner) is achieved within 96 h at 40°C, 24 h at 43°C and 16 h at 45°C (Bell, 1883). At 60% r.h, total mortality of Ephesia cautella (Walker) and Plodia interpunctella (Hübner) pupae can be achieved within 2 h at 50°C and 45°C respectively (Abogast, 1981).

R. dominica is the biggest challenge as it is with high temperature rapid disinfestation (Dermott and Evans 1987). However, Vardell and Tilton (1981) showed that no viable progeny of this species were produced by adults at any stage over a 6 wk period at 40°C, 60% r.h. Furthermore, Kirkpatrick (1978) showed that no immature development stages of insects kept at 41°C, 70% r.h. could survive. Kirkpatrick and Tilton (1973) determined that there was a >99.9% reduction in progeny after 4 days of oviposition at 43.3°C, 50% r.h., where, by comparison, the same level of reduction was achieved for S. oryzae at 39°C, 60% r.h. Similar
Response data for other stored product insect species are available. For example, immature development of Cryptolestes turcicus (Grouvelle) and Cryptolestes pusilloides (Steel & Howe) cannot occur at 35°C at ≤70% r.h. (Lefkovitch, 1962b; 1964). Further examples are summarized by Fields (1992). In the same way that delaying aeration can take advantage of disinfesting effects of high summer temperatures at harvest (Harein and Davis, 1992), similar strategies during drying may help reduce or remove insect contamination.

Since the tolerance of stored product insects to moderately high temperatures varies considerably from species to species, insect identification is essential to determine how effective a drying operation has been at pest control or whether it could be modified somewhat to also achieve a sufficient level of disinfestation. However, the potential for deterioration in grain quality must be kept in mind, so the length of time that a given temperature is maintained is critical. The effect on quality depends on many things such as grain type, initial moisture content, drying time, rate of drying and the ultimate use of the product. For example, the quality of seed grain and malting barley is generally considered safe up to 40°C, grain legumes for human consumption up to 43°C, and wheat for seed up to 45°C. For gritting maize and oil seeds a maximum of 46°C is recommended, while up to 54°C is considered safe for cereals for milling. On the other hand, rapid disinfestation of feed grains for animals is possible in seconds at higher temperatures up to 80°C (Hill, 1999).

Table 1

Protection and disinfestation from grain cooling

There are several important benefits from reducing grain temperature with aeration either by using ambient or refrigerated air. These include the maintenance of quality and the control of moisture migration. But lower temperatures will also have a considerable impact on the population parameters of insect and mites and hence can be a valuable method of control.

Protection

Complete protection can be achieved by holding grain at or below the minimum temperature for population growth. These temperatures vary considerably and appear to be only slightly affected by grain moisture at and above minimum conditions that are not severely detrimental to physiological function (e.g. about 35% r.h. for O.surinamensis, and R. dominica and 45% r.h. S. oryzae and T. castaneum (Beckett et al, 1994)). Table 2 lists the minimum theoretical threshold temperatures and relative humidities at which the values were determined for a range of major stored product insect and mite species. It can be seen that the temperatures cover a 10°C range with the mite species having the lowest threshold. However, as previously mentioned, mites do require relatively moist conditions to survive and develop. S. oryzae and C. pusillus, which have thresholds lower than most stored product beetles, also require moderately moist conditions (>35% and >45% r.h. respectively) for population growth (Beckett et al, 1994; Currie, 1967).
Another measure of the limit to a pest’s ability to increase in numbers is the theoretical threshold of immature development which is determined by a linear regression of 1/development time at a range of temperatures. This threshold is lower than that of population growth and again, for some species tends not to be greatly affected by environmental moisture above a certain level. Using this measure, the threshold for *Stegobium paniceum* (L.) females is 14°C at 70% r.h. (calculated from Lefkovitch, 1967). For *Trogoderma versicolor* (Creutzer) females, it is 17°C, but for *Trogoderma granarium* (Everts) females, it is 13.5°C (calculated from Hadaway, 1956). In the latter case, the insect is found in a state of quiescence at 20°C, where it can remain for over a year (Hadaway, 1956). However, Burges (2008) has shown that populations decrease at 20°C/70% r.h.

Environment moisture appears to have some impact on the development threshold of *C. pusilloides*, with it being 11°C at 90% r.h. and 13°C at 70% r.h., (calculated from Lefkovitch (1964). Furthermore, Lefkovitch (1964) found that at 50% r.h. the species could only complete development at 27.5-30°C. The thresholds for *Cryptolestes capensis* (Waltl) and *C. turcicus* are 11 and 15°C respectively at 90% r.h. (calculated from Lefkovitch (1962a). While *C. turcicus* cannot develop at 40% r.h. and only at 27.5°C at 50% r.h. (Lefkovitch, 1962b), *C. capensis* can survive and develop post-oviposition at 30°C, 10% r.h. (Lefkovitch, 1962a) and so could potentially be difficult to control by drying and cooling.

