A SIMPLE MODEL FOR PREDICTING THE EFFECT OF HYGROTHERMAL CONDITIONS ON POPULATIONS OF HOUSE DUST MITE *Dermatophagoides pteronyssinus* (Acari: Pyroglyphidae)

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Abstract

A simple Mite Population Index (MPI) model is presented which predicts the effect on house dust mite populations of any combination of temperature and relative humidity (RH). For each combination, the output is an index, or multiplication factor, such that 1.1 indicates 10% population growth and 0.9 indicates 10% population decline. To provide data for the model, laboratory experiments have been carried out using lab cultures of *Dermatophagoides pteronyssinus*. The population change was observed for mites held in steady-state conditions at different combinations of temperature and RH over 21 days. From the results, a best-fit equation has been derived which forms the basis of the MPI model. The results also enable a new term to be defined: the *Population Equilibrium Humidity*, PEH, the RH for a given temperature at which house dust mite populations neither grow nor decline. It is similar to Critical Equilibrium Humidity, the RH below which house dust mites are unable to maintain water balance, but relates to a population of mites (rather than a physiological phenomenon) and is more able to take account of the observed effects of extremes of temperature and RH. Compared with previous population models, the MPI model is potentially more accurate and comprehensive. It can be combined with other simple models (described in previous papers), such as BED, which simulates the average hygrothermal conditions in a bed, given room conditions, and Condensation Targeter II, which simulates room conditions given a range of easily obtainable inputs for climate, house type and occupant characteristics. In this way it is now possible, for any individual dwelling, to assess the most effective means of controlling mite populations by environmental means, such as by improving standards of ventilation and insulation, or by modifying the occupant behaviour that affects the hygrothermal environment within a dwelling. Although the MPI model requires further development and validation, it has already proved useful for understanding more clearly how the different hygrothermal conditions found in beds and bedrooms can affect mite populations. It has also demonstrated that there is considerable scope for controlling mites by environmental means in cold winter climates such as the UK.

Keywords

House dust mites, environmental control, population model, relative humidity, temperature, ventilation

Introduction

It is well known that allergens contained in the faecal pellets of the house dust mite (HDM) play a major role in allergic disease, especially asthma (Voorhorst et al., 1969). HDMs require a particular combination of temperature and relative humidity (RH) to flourish and they can potentially be controlled by environmental means, i.e. by manipulating air temperature and RH in the home (Bronswijk, 1981). It is often suggested that the rise in asthma could at least partly be due to lower ventilation rates as a result of more airtight methods of construction (encouraged in the interests of energy efficiency), as well as the conscious efforts of householders to prevent heat escaping through windows. Without adequate ventilation, indoor levels of airborne moisture can rise and, in combination with increased bedroom heating (reflecting a greater demand for thermal comfort), this is more likely to provide the warm, humid conditions that favour mite proliferation. At the macro scale, regional differences in mite numbers can be related to overall climatic conditions, for example tending to be lower in the dry air of the Alps than in coastal areas (Charpin et al., 1988). At the micro scale, however, several studies (e.g. Voorhorst et al., 1969; Korsgaard, 1983a; Kuehr et al., 1994; Luczynska et al., 1998) have found marked differences in mite numbers and/or allergen concentrations between dwellings within the same region, ranging from high to non-existent. This reflects the fact that hygrothermal conditions can vary greatly from house to house according to factors such as different construction methods, heating and ventilation standards, and occupant behaviour (e.g. in relation to moisture production from washing and cooking, thermostat settings, window opening habits, etc). These factors interrelate in complex ways, so that it is not surprising that indoor hygrothermal conditions vary to the extent they do. Several studies have shown that the observed differences in both allergen levels and mite numbers within the same region can be related to differences in indoor climate, thereby indicating the scope for controlling them by environmental means (Korsgaard, 1983b; Hart and Whitehead, 1990; Strien et al., 1994; Sundell et al., 1995).

Environmental control of mites has two major advantages. First, as will be discussed below, our preliminary modelling results suggest that creating hygrothermal conditions that are unfavourable to mite growth is a more feasible option, even in the UK, than may have previously been assumed (e.g. Sporik et al., 1992; Colloff, 1994). If this conclusion is corroborated, it means that effective control will in many cases be possible by means of relatively minor adjustments to heating and ventilation, or occupant behaviour. Significant reductions in the prevalence of disease could thus be achieved at a cost far below that of the drug therapies that might otherwise be required. Moreover, where capital expenditure on the dwelling is shown to be required, this is often desirable for other reasons: for example, raising insulation standards (which, provided ventilation is adequate, can result in lower relative humidities) also improves energy efficiency and lowers Excess Winter Deaths. The second advantage is that environmental means of control have potential as preventive measures, that is to say before sensitization and symptoms have occurred. With adequate support from public health initiatives and regulatory bodies, they could be adopted by a high proportion of households.

Fig 1

The possibility of environmental control of mites has been recognised for some time by acarologists and clinicians, but it has only recently been taken up by building scientists (Cunningham, 1996; Lowe, 2000). Because of the complexity of the many interacting factors (see Fig. 1), it has until now been difficult to model hygrothermal conditions within dwellings and mite habitats in sufficient detail for determining the most effective, energy efficient and socially acceptable ways of achieving control. The development of reliable computer models and the advent of small cheap sensors and loggers have radically improved the situation, increasing current interest in this area.

A multi-disciplinary team of building scientists and acarologists has been working since 2000 to develop two complementary model suites, simple and complex. Each currently focuses on the bed environment, the most common habitat in the UK and Europe and consists of three component models (see Fig. 1):

1. An existing *bedroom* model to simulate hygrothermal conditions within the bedroom
2. A new *bed* model to simulate hygrothermal conditions within the bed
3. A new *population* model to simulate the effects of hygrothermal conditions within the bed on house dust mite populations.

Thus the bedroom model provides input data for the bed model, which in turn provides input data for the population model. (Alternatively, both bed and population models can use actual measured hygrothermal data as inputs.)

The complex suite of models attempts to take account of as many relevant factors as possible in as much

detail as necessary in order to simulate and investigate their effect on HDM populations. However, simple models that are easier to use and have fewer data inputs are also valuable. This is well understood in the field of building physics, where simple models, for predicting building energy consumption for example, are in daily use by environmental engineers and building designers, while data rich models of greater complexity are used by researchers to investigate detailed phenomena. Similarly, whilst complex models can be better at modelling the environment in an individual dwelling, simple models are better for looking at the impact of changes to housing groups or types and are more appropriate for use by policy makers and those responsible for large stocks of housing. The experience of building physics, moreover, is that simple models often perform surprising well in predicting the future when compared with more complex models. Of course they tend to over-simplify and they cannot take account of all that is known to affect the outcome, but by considering the aggregate effect, where one influence often cancels out another, they can usefully summarise the situation with sufficient accuracy for the purpose of comparing scenarios. Even in a research context, they can provide a valuable starting point, or clarify where some of the complexity in a more sophisticated model is in fact unnecessary and does not enhance its predictive power. In other words, simple models have an important practical role to play.

The population model presented in this paper is a simple model of this kind intended to provide a broad indication of how mite population growth is affected by hygrothermal conditions. When combined with the simple bedroom and bed hygrothermal models (see below), it has potential for widespread use as a practical tool for exploring the effects of modifying the environmental variables and enabling practitioners to quickly compare alternative strategies for the environmental control of HDM. The complex population model, which takes many more factors into account (such as water balance, fluctuating conditions, life cycle stage, etc) will be the subject of future papers.

The bedroom environment

A typical bed is occupied for about 8 hours a day, that is to say one third of the time. The results of our detailed laboratory studies of highly instrumented beds show that hygrothermal conditions within the mattress respond relatively quickly following occupation and again when the sleeper leaves the bed (Pretlove et al., 2001). Thus for most of the intervening 16 hours, bed conditions are in equilibrium with room conditions. In order to simulate temperature and RH in a bed, the logical starting point is thus to simulate conditions in the bedroom. This is achieved in the simple suite of models by making use of an established and validated room model, Condensation Targeter II (Oreszczyn and Pretlove, 1999), which takes account of the various interrelated factors that influence indoor hygrothermal environments (Fig. 1). The inputs required relate to: location (climate data sets are now available for almost any location worldwide), building type (construction, size, layout, etc), building services (heating and ventilation provision) and household characteristics (number of occupants, moisture production, heating/ventilation use patterns, etc). The outputs are average monthly bedroom temperature and RH.

The bed environment & the BED hygrothermal model

As described more fully elsewhere (Pretlove et al., 2005), BED is a model which can predict the environmental conditions in the bed. Using the bedroom temperature and RH (predicted or measured) as inputs, it simulates the temperature and RH at a single point within the core of the bed, that is to say the central point immediately under the occupant on top of the mattress. Simplifying assumptions (which can be varied) are made in relation to the characteristics of the bedding (e.g. vapour resistivity and thermal conductivity) and the sleeping occupant (e.g. skin area and temperature). The outputs are the average monthly temperature and RH in the core of the bed, taking account of both the time when it is occupied and when it is not (and in equilibrium with room conditions). These outputs are then used as inputs to the new simple population model presented in this paper.

