



A prediction of dust mite populations in different categories of housing quality in Auckland, New Zealand

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Summary

Background New Zealand has one of the highest asthma rates in the world, frequently linked to the quality of housing. A confirmed causal factor for asthma is the dust mite allergen, with environmental factors such as temperature and relative humidity (RH) linked to the proliferation of dust mites. Whilst significant research has been undertaken into the habitat and ecology of dust mites, little research has been conducted comparing different categories of housing quality in relation to dust mites.

Methods A dust mite population prediction algorithm (POPMITE) was used to undertake a comparative analysis of the potential of three housing types (old, newly constructed and newly constructed green certified) to harbour dust mites.

Results The results determined no statistically significant difference between the quality categories, and the hypothesis that newly constructed, more insulated dwellings would have lower predicted dust mite populations was rejected. Instead, the newly constructed dwellings exhibited a wide range of predicted dust mite populations indicating a potential sensitivity to occupant behaviour in new housing stock which was not experienced in the older vintage dwellings.

Conclusions Occupant behaviour is suggested as an influencing factor with a call for policy makers to consider real-time feedback loops to dwelling occupants, in conjunction with structural interventions, to improve the health of the interior environment.

Keywords Dust mites · Indoor environment · Temperature · Relative humidity · Housing · Asthma

Abbreviations

6HS	6-Homestar
AH	Absolute humidity
CEH	Critical equilibrium humidity
DP	<i>Dermatophagoides pteronyssinus</i>
IEA	International Energy Agency
LPWAN	Low-powered wider area network connection
MOTAT	Museum of Transport and Technology
NEW	New building stock
NZBC	New Zealand Building Code
OLD	Old building stock
POPMITE	A dust mite population prediction algorithm
RH	Relative humidity
WOF	Warrant of fitness

Introduction

Humans spend a significant time (up to 90%) indoors [1, 2] and it thus follows that the quality of the indoor environment constitutes one of the biggest influences on human health. New Zealanders in particular spend, on average, 70% of their time in their home [3].

New Zealand is gripped by a multi-faceted housing crisis with the poor quality of New Zealand housing gaining attention as “substandard housing is a major public health issue in New Zealand” [4, p. 1]. Substandard (cold, damp, mouldy and unsafe) New Zealand housing stock is strongly correlated with poor health [4–6]. According to Barnard et al. [4], approximately two-thirds of the housing stock is uninsulated and inadequately heated, with an average indoor temperature of 14.5 °C, which they link to higher respiratory-

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illness hospital admission rates in winter (74%) and excess winter mortality (20% greater than other seasons).

New Zealand has a high prevalence of asthma—one of the highest in the world—with one in seven children and one in eight adults reported to be taking asthma medication, making the context of what causes asthma in the New Zealand environment of interest globally [7]. The World Health Organization [8, p. 40] states that dampness or mould is associated with a range of adverse health effects, including asthma. This association has led to a strong vernacular on a link between poor-quality housing and poor health [3, 9–12], and New Zealand houses are typically decried as suboptimal, with statements like “New Zealand homes aren’t good enough. All too often, they are cold, draughty, expensive to heat” [13, n.p.].

Whilst there is a significant body of knowledge on the relationship between housing quality and health, the literature is conflicted. Linkages exist between cold and/or damp housing and reported poor health outcomes; however, no studies determine a threshold of damp exposure that causes ill health [14]. Despite the lack of a conclusive evidential base, many governments, councils and green building councils are intervening in the space of housing quality.

In New Zealand, the building code is the legislative policy mechanism that sets the minimum standard for new housing; however, a review by the International Energy Agency (IEA) [15] found that the current building code is below the standard required in most IEA countries with comparable climates. This has led to all New Zealand housing (both older vintage and newly constructed housing) being denounced as poor quality.

Until recently, no instruments were in place to address substandard existing housing, with one exception: the voluntary housing warrant of fitness (WOF). However, the clarion calls in relation to housing became so strident that, in 2019, government legislation—Residential Tenancies (Healthy Homes Standards) Regulations 2019—and a voluntary green building rating tool (HomeFit) were released for the sole purpose of evaluating existing houses. For new housing, the use of another green building rating tool, Homestar (at the six-star level), has been promoted as a panacea for the ills of an inadequate building code, gathering market adoption by social housing providers [16] and developers [17]. Thus, as of 2020, multiple policy instruments are available to apply to housing, from voluntary healthy-home checklists, and green building ratings tools to mandatory government legislation.

However, little research has been completed that reviews the potential for different levels of housing quality to provide a superior control framework to mitigate the growth and proliferation of one of the key causes of asthma: dust mites.

Literature review

The house dust mite, a tiny eight-legged arthropod, has been determined as a causative factor for asthma in the indoor environment, with the primary allergen from dust mites being their faecal waste pellets [18–20]. During their lifetime, mites produce approximately 1000 solid faecal waste particles, each about 25 μ in diameter. The weight and size of mite faecal particles are such that they become airborne when the soft substrate in which they are present is disturbed, for example by making a bed, moving one’s face on a pillow or walking on or vacuuming a carpet [19, 20]. Dust mite faecal particles are usually attached to the surface of indoor particulate matter (e.g. fine dust), which supports their transport to the respiratory tract [21]; however, other components of dust mites, such as mite bodies, egg cases and skin casts, are also associated with allergic disease [22].