While stored product moth species tend to be fairly susceptible to moderately elevated temperatures, some species are by contrast, able to commence breeding at relatively low temperatures. For example, *E. elutella* will start breeding at 10°C above 25% r.h. and *Ephestia kuehniella* Zeller will start breeding at 12°C at any humidity. However, most other major moth pests start breeding between 15 and 17°C at 20 to 30% r.h. (Rees, 2004).

At slightly higher temperatures, close to the minimum threshold, where populations grow very slowly, a significant level of pest control is still possible. At these temperatures, the combined effect of aridity can increase the level of control even more. If we again consider population growth over a two month period (Table 3), it can be seen that the beetle species struggle at 20°C at all humidities. At 22°C populations of *O. surinamensis* and *R. dominica* will multiply by 5.6 and 4.8 over two months respectively at 35% r.h., but will roughly double those rates at 70% r.h. On the other hand, populations of *S. oryzae* and *T. castaneum* will decline in numbers at 35% r.h., but will multiply by 64.9 and 8.6 respectively at 70% r.h. However, these values are small compared to those at 30°C, where multiplication rates of the beetle species range from 120 to 512 at 50% r.h and 536 to 1364 at 70% r.h. By contrast, populations of the mite, *A. siro*, will grow at very rapid rates at cooler temperatures as long as humidity is above 70%. However, by 30°C humidity must be even greater for growth to occur.

### Table 2

<table>
<thead>
<tr>
<th>Species</th>
<th>Temperature (°C)</th>
<th>Humidity (% r.h.)</th>
<th>Development Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Stegobium paniceum</em></td>
<td>14</td>
<td>70</td>
<td>Low</td>
</tr>
<tr>
<td><em>Trogoderma versicolor</em></td>
<td>17</td>
<td>Any</td>
<td>Normal</td>
</tr>
<tr>
<td><em>Trogoderma granarium</em></td>
<td>13.5</td>
<td>Any</td>
<td>Low</td>
</tr>
<tr>
<td><em>C. pusilloides</em></td>
<td>11</td>
<td>90</td>
<td>Low</td>
</tr>
<tr>
<td><em>C. turcicus</em></td>
<td>11</td>
<td>90</td>
<td>Low</td>
</tr>
<tr>
<td><em>Cryptolestes capensis</em></td>
<td>11</td>
<td>Any</td>
<td>Low</td>
</tr>
<tr>
<td><em>Ephestia kuehniella</em></td>
<td>12</td>
<td>Any</td>
<td>High</td>
</tr>
</tbody>
</table>

### Table 3

<table>
<thead>
<tr>
<th>Species</th>
<th>Temperature (°C)</th>
<th>Humidity (% r.h.)</th>
<th>Development Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>O. surinamensis</em></td>
<td>20</td>
<td>25</td>
<td>Low</td>
</tr>
<tr>
<td><em>R. dominica</em></td>
<td>20</td>
<td>35</td>
<td>Low</td>
</tr>
<tr>
<td><em>S. oryzae</em></td>
<td>30</td>
<td>50</td>
<td>Low</td>
</tr>
<tr>
<td><em>T. castaneum</em></td>
<td>30</td>
<td>70</td>
<td>High</td>
</tr>
<tr>
<td><em>A. siro</em></td>
<td>30</td>
<td>70</td>
<td>Very High</td>
</tr>
</tbody>
</table>
Disinfestation

While disinfestation of stored product pests with subzero temperatures is well documented (Collins and Conyers, In Press; Donahaye et al., 1995, Banks and Fields, 1995; Fields, 1992) and can be a useful tool in climates where winter temperatures commonly drop to these conditions, more moderate temperatures, often obtainable with refrigerated aeration, can also cause significant mortality during long term storage. Hunter and Taylor (1980) recommended that if wheat is harvested at 30 to 35°C at 12% moisture content (m.c.) the average grain temperature should be reduced to 9°C to make certain that the total grain bulk is below 13 to 15°C and hence below the threshold for population growth of most species. However, Evans (1983 and 1987) demonstrated that these conditions can also disinfest the grain bulk given sufficient time (Table 4).

Evans (1983 and 1987) found that after a year, over 99% of all stages of the major stored product beetles, C. ferrugineus, O. surinamensis, R. dominica, Sitophilus granarius (L.), S. oryzae and T. castaneum were killed at 13.5°C, 45% r.h. and 100% were killed at 9°C, 45% r.h. With the exception of R. dominica, over 95% of immature stages were killed after 6 months at 13.5°C, 45% r.h. and over 97% at 9°C, 45% r.h. Levels of immature mortality over 99% were even recorded at both temperatures after 3 months for C. ferrugineus, O. surinamensis and T. castaneum. Results after 6 months at 13.5°C, 45% r.h suggested that adults were more tolerant to moderately low temperatures than immatures. Nevertheless, adult mortality levels around 99% or more were recorded for all species after 3 and 6 months at 9°C, 45% r.h. Adult mortality was also recorded at 70% r.h. and again, moist conditions were shown to increase survival. The Sitophilus species, in particular, seem to benefit from higher relative humidity.