In combination, the bedroom and bed hygrothermal models allow considerable flexibility for exploring the effects of different climatic conditions, different house types and different types of occupant behaviour. From the sensitivity analysis we have conducted (Pretlove et al., 2005), it is interesting that varying these inputs has far more effect on the resultant hygrothermal conditions in the core of the bed than varying the other inputs or assumptions relating to the bed itself or the sleeping occupant. At first this may seem counter-intuitive, but since the bed is unoccupied and in equilibrium with bedroom conditions for almost two-thirds of the time, it is perhaps not surprising. Bedroom conditions can vary greatly from house to house, hour to hour and season to season, while core conditions inside the bed remain relatively constant during occupation. Although they are affected by different bedding and

personal characteristics, such differences are relatively small compared with the effect of different room conditions, which act over a longer time period, that is to say when the bed is unoccupied.

Mite physiology from a modelling perspective

Fig 2a & b HDMs rarely encounter liquid water and extract most of the moisture they need from unsaturated air by means of a hygroscopic secretion from supracoxal glands, as described by various authors (Arlian and Wharton, 1974; Wharton, 1978; Arlian and Veselica, 1979). However, this active pump mechanism can only operate when the RH of the ambient air in mite habitats is sufficiently high, so mite survival is highly dependent on RH. The *Critical Equilibrium Humidity* (CEH) is defined as the RH below which mites are unable to maintain their water balance and lose more water than they can gain. As the air RH rises above CEH, water intake from the active pump increases, supplemented by moisture absorbed passively and from the food they eat. Moister skin scales are easier to eat and they also encourage mould growth which may provide additional nutrition (Asselt, 1999). As a consequence, feeding, defecating, mating and egg production all increase rapidly (Arlian, 1992). However, mould activity also increases rapidly with rising RH and above a certain level mite populations decline sharply (see Fig. 2a). High mould densities are likely to have a negative effect on mite populations as a result of competition and physical deformation of the food, as well as contamination by mould toxins (Hay et al., 1992). Conversely, as RH falls below CEH, the water in the active mechanism is lost, causing the solutes to crystallise, thereby forming a plug that blocks the orifice of the supracoxal gland and closes down the pump. Physical activity also reduces in order to minimise both water demand and water loss. The further RH falls below CEH, the faster mites dehydrate and ultimately die, although the time required varies according to species and life cycle stage.

Fig. 3 However, mite development is highly dependent on temperature (see Fig. 3). Egg-to-adult development time is significantly longer below 23˚C, thus hampering population growth even when the RH is high. As temperature rises, development time reduces and egg production also increases. Beyond a certain temperature, however, adult female longevity and egg production fall off sharply, giving rise to the highly peaked graph shown in Figure 2b. The optimum population growth zone therefore appears to be tightly defined with respect to both temperature and RH, and the effects of both need to be taken into account for modelling purposes.

Arlian and Veselica (1981a) found that CEH for *D. farinae* (DF) varies with temperature, as shown in Figure 4. However, at 25˚C, their result of CEH = 58% was significantly lower than the previous result of CEH =70% at 25˚C found for DF by Larson (1969). Arlian and Vaselica (1981b) suggest that this was probably due to differences in experimental methodology. In their case, the test mites were pre-dehydrated by being held at 0% RH for 24 hours, so that they lost 30-50% of their body water, before being exposed to the test conditions for 24 hours. The RH at which net water gain occurred for each temperature was then calculated from the results. The authors state that Larson also pre-dehydrated his test mites but only for 6 hours, which, they suggest, would not have resulted in significant water loss. In other words, whereas they re-hydrated dehydrated mites to observe when net water gain occurred, Larson dehydrated hydrated mites and observed when net water loss occurred.

Fig. 4 A similar situation has been reported with respect to *D. pteronyssinus* (DP). Arlian (1975) found the CEH at 25ºC to be 73%, using mites that had *not* been pre-dehydrated, but kept for three days at 25ºC and 75% RH. De Boer et al, using pre-dehydrated mites, found the CEH at 16ºC to be between 56-58% RH (1998) and at 20ºC to be between 58-60% RH (1997). The above results for both DF and DP are plotted in Figure 4 and show some consistency with respect to whether the test mites were pre-dehydrated or not. It is therefore conceivable that rather than a single value at a specified temperature there are CEH_{min} and CEH_{max} values depending on the mites' state of hydration.

Another question is whether the net water gain observed below CEH_{max} when mites are re-hydrated involves the active pump mechanism, or whether it is achieved primarily by passive means by transpiration through the mite's outer body surfaces. Whether it is by active or passive means, temperature and RH clearly have a major impact. De Boer (2000a) reports that DP mites took only one day to regain the same amount of body water that was lost during 1-2 weeks of dehydration, even when re-hydration was carried out at 18ºC and 63-64% RH. This is above CEH_{min} but below the likely value for CEH_{max} at 18ºC (see Fig. 4).

Fig. 5 However, it is not clear what effect CEH actually has on mite populations. DP egg production, for example, declines smoothly as RH falls, with no indication of a step change (Fig. 5). The possibility that

there is a range of values for CEH at a given temperature, rather than a single value, may help explain this lack of a step change. The time taken for a response to occur may be another factor. Arlian and Wharton (1974) report that it takes 14 hours for all the water in the active mechanism to be lost at low RHs. It is thus possible that such lags in response tend in practice to smooth out any step changes that one might otherwise expect, especially in the continually changing environment in which mites live. Although the CEH phenomenon is clearly important from the modelling perspective, more research is required to clarify its precise role in determining mite populations.

Cunningham's population model

Cunningham (1996) demonstrated that daily population growth and decline rates for different combinations of temperature and RH can be calculated if the relevant population doubling and halving times are known. For example, assuming a simple exponential growth curve, the daily population growth rate, *r*, is given by

$$r = \ln 2 / t_d \quad (1)$$

where t_d is the population doubling time in days for a particular combination of temperature and RH.

To provide the required data, Cunningham collated or calculated doubling and halving times from various sources, for a range of temperature and RH combinations and for the three most common HDM species (DP, DF and *Euroglyphus maynei*). Unfortunately, as he acknowledges, the available data set is incomplete for any one species and does not cover a wide range of hygrothermal conditions. In some cases, the data was also obtained using samples containing a very small number of mites.

In order to determine the dividing line between growth and decline, Cunningham (2000) proposed a simple model, based on the assumption that population growth occurs above the CEH and that population decline occurs below it. First, he curve-fitted the CEH vs. temperature (T) data from the Arlian and Veselica 1981 study (i.e. the CEH_{min} values for DF), resulting in the equation:

$$CEH_{min} = 56.75 - 0.9917\,T + 0.05\,T^2 - 0.0003\,T^3 \quad (2)$$

He then curve-fitted the population halving and doubling times collated in the earlier paper to yield equations for the two cases:

$$\text{If } RH > CEH_{min} \quad \text{Growth} = 1 + 4.9 \times 10^{-5}\,T\,(RH - CEH_{min}) \quad (3)$$

$$\text{If } RH < CEH_{min} \quad \text{Decline} = 1 - 3.38 \times 10^{-4}\,T\,(CEH_{min} - RH) \quad (4)$$

where "Growth" and "Decline" are population multiplication factors per day (such that 1.1 represents 10% population growth per day). Since the data set used for (3) and (4) is for all three HDM species combined, the model is not species specific, but is rather intended to demonstrate the principle.

Fig. 6 The resultant model of mite population growth for different combinations of RH and T is illustrated in Figure 6 (for reasons explained later, the population growth factors are calculated for 21 days). The solid line represents zero growth (i.e. Equation 2). Although not yet validated, the Cunningham model is a major advance on previous models, potentially able to predict mite population growth over time for any location for which RH and T are known. Cunningham was one of the first to exploit modern micro hygrothermal monitors for measuring conditions at a detailed level within mite habitats such as bedding and carpets (Cunningham 1998). Using these data sets as inputs to the model, he was able to predict the effects of real life conditions on population growth over time and at different locations within, for example, a mattress or carpet (Cunningham 1999), demonstrating the potential value of a simple population model of this kind.

On the other hand, the model as it stands has the limitation that there are no constraints on growth at high values of RH, which are known to exist in reality (Fig. 2a). Using CEH to determine the lower limit of growth in terms of RH has the advantage of being based on a known physiological phenomenon (rather than statistical curve-fitting), but an upper limit is also required. Similarly, constraints on growth are required at extreme values of temperature (Fig. 2b).

The Mite Population Index model: methodology

Having concluded that CEH on its own is insufficient for determining the dividing line between population growth and decline, the next step in developing a simple population model depends on obtaining a better data set. Accordingly, a series of preliminary experiments have been carried out. Rather

than population doubling and halving times, changes in population were observed at the end of a set time period, 21 days, for a range of steady state RH and T combinations, using large sample sizes of a single HDM species, in this case laboratory-reared DP mites. In this way a more comprehensive and consistent data set was obtained than previously available. The preliminary nature of the experiments, however, should be emphasised.