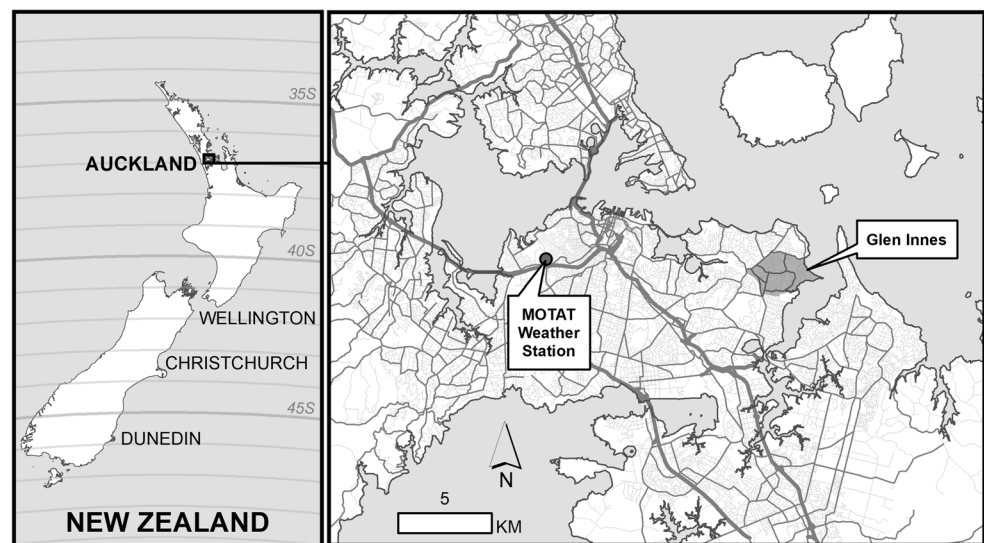
The *Dermatophagoides pteronyssinus* (DP) is the most prevalent dust mite in the world, thriving in climates with a median temperature between 8.9°C and 18.4°C and relative humidity (RH) between 65% and 82% [23]. It is also the dominant dust mite in New Zealand, with 90% of mites in a Wellington study classified as this species [24].

The indoor environment is an important factor for dust mite survival with mites flourishing in the microenvironments that exist throughout rooms and dwellings [25, 26]. Koekkoek et al. [27] determined that the optimum temperature for dust mites is 25°C. Koekkoek et al. also found that at 30°C the dust mite population is 40% less, and at 20°C the growth is very slow, with populations declining below 10°C and above 35°C. The seminal work in the area of dust mites and humidity is that of Korsgaard and Hallas [28] which suggested a lower limit of 7 g/kg below which house dust mites will not proliferate. Korsgaard [29] believed that winter humidity levels were the critical factor for the occurrence of the dust mites throughout the year. If dust mites were eradicated during the dry winter season (when the indoor air is heated) the more humid summer period was too short for the dust mites to re-establish themselves [30].

However, more recent research has refuted the findings of Korsgaard, noting that his study was undertaken on Danish housing (with typical indoor temperatures of 20–22°C and 45% RH [31]), stating that RH is more important than absolute humidity (AH) in determining mite survival [32].

The literature is conflicted on the optimal RH values for dust mite population growth and survival. Some DP researchers claim the optimal RH is 60%–65% [33]. However, this not supported by others who reference earlier research by van Bronswijk in 1981 [34] to show that a growth range of 60%–80% is more appropriate for the DP, with an optimal zone of 70%–80% [35].

Fig. 1 Study location. MOTAT Museum of Transport and Technology



Some researchers reference a critical equilibrium humidity (CEH) below which mites feed sparingly, produce little faecal material and gradually dehydrate and die [25, 35]. Cunningham [36] proposed a simple model based on the CEH where population growth occurs above the CEH and decline occurs below it. The CEH is therefore defined as the RH below which mites are unable to maintain their water balance and lose more water than they can gain. The CEH can be calculated using Eq. 1 [35]:

$$\text{CEH}_{\text{min}} = 56.75 - 0.9917T + 0.05T^2 - 0.0003T^3 \quad (1)$$

where T is the temperature.

There are some limitations to the use of the CEH, with Crowther et al. [35] noting that the CEH does not place a constraint on the growth at high RH, which is known to exist in reality. Similarly, constraints on growth are also known to exist at extreme values of temperature.

Whilst CEH has the advantage of being easy to implement, it can result in misleading results even during periods of constant conditions. For example, a population of eggs is unable to grow until at least one mating pair has matured, and, as a population develops, the numbers of egg-laying females will fluctuate naturally. This leads to fluctuating rates of population growth, which would cause problems for the more simple models, both in terms of calibration and use [37]. Due to complexities like this, and the large number of variables in relation to mite population dynamics, a modelling approach is typically required. One such model is the computer simulation program POPMITE, which can be used to study dust mite populations in beds based on varying environmental factors [37].

This research utilises the POPMITE program to predict potential dust mite populations across three different categories of housing in Auckland, New

Zealand, postulating that improved housing quality would result in lower dust mite populations, through the provision of warmer, drier indoor environments.

Data and methods

This study was completed over the 2019 summer/autumn period in Auckland, New Zealand. The study population consisted of 22 houses in Glen Innes, Auckland (see Fig. 1), a suburb dominated by social housing. All of the dwellings are owned by a single social housing provider and are occupied by social housing tenants with subsidized rents and are therefore quite homogeneous.

This suburb was specifically selected for the study as it is currently undergoing major redevelopment. This has resulted in the unique situation of a large number of old and new housing types being present at the same time. In addition, some of the new housing has been certified using a green building rating tool called Homestar. The dwellings can therefore be categorised as either:

- (i) Old building stock (OLD): i.e. built in the 1950s to a previous version of the New Zealand Building Code (NZBC)
- (ii) New building stock (NEW): i.e. new houses that completed construction in 2018 under the new version of the NZBC (2007)
- (iii) 6-Homestar (6HS): i.e. new building stock that completed construction in 2018 under the new version of the NZBC that also held a 6-Homestar Built Rating

Data loggers were used to monitor the indoor temperature of the dwellings. One device was installed per dwelling, on an interior wall adjacent to another internal room, in the main living area, at seated head height (1.1 m off the floor) in accordance with previous research in NZ [38]. The data loggers are bat-

tery powered, the size of a standard smoke alarm and are able to measure temperature from a range of between -40°C and 85°C , at an accuracy of $\pm 0.2^{\circ}\text{C}$, with a reading taken every 30 min.