Table 4

Discussion and Conclusions

The data show that there is a considerable range in insect and mite response to temperature and relative humidity. For example, there is a 6°C range (14 to 20°C) in the threshold temperatures for population growth of seven major beetle species alone (Table 2), but in effect, five of them can be controlled at 18°C. Furthermore, certain species are particularly sensitive to reduced levels of environmental moisture with mites generally limited to conditions above 65% r.h., psocids above 60% r.h., and populations of S. oryzae and T. castaneum unable to grow below 35% r.h. In contrast to this, certain stored product moths such as E. elutella and E. kuehniella will reproduce to some extent at lower temperatures and relative humidities. Thus, the extent to which a commodity can be dried and cooled can certainly influence the amount and diversity of potential infestations.

At temperatures just above the threshold for population growth of major stored product insects (often up to 22 or 23°C), numbers will increase very slowly,
particularly if relative humidity is kept as low as possible (Table 3). However, as temperature increases, population growth becomes more rapid and the probability of infestation more likely. For example, at 22°C the multiplication rates of *O. surinamensis* and *R. dominica* over two months roughly double between 35 and 70% r.h., but are respectively 6 and 8 times greater again at 25°C, 70% r.h. The number of *T. castaneum* will double over two months at 22°C, 50% r.h., but will multiply 18 times at conditions just 3°C hotter. Thus, the establishment of populations is severely limited at suboptimum conditions and this could allow commodities to be stored safely for some time, particularly if the storage structure is well sealed and the commodity is free of insects to start with or insect presence is minimal.

A potential way to initially achieve minimal or no pest contamination in a chemical free environment is to take advantage of the disinfesting effects of grain drying with hot air followed by rapid cooling. However, depending on the temperature, sufficient treatment time is required. Certain species appear particularly susceptible to these conditions, such as certain *Sitophilus* species, *Tribolium confusum* Jacquelin du Val and the Psocoptera, *Liposcelis bostrichophila* Badonnel and *Liposcelis paeta* Pearman, where 99% or more of the most tolerant life stage of each species can be killed in 2.5h at 50°C. While some stored product moths are resilient and can breed at fairly cool dry conditions, some moths, by contrast, appear to be relatively sensitive to heat, such as *E. elutella*, *E. cautella* and *P. interpunctella*. Currently, data suggest that commercial dryers are effective at removing susceptible species at moderate temperatures where grain damage is less likely, but more reliable temperature control, particularly at higher temperatures is required to increase their capacity as disinfesters (Bruce et al., 2004; Qaisrani and Beckett, 2003a&b).

On the other hand, if commodities in long term storage at fairly dry conditions (≤45% r.h.) can be cooled to temperatures roughly 6°C below the threshold for population growth of particular major insect pests, results suggests that >99% mortality of all development stages of those pests should be achieved by 9 months. At roughly 9°C below the threshold, ≥97% mortality should be achieved by 6 months. However, the possibility of acclimation, which affords the pest some degree of tolerance to lower temperatures, must be taken into consideration if the rate of cooling is slow (Fields and White 1997; Evans, 1983). Temperature variability, predominantly at the periphery of the commodity can also be a challenge.

The degree to which commodities can successfully be delivered pest-free while maintaining chemical free status might be enhanced further by mechanical processes such as grain cleaning (Weller et al., 1998; Armitage et al., 1996) and impact disinfection (Beckett, in press; Banks and Fields, 1995) at either in- or out-loading. Even just the removal of adults by such methods can be valuable provided immature stages can be effectively controlled by drying and cooling. If further improvements in these techniques can be made, there may be even greater opportunities to hold specific products in chemical-free storage and in conjunction with appropriate mechanical treatment, reliably ensure that they are sufficiently pest-free at point of sale.

The objective of this review has been to reexamine the effectiveness of temperature and moisture manipulation during storage to support current efforts to limit the use of chemical treatments, both to satisfy increasing market demand for products free from any chemical treatment, and because any breaks in such treatments is a way to
control the increase in pesticide resistance (Subramanyam and Hagstrum, 1996; Denholm and Rowland, 1992). There are clearly circumstances, either by virtue of climate or weather (Longstaff, 1995; Armitage and Cook, 2003), where the appropriate conditions for insect or mite control are difficult or impossible to achieve. However, the data show that within a range of moderately low and high temperatures at fairly dry conditions a general level of protection against or disinestation of stored product insects and mites is achievable. Furthermore, it can be seen that under certain circumstances certain species appear to be especially vulnerable. In these cases, a potential opportunity arises where a specific pest can be targeted without a significant financial impost.

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