Initially, experiments were conducted at 20, 25 and 30ºC and six RHs, ranging from 32 – 87% RH. Relative humidity was maintained using tissue soaked in saturated salt solution , contained within airtight plastic containers, which were placed in incubators maintained at the test temperatures, as checked by an independent thermometer. Several different containers, each at a different RH, were thus placed within the same incubator. With the advent of small RH loggers, it has become possible to check the actual RH values achieved with salt solutions inside experimental containers of this kind. Accordingly a single Hobo data logger (Onset Computer Corporation) was placed inside each one in turn to monitor conditions every 30 seconds for approximately 30 minutes near the end of the 21 days. After an initial short period during which equilibrium was re-established following the container being opened, the logged values obtained were constant. In most cases, the values were close to those given by Winston and Bates (1960), demonstrating that the Hobo was reasonably well calibrated. In some cases, however, the logged values were significantly different, indicating that there had been unforeseen problems with mixing some of the salts. Subsequent experiments have confirmed that there are some salts with which it is considerably more difficult to achieve the target RH than with others. This did not matter in itself for the purpose of determining data points for the model, provided the actual RH was known. In the current case, the stable values measured by the logger were assumed to have been correct throughout the 21 days.

In each case, a weighed sample (approx. 0.05g) of DP well mixed culture with a known density of mites (adults and juveniles) was added to 0.5g of mite food (1:1 by weight liver and yeast) contained within 7.23 cm^3 plastic vials with screw-on lids with three 4mm holes. To prevent the mites from escaping, a layer of mite-proof vapour permeable fabric was placed under the lid. The previously measured density of the culture was 22,897 mites/g (extrapolated from the mean of several weighed samples) and the mean starting population of mites in the tubes was 1,161. The density of eggs in the culture was not determined, but the culture was flourishing and mature (i.e. with a spread of all ages) and, being well mixed, each sample from it is likely to have contained a similar number of eggs, as well as adults and juveniles. The mites were not pre-conditioned and were kept at 25˚C and 75% RH before being placed in test conditions. However, prior to the addition of any mites, the food was incubated at the appropriate combination of temperature and RH for 24 hours. The mite populations (three replicates in each case) were incubated under the test conditions for 21 days, the containers being gently shaken twice a week for the duration of the experiments. The number of live adult and juvenile mites in each tube was then determined first by counting the number of mites in a weighed sample (approx. 0.01g) from the tube (by spreading the sample on a glass plate under a microscope and using a 0.5mm square grid and a tally-counter) and then using the total weight of culture in the tube to extrapolate to the total number of mites.

Further experiments were conducted at 15 and 35ºC over the same range of RHs, with the addition of 94.5% RH at 35ºC. (Limited incubation space had precluded doing this at the same time as the above.) At 15ºC, 0.05g of culture was again added to the 0.5g of food in the tubes, but this culture contained a lower density of mites, 15,645 mites/g, giving a mean starting population in these tubes of 790 mites. At 35ºC, the culture was even less dense, 12,280 mites/g, and it was decided to increase the mass of culture added to the tubes so as to arrive at a mean starting population that was closer to the initial round of experiments. Accordingly, 0.095g of culture was added to provide a mean starting population of 1,164 mites.

Results

Table 1 The population change after 21 days for each RH and T combination is shown in Table 1. The variations in the starting population were the result of small variations in the mass of culture added to each tube. It can be seen that significant population growth took place at the higher RHs, even after only 21 days, tending to confirm that the cultures from which the samples were taken were flourishing and mature, with a spread of all ages. However, it would undoubtedly have been better if it had been possible to use a single culture thoughout.

If the Mite Population Index (MPI) is defined as the population growth or decline multiplication factor (such that 1.1 represents 10% population growth, as with Cunningham's model), the following best fit equation has been determined:

$$MPI = \exp (a + bY + cY^2 + dX + eXY + fXY^2 + gX^2 + hX^2Y + iX^2Y^2) /100 \quad (5)$$

Where: X = temperature ºC, Y = RH% and

a = 2.3397246782 E+01; b = -2.2105777989 E-01; c = -2.4426126335 E-03
d = -1.9681192296 E+00; e = 2.7180575622 E-02; f = 1.8004352184 E-04
g = 3.0361144355 E-02; h = -3.8851175984 E-04; i = -4.1260780086 E-06

Fig. 7 The resulting surface is shown with the data points in Figure 7 in a way that is directly comparable with Figure 6; the solid line again represents zero growth or population equilibrium. Although broadly similar, growth peaks more significantly when conditions are ideal and falls off more quickly at extremes of temperature. With more data points, it is likely that a sharp fall-off at high RHs would also have been observed, as suggested by Figure 2a. In Figure 7, the zero growth line would then form a complete closed loop. This will require further experimentation. However, such high values of RH are not often found in mite habitats and the new data set does cover the main area of interest.

As with Cunningham's model, the new MPI model can be used to determine the likely effect of any particular combination of temperature and RH on mite population growth for any location for which hygrothermal conditions are known.

In Cunningham's case, daily growth or decline rates were determined from doubling and halving times by assuming that growth or decline occurs at a constant exponential rate (Equation (1)). The MPI model is different in being based on directly observed population changes over 21 days. Daily growth and decline rates can also be calculated by making use of an equation such as (1), so that the model can be used, in the same way as Cunningham's, to predict daily population changes over time. There is nothing to stop either model being applied at hourly intervals, but as Cunningham (2000) points out, it is incorrect to use a model based on steady state growth data for so short a time period.

In the context of the simple suite of models described earlier, the outputs from the BED hygrothermal model are monthly averages, so that the MPI values in this case need to be extrapolated, again assuming a constant rate, from 21 to 30 days. However, the constant rate assumption requires further study. Especially in the case of the largest populations found in this study, for example, the growth rates may have declined in the final days as carrying capacity was reached. Growth rates (and their constancy) may also be affected by the extent to which mites are pre-conditioned before being placed in test conditions (here they were not pre-conditioned). Finally, Colloff (1992) has demonstrated the importance of knowing the complete population structure at the start of population experiments, that is to say the number not only of adults and juveniles, but also of eggs. Here, the number of eggs in each sample at the start was not determined. The significance of population structure is greatest when the sample size is small and in this case the large sample size is likely to have at least partially smoothed the effect of whatever differences there might have been in the number of eggs. Thus while the data set presented here has been adequate to demonstrate the principle of the MPI model, and is more comprehensive and consistent than previously available data sets, there is still room for improvement.

Discussion

Fig. 8 Since CEH (whether CEH_{min} or CEH_{max}) varies with temperature, one can define CEH^T to be the CEH at a specified temperature T. PEH^T (*Population Equilibrium Humidity*) can then be defined in a similar way as the RH at which equilibrium between population growth and decline occurs for a specified temperature T. The units in each case are % RH. In effect Cunningham has assumed that CEH^T is the same as PEH^T. That this is partly true can be seen in Figure 8, which is a 2-dimensional plan view of Figure 7. The heavy dashed line is an assumed CEH_{min} curve for DP, based on Arlian and Vaselica's curve for DF plus 4 percentage points (in Figure 4, the two DP2 values are both 4 percentage points higher than the equivalent DF2 values). It is indeed remarkably similar to the population equilibrium line in the mid-range 20ºC – 30ºC, but it diverges sharply at the extremes. This is particularly relevant to the UK, where many bedrooms are kept at temperatures below 20˚C, especially in poorly insulated properties without central heating. In other words, although the new MPI model lacks (at present) a physiological explanation for the zero growth line, it more comprehensively takes account of how temperature and RH influence population growth than CEH alone. A further point is that CEH values have been determined primarily for adult mites and their relevance for eggs and larvae is unknown. By contrast, the new PEH values represent the net effect of given hygrothermal conditions on an entire population at all life stages.

Fig. 9 It is of interest to examine the implications of the MPI model in more detail. Figure 9 is the same as Figure 8, but with three boxed areas superimposed, representing the range of outdoor, bedroom and bed conditions typical of the UK. The bedroom and bed values have been derived from field and laboratory measurements (Pretlove et al., 2001, 2002). It can be seen that outdoor conditions in the UK are far from favourable to mites. Only in the warmest and most humid months (e.g. end of summer) are outdoor conditions sufficient to promote mite growth. In contrast, conditions in the bedroom and especially in the bed can range from being highly favourable to highly unfavourable. Although the outdoor climate can affect bedroom and thus bed conditions, it is only one of several factors. Building related variables such as heating pattern, occupancy, insulation, ventilation and demand temperature each have a considerable impact on bed conditions and the way that they can vary from house to house largely accounts for the range of conditions illustrated in Figure 9.

The implications of Figure 9 are:

1. The range of typical conditions in UK beds straddles the population equilibrium line in such a way that the net effect on mite populations ranges from almost x10 growth over 21 days to more than a x10 reduction.
2. Whether the conditions tend towards one extreme or the other depends on building related factors which can potentially be controlled.