Data loggers¹ were used to measure temperature, RH and pressure. These data loggers were specifically chosen for use in this study due to their ability to send information, on a real-time basis, over the low-powered wider area network connection (LPWAN) to a central server.

Additional information was also gathered from the social housing provider on the physical properties of each dwelling, as per Table 1. R-values for insulation are presented in this table as that is the unit of measurement for both insulation and overall wall constructions in NZ as opposed to U-values in other countries.

One notable difference between the different categories of dwellings is that newly constructed dwellings are a mix of apartments, terraced housing (form of attached townhouse) and standalone houses, whilst the OLD dwellings are all standalone (Table 1). This has resulted in the overall exposed thermal envelope of some of the newly constructed dwellings being smaller than the older dwellings as walls (as well as floors and ceilings in the case of the apartments) are adjacent to other occupied spaces.

None of the study houses had whole-house ventilation and only two had active cooling (via a heat pump) as these types of systems (as well as central heating) are not yet common in New Zealand, unlike other countries around the world.

Outdoor weather conditions were captured from the NZ national weather database CliFlo. CliFlo is the web system that provides access to NZ's National Climate Database. It returns raw data and statistical summaries in 10-min, hourly and daily frequencies. The Auckland MOTAT (Museum of Transport and Technology) weather station (15 km from the study houses) was identified as the most suitable and complete source of exterior weather information for this study.

A download of data was completed at the end of June 2019. The data were analysed to determine the number of data records present for each dwelling. Whilst most dwellings recorded ranges of 7000–8000 data points, some presented with lower figures. Any dwelling with fewer than 4000 data records was removed from the data set.

The remaining data records were then analysed using three baselines. The first being the non-dynamic thresholds for dust mite proliferation determined in the literature review of temperature: $20\text{--}30^{\circ}\text{C}$ (optimal temperature of 25°C), RH: 60%–80% and AH: $>7\text{ g/kg}$. The data set was encoded to determine when

a dwelling met each of the three requirements with the AH calculated using the recorded measurements of pressure and RH and Eq. 1 and 2:

$$RH = \frac{P_i}{P_{i(\text{sat})}} * 100\% \quad (2)$$

$$AIH = \frac{P_i * MW_i}{(P - P_i) * MW_{\text{dry}}} \quad (3)$$

where

P_i is the partial pressure in mm Hg

$P_{i(\text{sat})}$ is the saturation pressure at the particular temperature in mm Hg

MW_i is the molecular weight of water which is $18\text{ gH}_2\text{O/mol}$

P is measured in Pa

MW_{dry} is the average molecular weight of air which is 29 gair/mol .

As the data loggers measure pressure in Pa, a conversion needed to be undertaken to get from Pa to mm Hg ($1\text{ Pa} = 0.00750062\text{ mm Hg}$).

The amount of time that each dwelling spent in these zones was calculated and then aggregated into category totals.

The second baseline utilised is the CEH postulated by Cunningham [36] below which dust mite populations would decline. Equation 1 was utilised to determine the CEH at each temperature timestamp. The measured RH was then assessed against calculated CEH and records above the CEH flagged. The data was then aggregated into the amount of time each category spent above the CEH.

The third baseline is the dynamic dust mite population-modelling software POPMITE. The POPMITE version 8 computer software was sourced directly from Biddulph in 2019. The POPMITE executable requires three basic sets of information: (i) a species file that details the 23 separate parameters needed to describe a species of mite, (ii) an environmental file that provides the time-ordered hygrothermal (RH and temperature) conditions and (iii) a population file containing the initial numbers, ages, hydration and food content of mite eggs, juveniles and adults.

Although only one data logger was installed in each dwelling, in the living room (the bedroom was not able to be measured due to a limited number of devices), previous studies in New Zealand have indicated a good correlation between mean temperatures in living rooms and bedrooms, with Rangiwetua et al. [11] finding mean temperatures of 15°C and 14.9°C , respectively. The living room data records for temperature and RH from the data loggers were therefore utilised for the environmental file for the POPMITE simulation.

The species file used was that of the DP dust mite. For the population file each simulation with a population of 100 male and 100 female adult mites, each at a different rate of development between 0 and 100% (one male and female at each % development step).

¹ Human Participants Ethics Committee approval was granted prior to installation of the data loggers.