Figure 9 is specific to the UK and it would be a valuable exercise, using Figure 8 as a base, to map outdoor, bedroom and bed conditions for different climatic regions around the world. (For countries such as the USA, where DF is the predominant species, new data would be required to provide the equivalent of Figure 8 for DF.) In this way it would be possible to study the potential for environmental control in each case. In general, cold winter climates are likely to show a similar pattern to Figure 9, with a large part of the outdoor box outside the equilibrium line. The precise shape and position of the bedroom and bed boxes will vary from country to country, but as long as a substantial part of the outdoor box is outside this line, one would expect both the bedroom and bed boxes to straddle the equilibrium line, indicating the scope for environmental control. Conversely, in climates without cold winters, where the outdoor box may be substantially inside the equilibrium line, the scope for environmental control will be much less.

Strategies for environmental control

Fig. 10 Following Korsgaard (1983b), it is generally accepted that the most effective strategy for the environmental control of house dust mites in cold winter climates is to concentrate on providing hygrothermal conditions that are unfavourable to mite growth during the winter heating season. The argument is that there is little that one can do to prevent mite growth during late summer and early autumn when outdoor air is both warm and humid (edging above the equilibrium line in Figure 9) and when there is little difference between indoor and outdoor conditions. But in winter there is the opportunity, by means of adequate ventilation, to swap warm moisture-laden indoor air with outdoor air, which, being cold, contains little moisture in absolute terms. When this is heated, the resultant bedroom and bed relative humidity is too low for mites to survive (i.e. below the equilibrium line in Figure 9). If enough of the mites perish during the winter months, there will be too few survivors to benefit from more favourable conditions in the following summer. The seasonal nature of mite population growth, found by many authors (summarised in Colloff, 1991), is shown in Figure 10. This also demonstrates that, within the same region, mite numbers in one house can rise dramatically in late summer, while conditions in another house are such that they can be kept down to an insignificant level.

However, de Boer (2000b) reports that this strategy of seasonal culling does not always work as expected. In the Netherlands, he observed that temperatures in a mild winter may not be low enough for long enough to result in significant mite deaths. On the other hand, during a cool summer, they may not be high enough to result in significant mite population growth. Ideally, one needs to be able to take account of such climatic variations in fine tuning a seasonal culling strategy, which is what can now be done using modelling techniques.

At the 1987 WHO Workshop at Bad Kreuznach, it was noted that 7 g/kg is the level of absolute humidity (AH) above which mite proliferation is likely to occur (Platts-Mills and de Weck, 1987). This was based on a series of studies initiated by Korsgaard suggesting that mite populations can be controlled if winter AH values in the home are kept below this target level (Korsgaard, 1979, 1983b). At the time, there was some confusion as to whether the target was based on the assumption that mites were physiologically affected more by AH than by RH, which, as Arlian (1992) pointed out, is incorrect. However, it is clear

that Korsgaard (1983b, 1991) was considering the overall effect of hygrothermal conditions on mite population dynamics from a more practical viewpoint. For heating engineers it is a simple matter to calculate the ventilation rate required to achieve a specified AH, given dwelling volume, occupant numbers and moisture production rate. Controlling the RH however is more problematic because RH is a function of both AH and temperature. RH values therefore tend to change more than AH, varying continually with changes in temperature from hour to hour and day to day. Moreover, the seasonal variation of AH values (low in winter and high in summer) forms the basis for the environmental control strategies that Korsgaard (1991) advocates. The 7g/kg winter threshold was thus conceived as a simple rule of thumb that could be used as a practical guide for avoiding HDM proliferation. Moreover, many studies found that keeping below 7g/kg in winter was indeed effective in preventing mite infestation (Vervloet et al., 1991; Harving et al., 1991 & 1994; McIntyre, 1992; Wickman et al., 1994; Warner et al., 2000). On the other hand, other studies, particularly in the UK, have not found the 7g/kg threshold effective or have found poor correlation between absolute humidity and HDM populations (Fletcher et al., 1996; Raw et al., 1998, Niven et al., 1999).

The 7 g/kg curve is shown on Figure 8 as a dotted line. It intersects the x0.1 growth line at about 21ºC, above which conditions are clearly unfavourable for mite population growth. However, as temperature falls below 21ºC, the 7g/kg threshold conditions become more favourable. At about 17ºC, the curve intersects the CEH_{min} line and thereafter it is dangerously close to the equilibrium line. Bed conditions need only be marginally more favourable than room conditions for mite population growth to occur. Given that UK bedroom temperatures have historically been lower than in continental Europe, Figure 8 thus explains not only why some studies found the 7g/kg threshold to be effective, but also why others, especially in the UK, did not. One can thus conclude that while the 7g/kg threshold may be appropriate where bedroom temperatures are kept high, not least for providing an easy-to-use rationale for determining adequate ventilation, it lacks generality and is too simplistic a tool for widespread applicability. Using a different method of analysis, Lowe (2000) has also noted that it is inappropriate in a UK context.

Conclusions

The environment within a bed is determined by a number of different factors (Fig 1). There are thus no simple rules for establishing the most effective strategies for the environmental control of mites: the contexts vary greatly from hour to hour, dwelling to dwelling, season to season and region to region. The modelling approach, where all such factors can be taken into account, is therefore particularly relevant to the control of house dust mites.

Building on the work of Cunningham (1996, 2000), a simple Mite Population Index model has been presented that predicts how mite populations grow or decline when held at different combinations of temperature and RH. The model is based on a preliminary set of new laboratory experiments that have been carried out to obtain a more comprehensive and consistent data set than has hitherto been available. These experiments, using DP mites exposed to different hygrothermal conditions, have been described and the results have been used to derive a best-fit equation for population change. The results have also enabled us to define a new term, the *Population Equilibrium Humidity*, which can be seen as similar to but distinct from the Critical Equilibrium Humidity. The limitations of the latter, on its own, for predicting the division between population growth and decline, especially at extremes of temperature and RH, have been discussed.

Compared with previous models, the new MPI model is potentially more comprehensive and accurate. It can be seen as a step towards a more detailed biological modelling approach while retaining simplicity of use. Although further validation is required, it has already proved useful for understanding more clearly how the different hygrothermal conditions found in bedrooms and beds can affect mite populations. It has also demonstrated the potential for environmental control of mites in cold winter climates such as the UK. In conjunction with the BED and Condensation Targeter II hygrothermal models, we can thus begin to explore, in broad terms, the likely effect on HDM populations of modifying the various factors that influence hygrothermal conditions in bedrooms and beds. In this way the combined hygrothermal/population model can be used to determine the most effective and appropriate means for controlling mite populations by environmental means.

The preliminary set of experiments, however, has usefully highlighted a number of issues. A more complete data set would enable the MPI model to predict the fall-off in growth that occurs at very high RHs more accurately. The effects of the initial population structure and of pre-conditioning also need to

be taken into account more ocmprehensively. A longer test period, with intermediate population counts, would clarify whether growth rates can be assumed to be constant. Ideally, the experiments should be repeated not with laboratory-raised mites, but with wild mites (i.e. collected from dwellings) fed on a diet as close as possible to what they are used to. In any repetition of the experiments, it would be better if RH conditions in each container were to be regularly checked or continuously monitored for the whole test period and if a single culture were to be used throughout.

However, the MPI model's most obvious limitation is that it currently assumes steady-state conditions. De Boer et al. (1997, 1998) have demonstrated that mite populations can survive and prosper in average conditions that are well below even CEH_{min}, provided that they are exposed to a few hours daily of favourable conditions. Similarly, Pike et al. (2005) have shown that an HDM population exposed to sinusoidal conditions averaging 20.5˚C and 62.5% RH responded as if they were in steady state conditions of 23˚C and 75% RH. This suggests that the MPI model will tend to underpredict mite population growth. If consistent, this would not necessarily invalidate it being used to examine the relative differences between dwellings (or to compare the effects of different options for improvement). Nevertheless more field data with which to test the model is clearly needed in order to determine how serious a limitation this is. If necessary, alternative ways of overcoming it can then be investigated. It is possible, for example, that the development of the more detailed, complex population model, currently in progress, will throw light on simple ways of taking the effect of fluctuating conditions into account. To summarise: progress has been made towards a simple, widely applicable population model, but more work is required.