Table 1 Dwelling features

Category	House number ^a	Type	Occupants	Orientation	Double glazing	Window restrictors	Floor Overall construction R value (m ² K/W)	Wall Overall construction R value (m ² K/W)	Ceiling Overall construction R value (m ² K/W)	Kitchen range-hood	Central heating/cooling
6HS	House 1	Terrace	4	SW	Y	Y	1.6	2	3.1	Y	N
	House 2	Apartment (ground)	1	N	Y	Y	1.7	2.1	3.4	Y	N
	House 3	Apartment (second)	1	SW	Y	Y	Na	2.1	3.4	Y	N
	House 4	Terrace	2	NE	Y	Y	1.6	1.9	3.1	Y	N
	House 5	Terrace	3	N	Y	Y	1.5	1.9	2.7	Y	N
	House 6	Apartment (second)	1	E	Y	Y	Na	2.1	3.4	Y	N
	House 7	Duplex	1	NW	Y	Y	1.6	2	3.4	Y	N
	House 8	Duplex	6	NW	Y	Y	1.8	2	3.4	Y	N
	House 9	Terrace	2	NW	Y	Y	1.8	2	3.4	Y	N
	House 10 ^a	Apartment (ground)	1	NE	Y	Y	1.7	2.1	3.4	Y	N
NEW	House 11 ^a	Standalone	6	NE	Y	Y	1.5	2.1	3.4	Y	N
	House 12	Apartment (Ground)	1	E	Y	Y	1.7	2.1	3.4	Y	N
	House 13	Duplex	1	NW	Y	Y	1.6	2	3.4	Y	N
	House 14	Terrace	2	S	Y	Y	1.3	1.9	2.9	Y	N
	House 15	Standalone	3	N	Y	Y	1.3	1.9	2.9	Y	N
	House 16	Standalone	5	NE	Y	Y	1.3	1.9	3	Y	N
	House 17	Standalone	4	NE	Y	Y	1.3	1.9	3.2	Y	N
	House 18 ^a	Standalone	4	N	Y	Y	1.25	2	3.4	Y	N
	House 19 ^a	Standalone	2	SE	Y	Y	1.38	1.85	2.4	Y	N
	House 20	Standalone	4	N	Y	Y	1.8	2	3.1	Y	N
OLD	House 21	Standalone	2	E	N	Y	1.2	1.35	1.7	N	N
	House 22 ^a	Standalone	4	S	N	Y	1.2	1.35	1.7	Y	N
	House 23	Standalone	1	S	N	Y	1.2	1.6	1.7	N	N
	House 24	Standalone	2	S	N	Y	1.2	1.35	1.7	N	N
	House 25	Standalone	4	S	N	Y	1.2	1.35	1.7	N	N
	House 26	Standalone	4	W	N	Y	1.2	1.35	1.7	N	N
	House 27	Standalone	2	E	N	Y	1.2	1.35	1.7	Y	N
	House 28 ^a	Standalone	2	E	N	Y	1.2	1.35	1.7	N	N
	House 29 ^a	Standalone	4	E	N	Y	1.2	1.35	1.7	Y	N
^a Original data collection was over 29 dwellings. seven were removed during analysis due to missing data											
6HS 6-Homestar, NEW new building stock, OLD old building stock, SW south west, NW north west, S south, SE south east, E east, NE north east, W west, Y yes, N no											

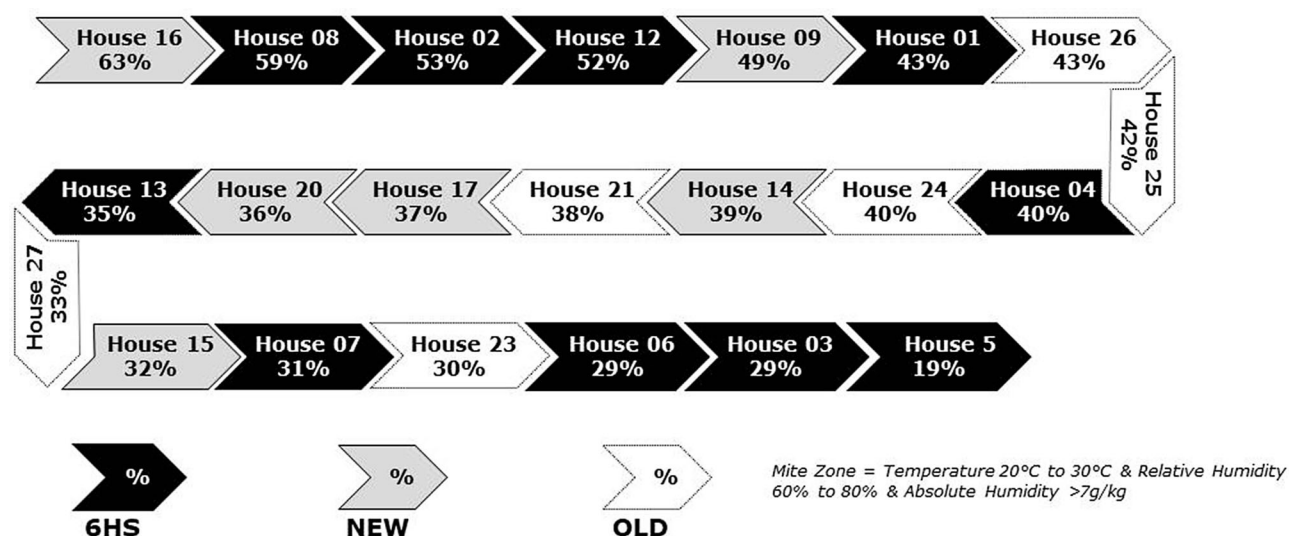


Fig. 2 Percentage of time each dwelling spent at the intersection of 20°C–30°C, 60%–80% relative humidity and >7g/kg absolute humidity (a theoretical 'mite zone' for the months of January through June 2019)

Table 2 Percentage of time per category of housing quality spent at the intersection of interior-environment-quality zones that support dust mite populations

	Dust mite growth zone 20 to 30 °C, 60 to 80% RH, >7g/kg AH
6HS	40%
NEW	41%
OLD	38%

RH relative humidity, *AH* absolute humidity, *6HS* 6-Homestar, *NEW* new building stock, *OLD* old building stock

This approach was determined to most realistically simulate the situation experienced in each of these dwellings where, particularly in the NEW and 6HS dwellings, the social housing tenants would have relocated existing furniture (including their existing dust mite populations) into the dwellings.

Results

The literature identified dust mite population growth at: (i) temperature 20°C–30°C, (ii) RH 60%–80% and (iii) AH of >7g/kg. However, whilst the temperature might be optimal for dust mite growth, it is possible that the humidity (either RH or AH) could be too low to support dust mites. A 'sweet spot' theoretically exists where the temperature, RH and AH all fall within the ranges for dust mite growth and proliferation, and the data was analysed to determine the amount of time a dwelling spent at the intersection of these three parameters.

The amount of time that each dwelling spent in the sweet spot or mite zone is shown in Fig. 2, with the results indicating that housing quality has no particular effect on the amount of time spent in the mite zone, with no particular grouping of dwellings evident. The data was also aggregated by category (Table 2), fur-

ther supporting a conclusion that the different levels of housing quality may have little effect on dust mite populations.