Acknowledgements

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References

Arlian LG, 1975. Dehydration and survival of the European house dust mite, *Dermatophagoides pteronyssinus*. Journal of Medical Entomology, 12/4: 437-442

Arlian LG, 1992. Water balance and humidity requirements of house dust mites. Experimental & Applied Acarology, 16: 15-35

Arlian LG, Neal JS and Vyszenski-Moher DL, 1999. Reducing relative humidity to control the house dust mite *Dermatophagoides farinae*. Journal of Allergy and Clinical Immunology, 104/4: 852-856

Arlian LG, Rapp CM and Ahmed SG, 1990. Development of *Dermatophagoides pteronyssinus* (Acari: Pyroglyphidae). Journal of Medical Entomology, 27/6: 1035-1040

Arlian LG and Veselica MM, 1979. Water balance in insects and mites. Comp Biochem Physiol, 64A: 191-200

Arlian LG and Veselica MM, 1981a. Effect of temperature on the equilibrium body water mass in the mite *Dermatophagoides farinae*. Physiology Zoology, 54/4: 393-399

Arlian LG and Veselica MM, 1981b. Re-evaluation of the humidity requirements of the house dust mite *Dermatophagoides farinae* (Acari: Pyroglyphidae). Journal of Medical Entomology, 18/4: 351-352

Arlian LG and Wharton GW, 1974. Kinetics of active and passive components of water exchange between the air and a mite, *Dermatophagoides farinae*. Journal of Insect Physiology, 20: 1063-1077

Asselt, L van, 1999. Interactions between domestic mites and fungi. Indoor & Built Environment, 8: 216-220

Boer R de, 2000a. Rates of water vapour uptake and loss by the house dust mite, *Dermatophagoides pteronyssinus* (Acari: Pyroglyphidae). Proceedings of Experimental & Applied Entomology, 11: 73-76

Boer R de, 2000b. Explaining house dust mite infestations on the basis of temperature and air humidity measurements, in Mites, Asthma and Domestic Design III (Eds: Siebers R, Cunningham M, Fitzharris P and Crane J). Wellington Asthma Research Group, Department of Medicine, Otago University, 2000

Boer R de and Kuller K, 1997. Mattresses as a winter refuge for house-dust mite populations. Allergy, 52: 299-305

Boer R de, Kuller K and Kahl O, 1998. Water balance of *Dermatophagoides pteronyssinus* (Acari: Pyroglyphidae) maintained by brief daily spells of elevated air humidity. Journal of Medical Entomology, 35/6: 905-910

Bronswijk JE van, 1981. House Dust Biology for Allergists, Acarologists and Mycologists. NIB Publishers, The Netherlands

Charpin D, Kleisbauer J, Lanteaume A, Razzouk H, Vervloet D, Toumi M, Faraj F and Charpin J, 1988. Asthma and allergy to house-dust mites in populations living in high altitudes. Chest, 93: 758-761

Colloff M, 1991. Practical and theoretical aspects of the ecology of house dust mites (Acari: Pyroglyphidae) in relation to the study of mite-mediated allergy. Review of Medical and Veterinary Entomology, 79 (11/12): 611-630

Colloff M, 1992. Age structure and dynamics of house dust mite populations. Experimental & Applied Acarology, 16:49-74

Colloff M, 1994. Dust mite control and mechanical ventilation: when the climate is right. Clinical and Experimental Allergy, 24: 94-96

Cunningham MJ, 1996. Controlling dust mites psychrometrically – a review for scientists and engineers. Indoor Air, 6: 249-258

Cunningham MJ, 1998. Development and performance of a small relative humidity sensor for indoor microclimate measurements. Building and Environment, 34: 349-352

Cunningham MJ, 1999. Modelling of some dwelling internal microclimates. Building and Environment, 34: 523-536.

Cunningham MJ, 2000. A proposed experimental programme towards control of dust mites by microclimate modification, in Mites, Asthma and Domestic Design III (Eds: Siebers R, Cunningham M, Fitzharris P and Crane J). Wellington Asthma Research Group, Department of Medicine, Otago University, 2000

Fletcher A, Pickering CA, Custovic A, Simpson J, Kennaugh J and Woodcock A, 1996. Reduction in humidity as a method of controlling mites and mite allergens: the use of mechanical ventilation in British domestic dwellings. Clinical and Experimental Allergy, 26, 1051-1056

Gamal-Eddin F, Shehata K, Abou-Sinna F, Tayel S, Aboul-Atta A, El-Ahmedaawy B-E, Fayed M, Hafez A and Imam M, 1983. Duration and the development stages of house-dust mites *Dermatophagoides farinae* and *D. pteronyssinus* under controlled conditions to pave the way in front of the workers in the field of house-dust mite asthmatic bronchitis. 2. Oviposition period, fecundity and oval duration. Journal of the Egyptian Society of Parasitology, 13: 557-581

Hart BJ and Whitehead L, 1990. Ecology of house dust mites in Oxfordshire. Clinical and Experimental Allergy, 20: 203-209

Harving H, Hansen L, Korsgaard J, Nielsen P, Olsen O, Rømer J, Svendsen U and Østerballe O, 1991. House dust mite allergy and anti-mite measures in the indoor environment. Allergy, 46/S11: 33-38

Harving H, Korsgaard J and Dahl R, 1994. Clinical efficacy of reduction in house-dust mite exposure in specially designed, mechanically ventilated “healthy” homes. Allergy, 49: 866-870

Hay DB, Hart BJ, Pearce RB, Kozakiewicz Z and Douglas AE, 1992. How relevant are house dust mite-fungal interactions in laboratory culture to the natural dust system? Experimental and Applied Acarology, 16: 37-47

Korsgaard J, 1979. Husstøvmider (Pyroglyphidae, Acari) i danske boliger [House dust mites (Pyroglyphidae, Acari) in Danish homes]. Ugeskr Laeger, 141: 882-892

Korsgaard J, 1983a. Mite asthma and residency. American Review of Respiratory Disease, 128: 231-235

Korsgaard J, 1983b. House-dust mites and absolute indoor humidity. Allergy, 38: 85-92

Korsgaard J and Iversen M, 1991. Epidemiology of house dust mite allergy. Allergy, 46, Supplement 11: 14-18

Kuehr J, Frischer T, Karmaus W, Meinert R, Barth R, Schraub S, Daschner A, Urbanek R and Forster J, 1994. Natural variation in mite antigen density in house dust and relationship to residential factors. Clinical and Experimental Allergy, 24: 229-237

Larson DG, 1969. The critical equilibrium activity of adult females of the house dust mite *Dermatophagoides farinae* Hughes. PhD Thesis, Ohio State University, Columbus, Ohio

Lowe RJ, 2000. Psychrometric control of dust mites in UK housing. Building Services Engineering & Research Technology, 21/4: 274-276

Luczynska C, Sterne J, Bond J, Azima H and Burney P, 1998. Indoor factors associated with concentrations of house dust mite allergen, Der p 1, in a random sample of houses in Norwich, UK. Clinical and Experimental Allergy, 28: 1201-1209

McIntyre D, 1992. The control of house dust mites by ventilation: a pilot study. Proceedings of 13th AIVC Conference: Ventilation for Energy Efficiency and Optimum Indoor Air Quality, 15-18 September 1992, Nice, France, Oscar Faber plc on behalf of International Energy Agency

Niven R, Fletcher A., Pickering A, Custovic A, Sivour J, Preece A, Oldham L and Francis H, 1999. Attempting to control mite allergens with mechanical ventilation and dehumidification in British houses. Journal of Allergy and Clinical Immunology, 103: 756-62

Oreszczyn T and Pretlove S, 1999. Condensation Targeter II: modelling surface relative humidity to predict mould growth in dwellings. Building Services Engineering Research & Technology, 20/3: 143-153

Pike A, Cunningham M and Lester P, 2005. Development of *Dermatophagoides pteronyssinus* (Acari: Pyroglyphidae) at constant and simultaneously fluctuating temperature and humidity conditions. Journal of Medical Entomology, 42/3: 266-69

Platts-Mills T and de Weck A, 1987. Dust mite allergens and asthma – a world wide problem. Report on International Workshop, Bad Kreuznach, September 1987. Journal of Allergy and Clinical Immunology, 83: 416-427

Pretlove S, Ridley I, Horwood J, Leung B, Cox P, Thomson D, Baker N, Crowther D and Oreszczyn T, 2001. A combined transient hygrothermal and population model of house dust mites in beds. Proceedings of IAQ 2001: Moisture, Microbes and Health Effects: Indoor Air Quality and Moisture in Buildings, ASHRAE, San Francisco, USA, November 4 – 7, 2001

Pretlove S, Critchley R, Howard R and Oreszczyn T, 2002. The Nottingham energy, health and houseing study: reducing relative humidity, dust mites and asthma. Building Services Engineering Research & Technology, 23/1: 43-55

Pretlove S, Oreszczyn T, Ridley I, Wilkinson T and Crowther D, 2005. A steady state model for predicting hygrothermal conditions in beds in relation to house dust mite requirements. Building Services Engineering Research & Technology, 26/4: 301-314

Raw G, Weich C, Crump D, Brown V, Hunter C, Frederick J, Warner J, McIntyre D, Stephen F and Lane A, 1998. Asthma, Dust Mites, Ventilation and Air Quality: a field study of an environmental approach to reducing asthma. BRE Note N21/98, Building Research Establishment, Garston, UK

Sporik R, Chapman M and Platts-Mills T, 1992. House dust mite exposure as a cause of asthma. Clinical and Experimental Allergy, 22: 897-906

Strein R van, Verhoeff A, Brunekreef B and Wijnen J van, 1994. Mite antigen in house dust: relationship with different housing characteristics. Clinical and Experimental Allergy, 24: 843-853

Sundell J, Wickman M, Pershagen G and Nordvall S, 1995. Ventilation in homes infested by house-dust mites. Allergy, 50: 106-112

Vervloet D, Pradal M, Porri F and Charpin D, 1991. The epidemiology of allergy to the house dust mite. Revue des Maladies Respiratoires, 8: 59-65

Voorhorst R, Spieksma F and Varekamp H, 1969. House Dust Atopy and the House Dust Mite, *Dermatophagoides pteronyssinus* (Trouessart, 1897). Stafleu's Scientific Publishing Company, Leiden