The CEH for each hour was calculated using the measured temperature data and each data record was coded to determine whether the humidity in the dwelling was above this threshold. The results were aggregated into the percentage of time each dwelling and category spent over the CEH (Fig. 3 and Table 3).

It is interesting to note that the CEH presents conflicting results when compared to the findings of the mite zone (temperature, RH and AH intersection) analysis. Regardless of dwelling type, all dwellings spent over 50% of the study timeframe above the CEH. The older vintage housing spent the greatest amount of time above this threshold, with the newer housing in the middle and the green certified dwellings spending the least amount of time above the CEH.

However, as identified in the literature, the CEH does not constrain population at high RH, and as the older vintage dwellings spend 13% of the time above 80% RH, the CEH is likely not the best prediction of the relative performance between the three categories of dwelling quality. POPMITE simulations were therefore also run for each dwelling.

The outputs from POPMITE consist of hourly predicted-population counts of: (i) eggs, (ii) juveniles, (iii) adult females and (iv) adult males. It is not possible to simply take the final predicted adult-population figure, as predicted-population counts vary over time as shown in Fig. 4. The maximum predicted mite population at any one time is also of interest as the amount of allergen present in a dwelling is linked to the excretions/secretions of dust mites rather than the current live population count.

To gain an understanding around the relative performance of the different categories of housing, the

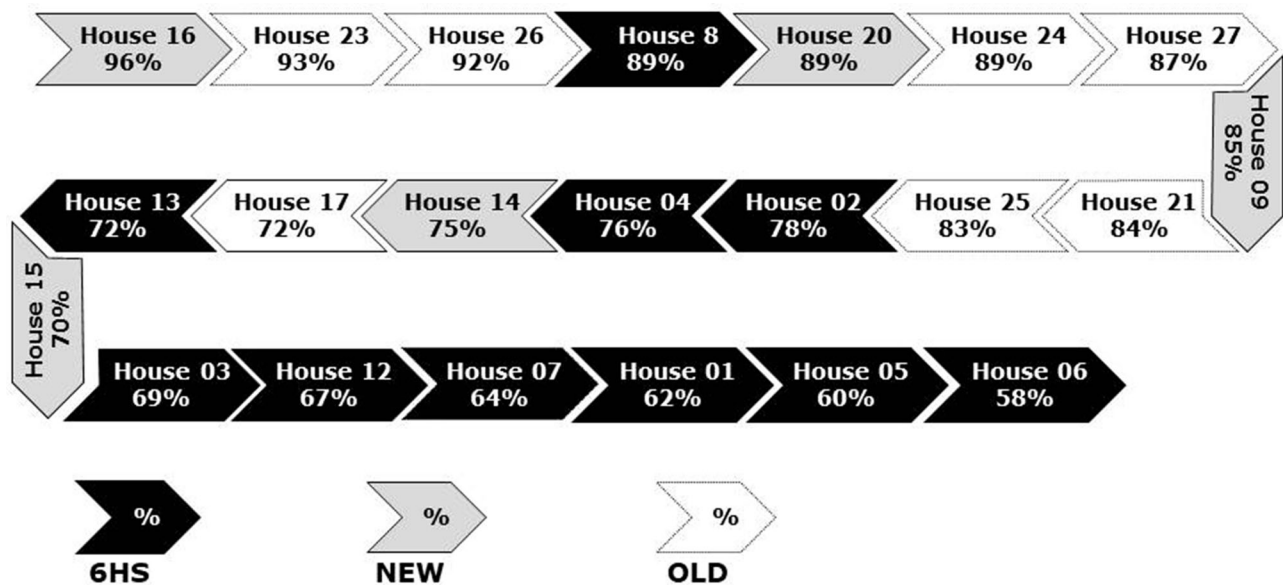


Fig. 3 Percentage of time each dwelling spent above the critical equilibrium humidity in the months of January through June, 2019

Table 3 Percentage of time each category spent above the critical equilibrium humidity (CEH) in the months of January through June, 2019

	Percentage of time above the CEH	Percentage of time above 80% RH
6HS	71	1
NEW	79	2
OLD	88	13

RH relative humidity, *CEH* critical equilibrium humidity, *6HS* 6-Homestar, *NEW* new building stock, *OLD* old building stock

outputs from the simulations were aggregated to give the median, mean, minimum and maximum mite population figures—comprising the addition of the juveniles and adult males and females (Table 4).

Table 4 and Fig. 5 show a disparity between the different categories of dwelling quality, particularly in terms of maximum population figures. A Kruskal-Wallis test, commonly referred to as a non-parametric one-way analysis of variance (ANOVA), was utilised to determine whether there was a significant difference across the results of the categories. The test results indicate that whilst there are differences between each category, the differences are not statistically significant.

Table 5 shows that the newer dwellings (6HS and NEW) cluster at the upper and lower total population counts with older vintage dwellings (OLD) mostly clustered in the middle. This correlates well with the findings presented in Fig. 2, but is contradictory to Fig. 3. This contradiction is likely due to the fact that the OLD dwellings spend more time in the upper RH range, past the cut-off point for dust mite population growth which the CEH does not recognise. The wide disparity within the newer vintage dwellings' (NEW and 6HS) predicted populations indicates that it may

not be possible to evaluate the results solely in terms of the quality category.

The majority of the studied dwellings face north (either due north, north east or north west) and a Kruskal-Wallis test was undertaken to determine whether there was any statistical significance for orientation in the dust mite population counts. This test returned a result of 0.881, 0.988 and 0.999 for the median, mean and maximum population counts, respectively, indicating that the orientation of the dwelling also does not affect the predicted mite populations.