Warner J, Frederick J, Bryant T, Weich C, Raw G, Hunter C, Stephen F, McIntyre D and Warner J, 2000. Mechanical ventilation and high efficiency vacuum cleaning: a combined strategy of mite and mite allergen reduction in the control of mite-sensitive asthma. Journal of Allergy and Clinical Immunology, 106, 75-82

Wharton G, 1978. Uptake of water vapour by mites and mechanisms utilized by the Acaridae. In Comparative Physiology: Water, Ions and Fluid Mechanics (Eds: Schmidt-Nielsen K, Bolis L and Maddrell S). Cambridge University Press, Cambridge

Wickman M, Emenius G, Egmar A-C, Axelsson G and Pershagen G, 1994. Reduced mite allergen levels in dwellings with mechanical exhaust and supply ventilation. Clinical and Experimental Allergy, 24: 109-114

Winston P and Bates D, 1960. Saturated solutions for the control of humidity in biological research. Ecology, 40/1: 232-237

Fig. 1 Schematic diagram showing factors affecting the hygrothermal conditions and hence the mite population in a bed, and the linkages to models used to predict the population

Fig. 2 Effects of RH (A) and temperature (B) on DP mite population growth
A from Bronswijk, 1981; B average of 2 experiments reported by Bronswijk, 1981

Fig. 3 DP Egg-to-adult development at varying temperatures
from Arlian et al., 1990

Fig. 4 Published results for Critical Equilibrium Humidity
DF1 = Larson, 1969; DF2 = Arlian & Veselica, 1981a
DP1 = Arlian, 1975; DP2 = de Boer, et al., 1997, 1998

Fig. 5 DP egg production at varying RHs
after Gamal-Eddin et al., 1983

Fig. 6 Graphic representation of the Cunningham (2000) population model

Fig. 7 The MPI model: graphic representation of lab results for population growth at varying combinations of T and RH

Fig. 8 Plan view representation of lab results with isogrowth lines added

Fig. 9 As Fig. 8, with the range of monthly average hygrothermal conditions typically found in the UK marked as zones for outdoors, bedroom and bed

Fig. 10 Seasonal variation of mite numbers in 3 Dutch houses
from Voorhorst et al., 1969

Table 1 Experimental results for DP population growth at different combinations of T and RH

Temperature	**Population at start**	**RH**	**Population after 21 days**		**Multiplication factor**
	no. mites		no. mites		
degC	mean of 3 replicates	%	mean of 3 replicates	*standard deviation*	
15	776	33.4	130	*121*	0.17
	795	46.2	116	*128*	0.15
	799	63.0	656	*208*	0.82
	794	66.0	754	*213*	0.95
	794	75.0	633	*201*	0.80
	781	87.0	763	*402*	0.98
20	1,157	32.4	183	*65*	0.16
	1,171	46.0	385	*153*	0.33
	1,153	68.5	6,389	*541*	5.54
	1,142	82.0	7,265	*660*	6.36
	1,129	84.4	8,864	*1,266*	7.85
	1,147	85.6	7,479	*1,218*	6.52
25	1,156	34.4	0		-
	1,141	50.4	0		-
	1,177	66.6	9,264	*373*	7.87
	1,181	68.6	8,408	*508*	7.12
	1,177	85.4	15,029	*1,758*	12.77
30	1,196	40.6	0		-
	1,184	53.3	0		-
	1,167	69.8	9,705	*3,173*	8.32
	1,113	86.6	21,659	*2,583*	19.46
	1,160	88.1	22,088	*3,614*	19.04
35	1,162	32.5	0		-
	1,164	40.0	0		-
	1,176	55.0	0		-
	1,156	71.0	1,068	*667*	0.92
	1,159	79.0	4,531	*1,365*	3.91
	1,174	83.0	1,677	*300*	1.43
	1,157	94.5	431	*161*	0.37

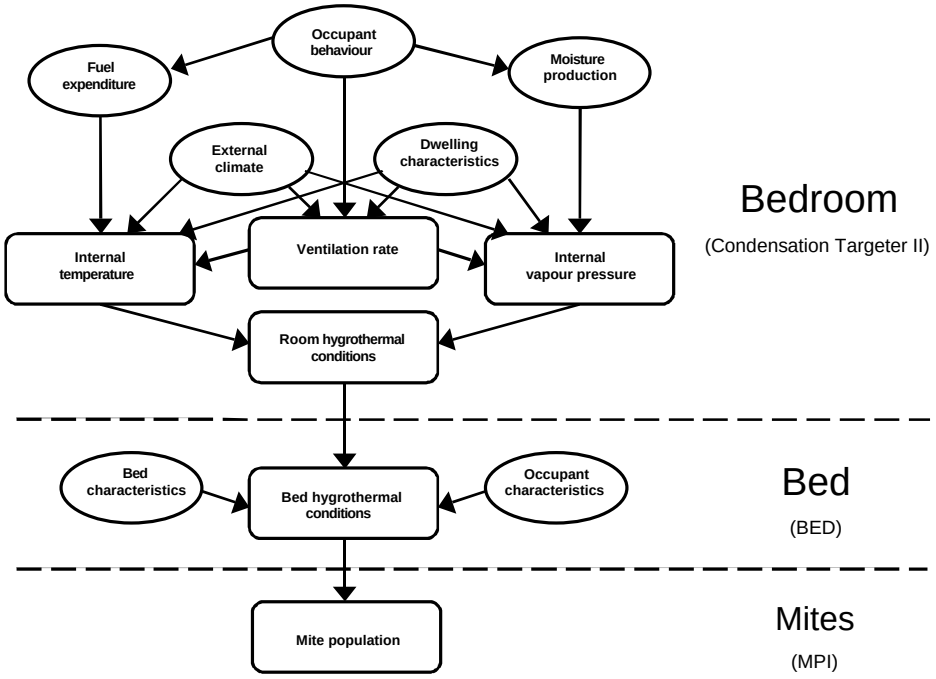
Occupant behaviour
Fuel expenditure
Moisture production
External climate
Dwelling characteristics
Internal temperature
Ventilation rate
Internal vapour pressure
Room hygrothermal conditions
Bedroom
(Condensation Targeter II)
Bed characteristics
Bed hygrothermal conditions
Occupant characteristics
Bed
(BED)
Mite population
Mites
(MPI)

Fig. 1

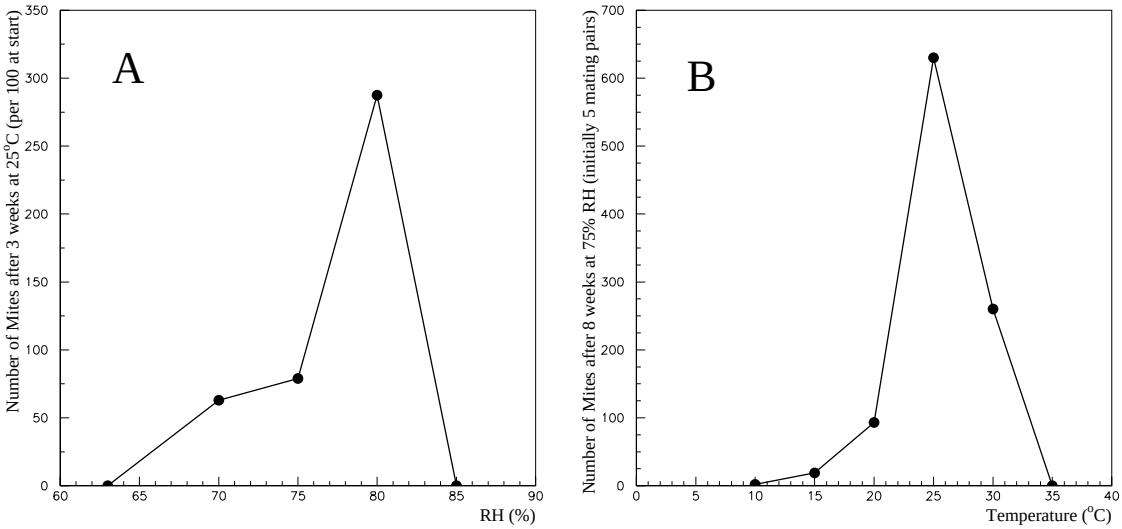
A
Number of Mites after 3 weeks at 25°C (per 100 at start)
RH (%)
B
Number of Mites after 8 weeks at 75% RH (initially 5 mating pairs)
Temperature (°C)