The two dwellings with the lowest population counts are located on the second floor of an apartment building, and a Kruskal-Wallis test indicates that there is a significant difference between these dwellings and the ground-floor dwellings. However, with only two data points above ground, strong conclusions cannot be drawn from this, although it is possible that a stack effect is occurring that is increasing the temperature (and thus reducing RH) to a point where dust mite populations cannot be supported.

Discussion, limitations and conclusions

Discussion

According to Letitia O'Dwyer, the previous chief executive of the Asthma and Respiratory Foundation of New Zealand, dust mite numbers peak in New Zealand in March and April [39], and this was the time period when predicted dust mite populations of five newly constructed dwellings exploded.

Older vintage housing is typically maligned as being cold and damp, which is linked to poor health out-

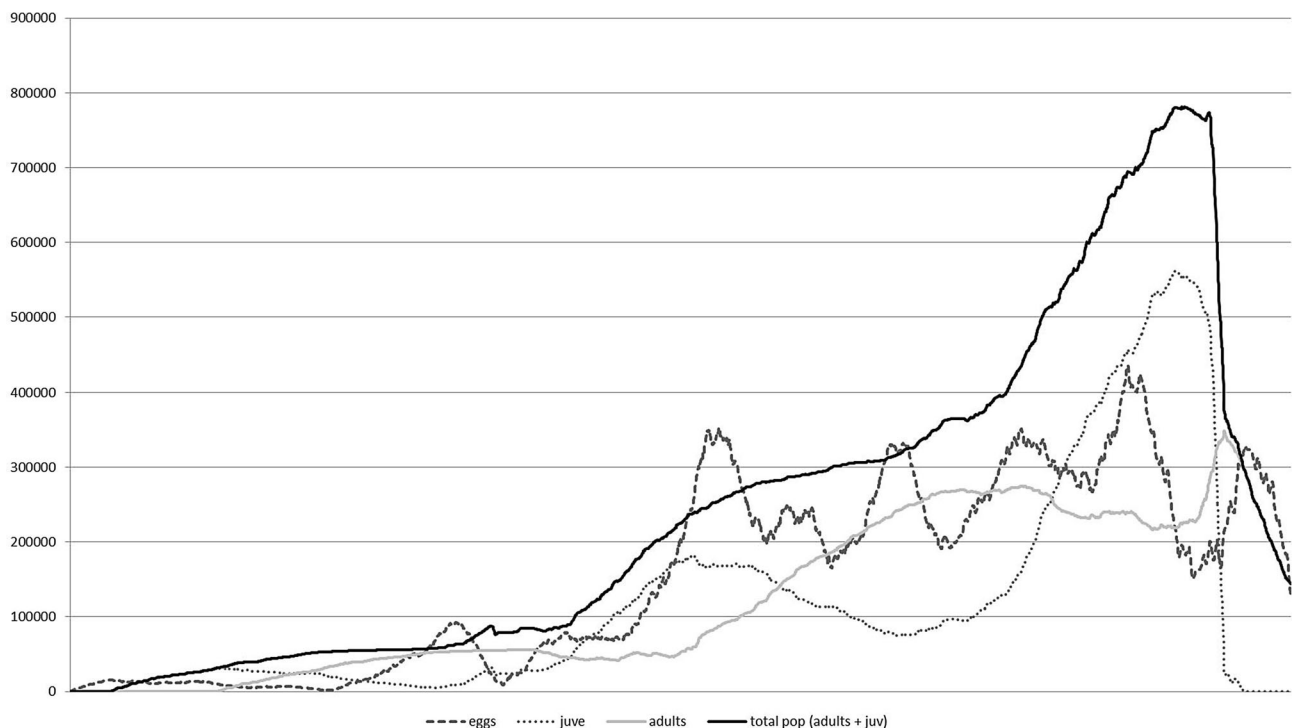


Fig. 4 Example POPMITE simulation result for a dwelling (6HS | House 1), starting population 100 males and 100 females, over the period of January through June 2019.

eggs dust mite eggs, *juve* juvenile dust mites (male and female), *adults* adult dust mites (male and female)

Table 4 Exploration of predicted dust mite populations by category

		Maximum	Mean	Median
Starting population of 100 males and 100 females	6HS	3,843,099	460,466	73,996
	NEW	3,432,409	433,280	215,877
	OLD	656,342	272,686	314,998
Kruskal-Wallis Test significance results	—	0.931	0.788	0.257
6HS 6-Homestar, NEW new building stock, OLD old building stock				

comes including asthma. The findings of this study support this conclusion, with all the older vintage dwellings performing in a very consistent, typically poor manner. The newer housing stock presents confounding results, with some dwellings performing exceptionally well, whilst others perform badly. These differences could not be segregated by quality category (i.e. NEW and 6HS) and no difference was identified in the performance of the new housing built to code (NEW) and the green certified (6HS) dwellings. Three newly constructed dwellings experience high modelled dust mite populations and, in counterpoint, there are four, also newly constructed, dwellings that have extremely low modelled populations. Two of the dwellings with low population counts are second level apartments. It is therefore possible that a stack effect is occurring, increasing interior temperature and reducing RH to a point where dust mite populations cannot be supported.

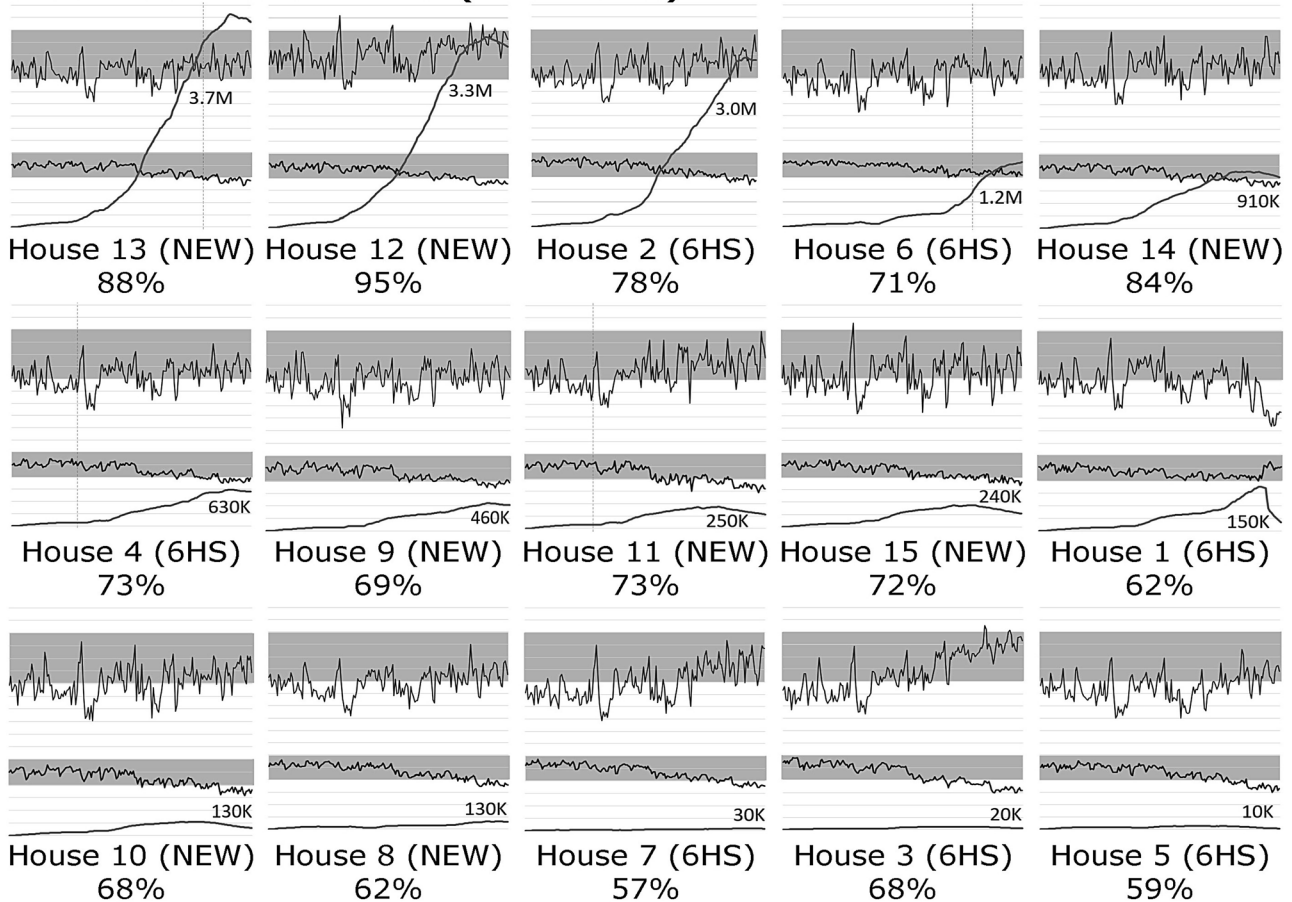
Occupant behaviour is another likely influence. Fig. 4 shows that House 1 experiences a temperature jump in late May (which is late autumn/early winter in New Zealand) corresponding to a crash in predicted dust mite population, which until that point in time had been steadily increasing. This temperature change may be attributable to the dwelling occupant using some type of space heating, raising the temperature, depressing RH and suppressing the dust mite population.

The results appear to indicate that the more highly engineered (insulated) thermal envelopes of new housing may be less forgiving to occupant behaviour when compared to the older housing stock. The older vintage housing, with lower levels of insulation, does not experience the extreme highs or lows of predicted dust mite populations of the newer dwellings. This may indicate that the lower performing thermal envelope plays a role in regulating dust mite populations.

Some new housing is predicted to have low mite populations, whilst others are predicted to reach extremely high counts, potentially documenting that, whilst the newer housing stock is meant to be superior, if it is operated poorly it can actually perform worse than the older vintage housing.

Currently, there is no requirement in the mandatory building code or voluntary green building rating tools for the inclusion of real-time interior-environment-quality monitoring and occupant reporting, with the provision of a healthy interior environ-

NEWLY BUILT DWELLINGS (6HS & NEW)



OLD DWELLINGS (OLD)