Fig. 2a & b

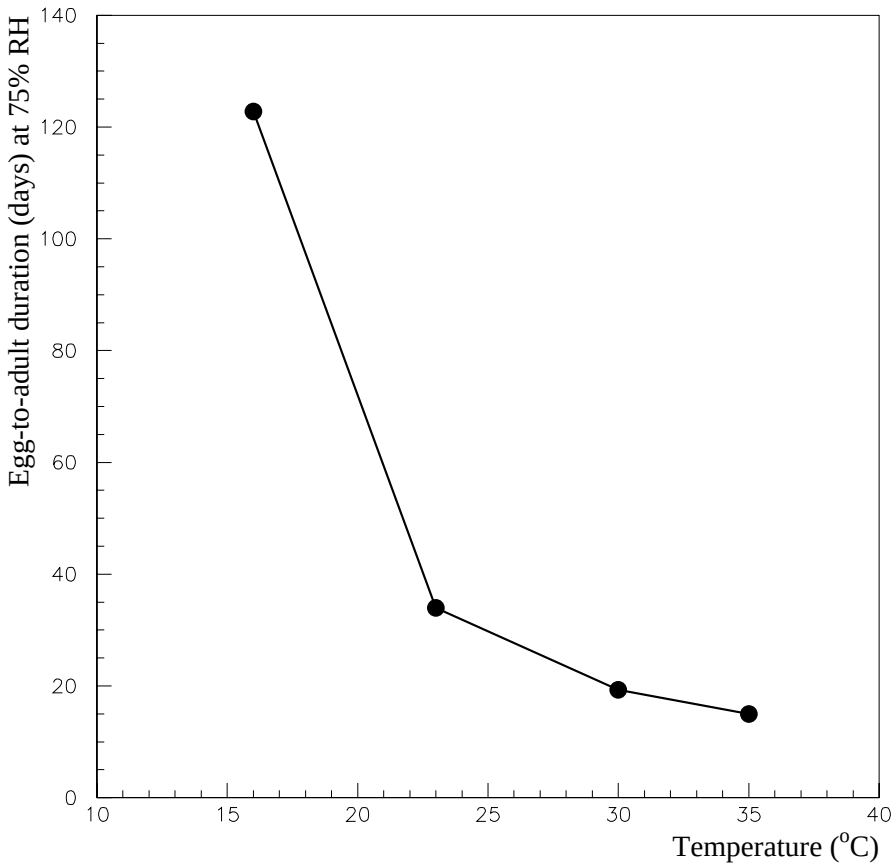
Egg-to-adult duration (days) at 75% RH
140
120
100
80
60
40
20
0
10
15
20
25
30
35
40
Temperature (°C)

Fig. 3

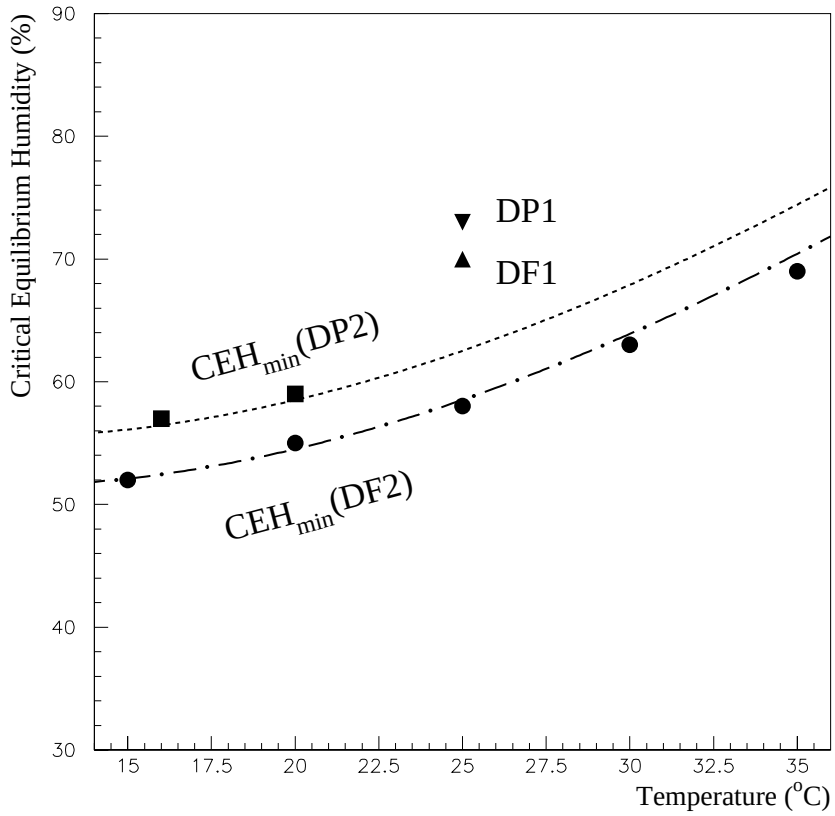
Critical Equilibrium Humidity (%)
90
80
70
60
50
40
30
15
17.5
20
22.5
25
27.5
30
32.5
35
Temperature (°C)
DP1
DF1
CEHmin(DP2)
CEHmin(DF2)

Fig. 4

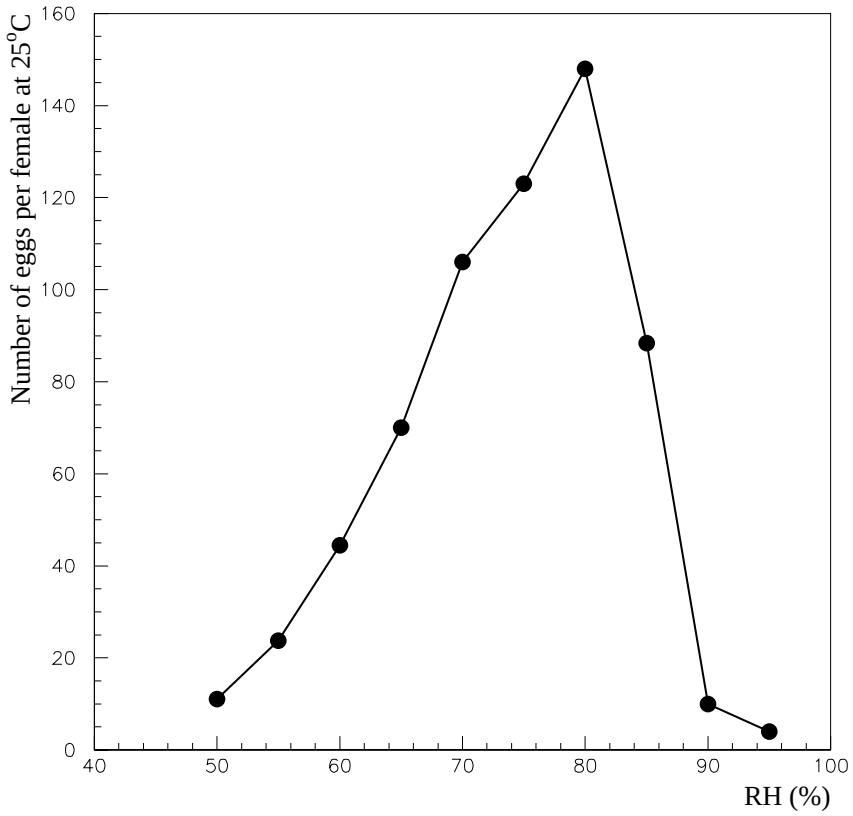
Number of eggs per female at 25°C
160
140
120
100
80
60
40
20
0
40
50
60
70
80
90
100
RH (%)

Fig. 5

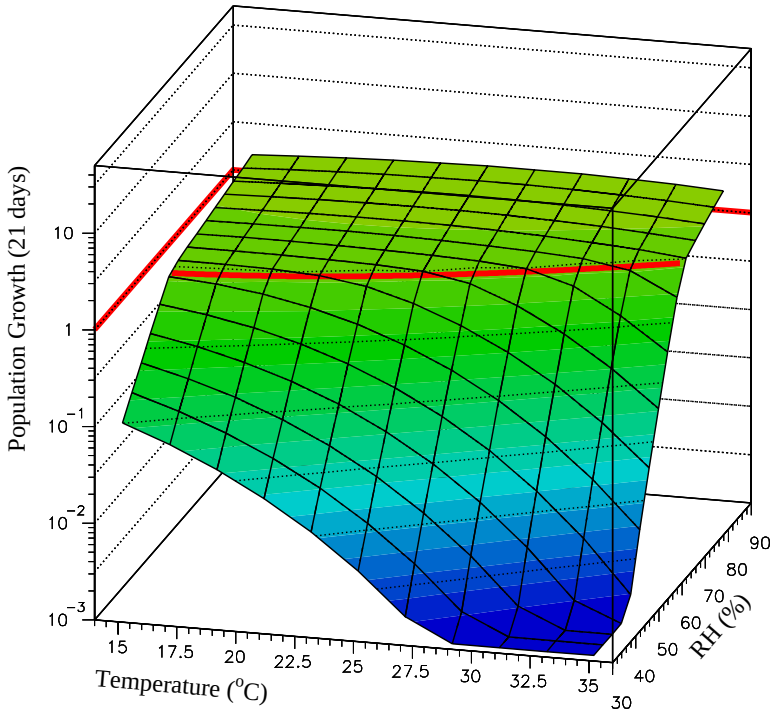
Population Growth (21 days)
10
1
10^{-1}
10^{-2}
10^{-3}
15
17.5
20
22.5
25
27.5
30
32.5
35
Temperature (^{o}C)
30
40
50
60
70
80
90
RH (%)