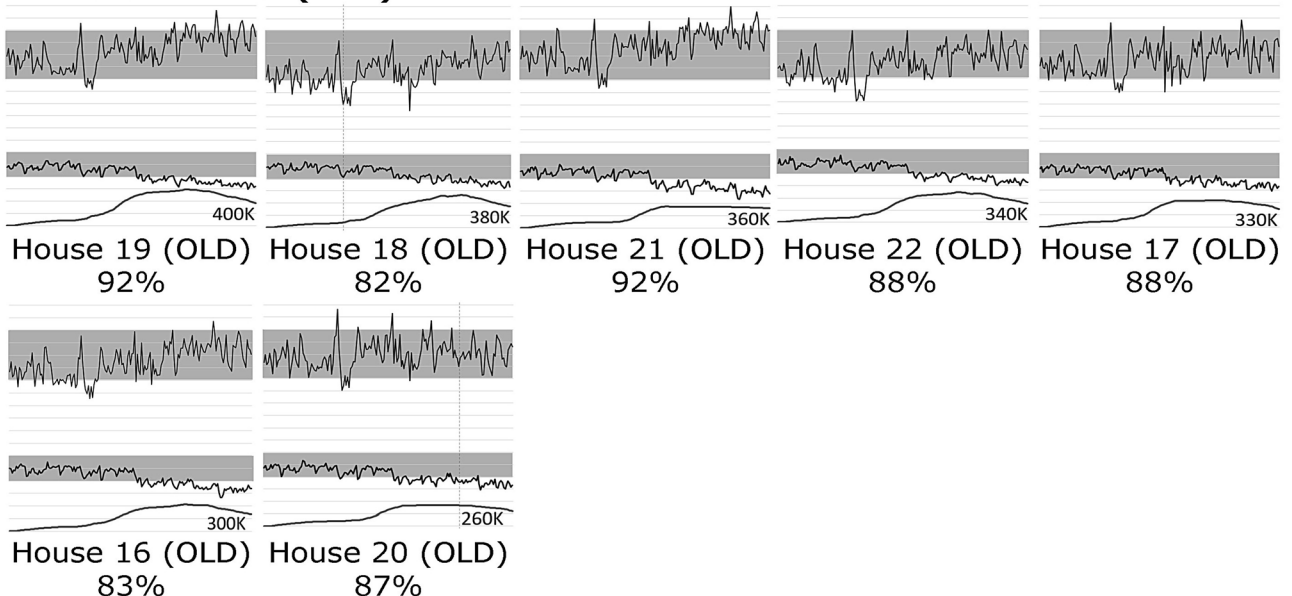


Fig. 5 POPMITE simulation results for each dwelling with population dynamics (*bottom*) and temperature (*middle*—healthy range in grey) and relative humidity (*top*—healthy

range in grey) plotted and maximum population count notated for the period January through June 2019. 6HS 6-Homestar, NEW new building stock, OLD old building stock

Table 5 Ranked summary of maximum dust mite population counts

Maximum	Median	Mean	CEH (%)	Category	House number	Orientation	Type
3,843,099	719,718	1,418,066	89	6HS	House 08	NW	Duplex
3,432,409	777,835	1,321,754	96	NEW	House 16	NE	Standalone
3,056,750	442,990	1,026,927	78	6HS	House 02	N	Apartment (ground)
1,166,350	182,370	321,860	67	6HS	House 12	E	Apartment (ground)
1,016,555	471,990	481,980	85	6HS	House 09	NW	Terrace
781,327	202,439	241,038	62	6HS	House 01	SW	Terrace
662,069	246,179	274,846	76	6HS	House 04	NE	Terrace
656,342	441,021	358,145	92	OLD	House 26	W	Standalone
593,951	345,423	294,436	83	OLD	House 25	S	Standalone
558,314	362,902	295,449	89	NEW	House 20	N	Standalone
493,816	220,362	215,311	75	NEW	House 14	S	Terrace
483,479	340,765	278,759	89	OLD	House 24	S	Standalone
473,487	309,266	254,893	84	OLD	House 21	E	Standalone
395,411	343,711	203,816	72	NEW	House 17	NE	Standalone
389,243	279,894	234,592	93	OLD	House 23	S	Standalone
389,033	241,184	196,041	72	6HS	House 13	NW	Duplex
371,422	269,805	218,288	87	OLD	House 27	E	Standalone
243,020	139,570	130,071	70	NEW	House 15	N	Standalone
135,800	55,382	59,987	64	6HS	House 07	NW	Duplex
54,027	34,357	35,336	60	6HS	House 05	N	Terrace
50,955	23,952	27,779	69	6HS	House 03	SW	Apartment (level 2)
40,407	18,888	19,643	58	6HS	House 06	E	Apartment (level 2)

CEH critical equilibrium humidity, 6HS 6-Homestar, NEW new building stock, OLD old building stock, SW south west, N north, NE north east, E east, NW north west, S south, SE south east, W west

ment instead predicated on the provision of structural building elements such as insulation. Occupants are thus unaware of whether their interior environment has drifted into risk zones. If dwellings were actively monitored, with occupant feedback loops that alert when dust mite risk zones are reached, occupants could implement positive actions (like turning on a space heater) to improve their interior environment.

Limitations and future research

This study explored the potential for different categories of housing quality to support dust mite populations, utilising measured interior-environment data. Whilst POPMITE is the most advanced prediction methodology currently available, the outputs from the model have, to date, only been verified within a laboratory with 6 weeks of population growth data from caged mites. This study has extended the capabilities of the modelling program, utilising it over a 6-month timeframe. Future research could team the methodology of this study with actual dust mite and allergen counts from houses to determine whether a difference is experienced in reality between the three housing types over a wider population base and extended study timeframe.

The results of this study are also limited by the small number of dwellings reviewed in the study (seven 6HS,

eight NEW and seven OLD), the single subdivision location and the heterogeneity of the building orientations. Whilst information was gathered from the social housing provider on structural building characteristics such as insulation levels, a more in-depth interview process with dwelling occupants was not undertaken. The authors therefore have no understanding regarding the personal preferences or behaviour of the occupants. The findings of the study indicate that occupant behaviour may exert an influence and future research could team the methodology of this study with a survey of occupant behaviour.

Conclusions

This study is the first identified attempt at predicting dust mite populations in dwellings of differing quality (older vintage, newly constructed and newly constructed green certified) utilising measured temperature and RH data.

The results determined no statistically significant difference between the quality categories and the hypothesis that newly constructed, more insulated dwellings would have lower predicted dust mite populations must be rejected. Instead, the newly constructed dwellings exhibited a wide range of predicted dust mite populations, indicating a potential sensitivity to occupant behaviour in new housing

stock which was not experienced in the older vintage dwellings.

These findings hold significant implications for policy makers, illustrating that a reliance on structural interventions, such as increased insulation levels, may not be sufficient to deliver healthy housing. Instead, policy makers may need to look towards teaming occupant education programmes, in conjunction with real-time delivery of interior-environment information, with current programmes to improve the structural fabric of dwellings.

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Conflict of interest R. Ade is a Homestar Assessor and has worked as a Homestar Assessor for the Building Excellence Group. R. Ade also has an interest in Tether. M. Rehm declares that he has no competing interests.

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