Fig. 6

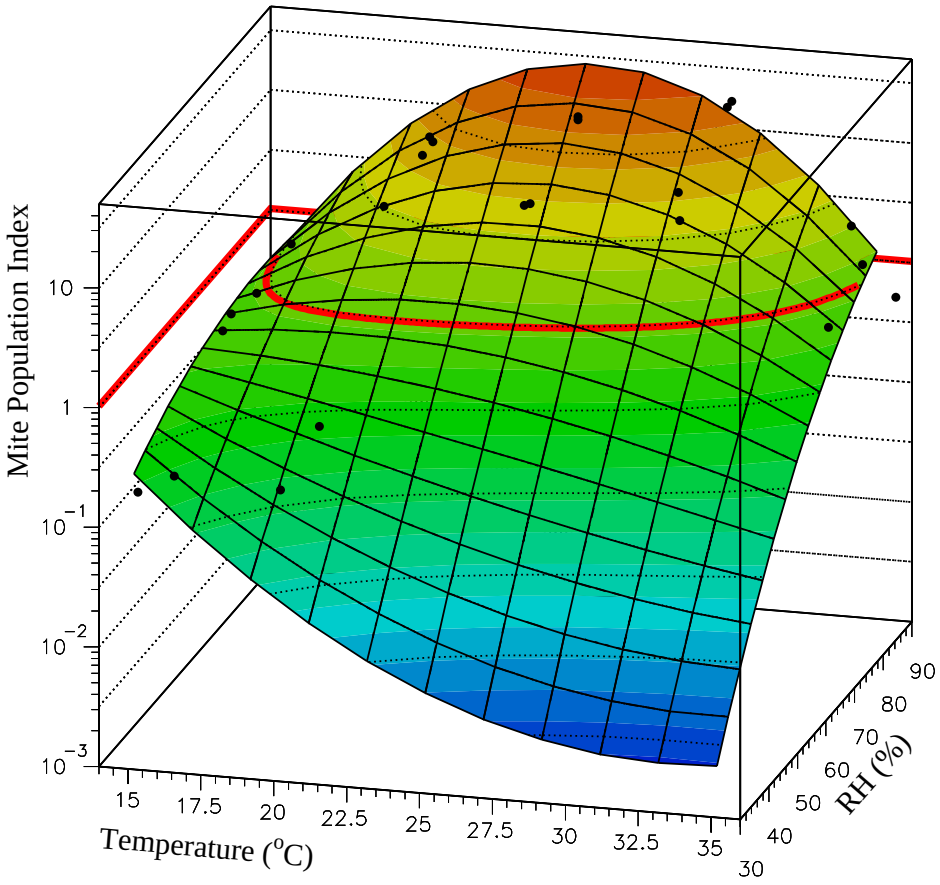
Mite Population Index
10
1
10^-1
10^-2
10^-3
15
17.5
20
22.5
25
27.5
30
32.5
35
Temperature (°C)
30
40
50
60
70
80
90
RH (%)

Fig. 7

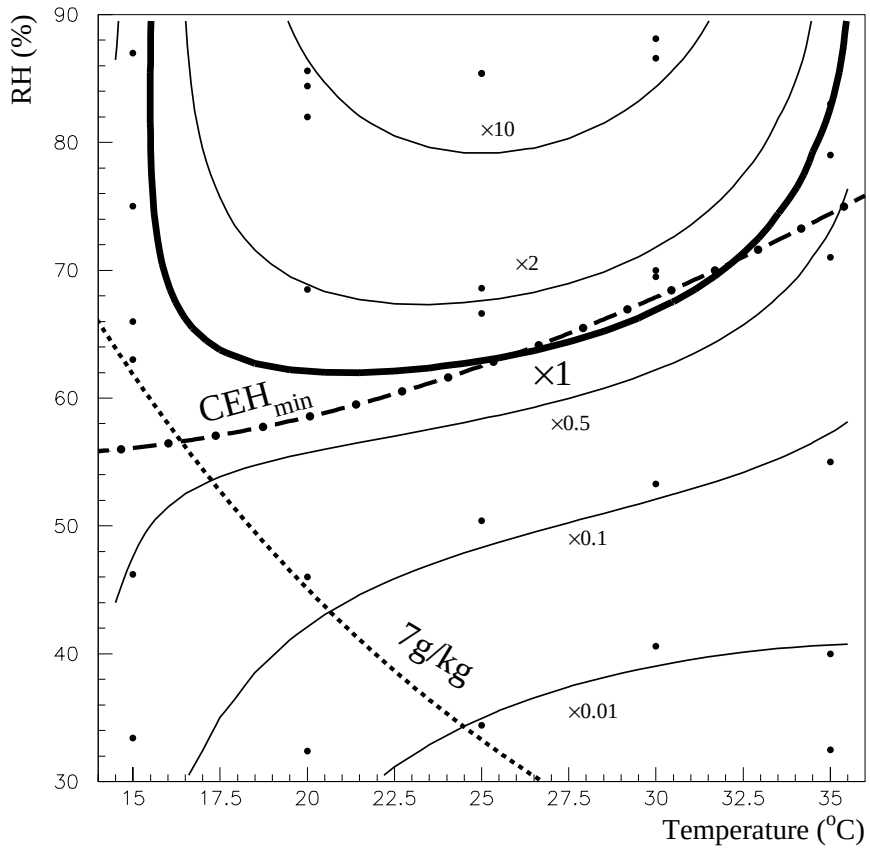
RH (%)
90
80
70
60
50
40
30
15
17.5
20
22.5
25
27.5
30
32.5
35
Temperature (°C)
×10
×2
×1
CEH min
×0.5
×0.1
7g/kg
×0.01

Fig. 8

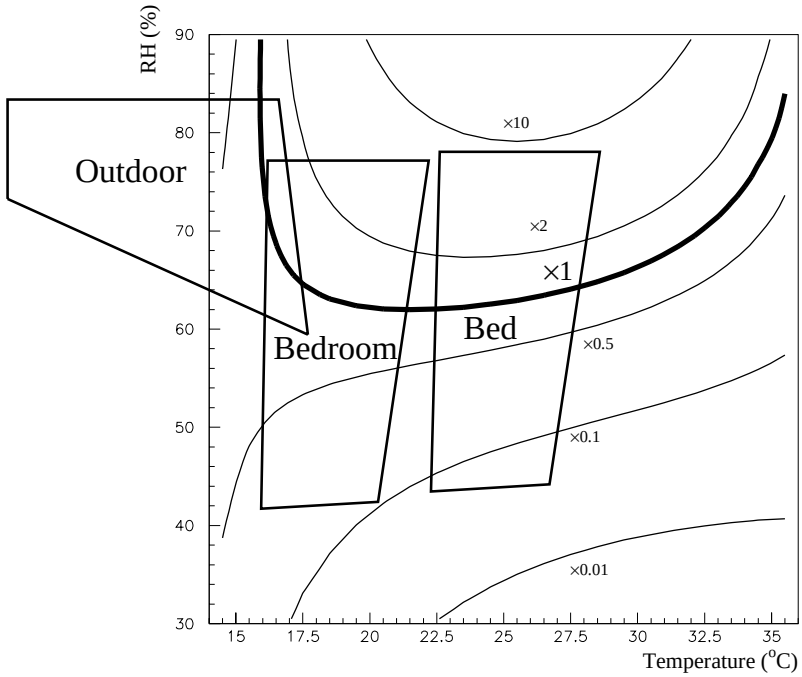
RH (%)
90
80
70
60
50
40
30
15
17.5
20
22.5
25
27.5
30
32.5
35
Temperature (°C)
Outdoor
Bedroom
Bed
×10
×2
×1
×0.5
×0.1
×0.01

Fig. 9

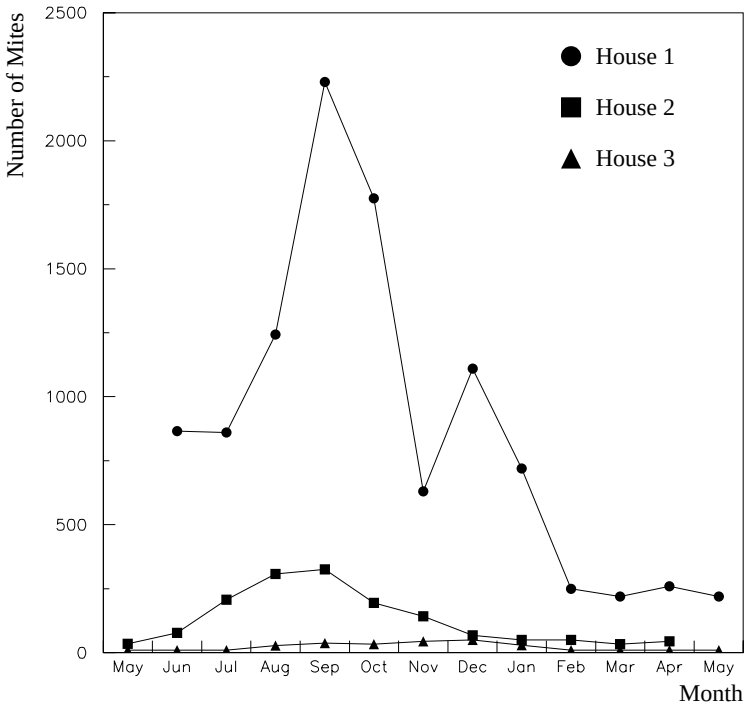
Number of Mites
2500
2000
1500
1000
500
0
House 1
House 2
House 3
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Month

Fig. 10